# The 14th World Construction Symposium - 2026

*Towards a Regenerative Built Environment: From Foresight to Action*

Towards a Regenerative Built Environment: From Foresight to Action
10-11 July 2026 - Colombo

S Y M P O S I U M

# PROCEEDINGS

**10 - 11 JULY** 2026

**COLOMBO** SRI LANKA

## ORGANIZED BY

CEYLON INSTITUTE OF BUILDERS (CIOB) SRI LANKA

DEPARTMENT OF BUILDING ECONOMICS
UNIVERSITY OF MORATUWA

## ENDORSED BY

MINISTRY OF HOUSING, CONSTRUCTION AND WATER SUPPLY
MINISTRY OF ENERGY
MINISTRY OF TRANSPORT, HIGHWAYS AND URBAN DEVELOPMENT

## ASSOCIATE PARTNERS

CSCT CAMPUS
WESTERN SYDNEY UNIVERSITY
DEAKIN UNIVERSITY
Adelaide University
MASSEY UNIVERSITY
UNIVERSITY OF NEW ZEALAND
BNCA

PROCEEDINGS

of

THE 14TH WORLD CONSTRUCTION SYMPOSIUM 2026

ON

# TOWARDS A REGENERATIVE BUILT ENVIRONMENT: FROM FORESIGHT TO ACTION

10-11 July 2026


EDITORS

Prof. K.G.A.S. Waidyasekara
Dr. H.S. Jayasena
Dr. H. Chandanie
Dr. G.A. Tennakoon

Building Economics and Management Research Unit (BEMRU)
Department of Building Economics
University of Moratuwa

Edited by Prof. K.G.A.S. Waidyasekara, Dr. H.S. Jayasena, Dr. H. Chandanie and Dr. G.A. Tennakoon

ISSN: 2362-0919
© Ceylon Institute of Builders - Sri Lanka

The papers published in this proceeding reflect the opinion of the respective authors. Information contained in this proceeding has been obtained by the editors from sources believed to be reliable. Authors of specific papers are responsible for the accuracy of the text and technical data. Neither the publisher nor the editors guarantee the accuracy or completeness of any information published herein, and neither the publisher nor the editors shall be responsible for any errors, omissions, or damages arising out of use of this information. Trademarks are used with no warranty of free usability.

All rights reserved. No part of this publication, including the cover design, may be reproduced, stored or transmitted in any form or by any means, whether electrical, chemical, mechanical, optical, recording or photocopying, without prior permission of the publisher.

# SYMPOSIUM ORGANISERS

## The Ceylon Institute of Builders (CIOB), Sri Lanka

Established in 1961, the Ceylon Institute of Builders (CIOB) is the premier institute for Building Professionals in Sri Lanka with a strong network of Engineers, Architects, Surveyors and similar allied professions who work to inspire, encourage, educate and train students, builders, and professionals in the country. The institute welcomes young entrants and mature professionals with or without a background in construction to achieve professional level careers in the country. They are provided with a well-structured development programme that eventually leading to gaining corporate membership of the institute.

http://www.ciob.lk/

## Department of Building Economics University of Moratuwa, Sri Lanka

The Department of Building Economics, University of Moratuwa, Sri Lanka was founded in 1983. It is currently the pioneer Sri Lankan institution to offer programmes in Quantity Surveying, Project Management, and Construction Law and Dispute Resolution. Building Economics and Management Research Unit (BEMRU) is the research arm of the Department of Building Economics, which specialises in research in Building Economics and Management in the country as well as internationally.

https://uom.lk/becon

# ASSOCIATE PARTNERS

## Adelaide University

Adelaide University is a newly established institution formed through the merger of University of Adelaide and University of South Australia. As one of Australia's largest universities that is a member of Group of 8, it is designed to be a globally competitive, research-intensive institution offering innovative and industry-aligned education across disciplines including architecture, engineering, design, and the built environment.

Adelaide University offers a broad range of undergraduate and postgraduate programs supported by contemporary infrastructure and interdisciplinary learning spaces. Its campuses integrate advanced laboratories, design studios, and collaborative environments that emphasize hands-on learning and real-world application. Facilities include digital fabrication labs equipped with 3D printing, immersive technologies, and emerging digital technologies that support creative exploration and technical development.

The university also provides comprehensive student amenities, including modern libraries, digital learning platforms, and vibrant campus communities. With a strong focus on global collaboration, sustainability, and innovation, Adelaide University promotes a holistic educational approach, preparing students to become future-ready professionals and leaders in a rapidly evolving world.

https://www.adelaide.edu.au/

## Centre for Smart Modern Construction, Western Sydney University, Australia

Western Sydney University is a world-class university with a growing international reach and reputation for academic excellence and impact-driven research. It is ranked amongst the top three percent of universities in the world, globally focused, research-led and committed to making a positive impact – at a regional, national and international level. It was established as a modern university in 1989 from its predecessors dating back to 1891. The WSU currently has over 40,000 students in a sprawling series of campuses across the Western Sydney region.

https://www.westernsydney.edu.au/

## Deakin University, Australia

Deakin University is a public university in Australia, with multiple campuses across Victoria and New South Wales. It was founded in 1974 and is named after Alfred Deakin, Australia's second Prime Minister. Deakin University offers undergraduate, postgraduate, and research courses across a wide range of disciplines, including Arts, Business and Law, Education, Engineering, Health, Information Technology, Science, and Sport.

https://www.deakin.edu.au/

# ASSOCIATE PARTNERS

## Indian Institute of Technology Madras (IIT Madras), India

Indian Institute of Technology Madras is one among the foremost institutes of national importance in higher technological education, basic and applied research. The institute has sixteen academic departments and a few advanced research centres in various disciplines of engineering and pure sciences, with nearly 100 laboratories organized in unique pattern of functioning.

http://www.iitm.ac.in

## Massey University, New Zealand

Massey University is a reputable institution of higher learning located in New Zealand that prides itself on academic leadership, research excellence, and innovative teaching grounded in real-world issues. The university offers a range of academic programs and services to support the academic and personal development of its students. The university offers postgraduate degrees that you can complete fully online and is the leading university in New Zealand for online and borderless education.

https://www.massey.ac.nz/

## MKSSS's Dr B N College of Architecture for Women, Pune, India

Dr. Bhanuben Nanavati College of Architecture for Women (BNCA), located in Karve Nagar, Pune, is a premier institute affiliated with Savitribai Phule Pune University and part of the Maharshi Karve Stree Shikshan Sanstha. It offers undergraduate and postgraduate programs in architecture exclusively for women. The campus features advanced facilities, including India's first Fab-Lab in Digital Architecture with 3D printing, CNC machines, and robotic arms. BNCA also provides a well-stocked digital library, paperless LMS, modern studios, and fully equipped workshops. Hostel accommodation is available for over 1,200 students, with amenities like a gym, dining halls, and solar water heating. As a United Nations Academic Impact (UNAI) Hub, BNCA promotes global collaborations and holistic education, nurturing future-ready architects.

https://bnca.ac.in/

## Colombo School of Construction Technology (CSCT), Sri Lanka

The CSCT was established in 2008, with the motto 'Sapientia et Doctrina', which is Latin for Wisdom and Learning. It strives to create a learning environment to nurture the development of critical thinking skills; support innovation; and develop knowledge and expertise of our students. CSCT faculty have expertise in a broad range of specialties and have developed curriculums in each of the programs that meet the needs of the construction industry.

https://csct.edu.lk/

# ASSOCIATE PARTNERS

## The University of Newcastle, Australia

The University of Newcastle, Australia, established in 1965, is a leading public university with campuses across Newcastle, the Central Coast, Port Macquarie, and Sydney. Offering a wide range of undergraduate, postgraduate, and research programs spanning diverse disciplines such as Arts, Business, Engineering, Health Sciences, and Environmental Studies, the university is committed to academic excellence, research innovation, and community engagement, preparing students for successful careers and meaningful contributions to society. With a strong emphasis on interdisciplinary collaboration and industry partnerships, the University of Newcastle ensures students gain practical experience and skills relevant to today's workforce.

https://www.newcastle.edu.au/

## Built Environment Project and Asset Management (BEPAM)

### Journal, Published by Emerald Group Publishing

BEPAM provides, a unique one-stop forum that publishes peer-reviewed research and innovative developments in both project management and asset / facilities management of building and civil engineering infrastructure. The journal also targets important interface issues between the planning, design and construction activities on the one hand, and the management of the resulting built assets / facilities on the other. Launched in 2011, BEPAM is well established internationally, e.g., being encouraged by CIB, recognised by the Australian Business Deans Council and indexed in SCOPUS, EBSCO, INSPEC and the Emerging Sources Citation Index (ESCI) of Thomas Reuters.

http://www.emeraldinsight.com/bepam.htm

## International Council for Research and Innovation in Building and Construction (CIB)

The International Council for Research and Innovation in Building and Construction (CIB) is a global organization that promotes research, innovation, and collaboration within the building and construction industry. Established in 1953, CIB connects researchers, academics, industry professionals, and policymakers to address challenges and improve the performance of the built environment. Its mission is to encourage the exchange of knowledge, support interdisciplinary research, and advance sustainable and resilient construction practices.
CIB operates through international working commissions and task groups that focus on topics such as sustainable construction, digital technologies, building performance, construction management, and resilience. The organization also hosts conferences, workshops, and seminars where experts share research findings and best practices.

# ASSOCIATE PARTNERS

Additionally, CIB publishes technical reports and research publications that contribute to the development of innovative construction methods and policies. By fostering international cooperation and knowledge sharing, CIB plays a vital role in improving the quality, sustainability, and efficiency of the global building and construction industry.

https://cibworld.org/

# ACKNOWLEDGEMENT

We extend our sincere appreciation to the Ceylon Institute of Builders (CIOB) for inviting the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, to jointly organise the 14th World Construction Symposium (WCS) under the theme *"Towards a Regenerative Built Environment: From Foresight to Action."* This symposium marks the 14th milestone in the WCS series, which commenced in 2012 and has since been continued through the generous contributions and support of numerous individuals and organisations.

We gratefully acknowledge our Associate Partners: Adelaide University, Australia; Centre for Smart Modern Construction, Western Sydney University, Australia; Deakin University, Australia; Indian Institute of Technology Madras (IIT Madras), India; Massey University, New Zealand; MKSSS's Dr. Bhanuben Nanavati College of Architecture for Women, Pune, India; Colombo School of Construction Technology (CSCT), Sri Lanka; The University of Newcastle, Australia; Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Group Publishing; and the International Council for Research and Innovation in Building and Construction (CIB).

We are especially thankful to all the authors who chose the 14th WCS as a platform to disseminate their research. Our heartfelt gratitude is also extended to the international and local scientific committee members for their rigorous reviews and constructive feedback, which ensured the high standard of accepted papers. We would like to further extend our gratitude to the chief guest, keynote speakers, panellists, session chairs, session coordinators, paper presenters, and other invitees, whose commitment and active participation greatly enriched the symposium. Their support enabled us to maintain the momentum of the annual WCS series, leading to its successful 14th iteration this year, held on 10 -11 July 2026 at the Hilton, Colombo.

We also express our appreciation to the Editor-in-Chief of BEPAM and the team at Emerald Group Publishing for their collaboration, as well as to our sponsors, including Tokyo Cement as Gold Partner, whose generous contributions made this year's event possible. Our gratitude is further extended to government and other institutions and all other supporting partners who provided assistance in various forms to make this symposium a success.

Thanks are also extended to the panellists and moderator of the Roundtable Brainstorming session on "Sustainable Supply Chains for Resilient Construction Industries in Developing Countries," which drew over 150 in-person and online participants. Prof. Mohan Kumaraswamy (Editor-in-Chief, BEPAM, Emerald Publishing) moderated, with Dr. Suranga Jayasena as Thematic Summary Contributor, and the panel comprised Prof. Hemanta Doloi, Dr. Josephine Vaughan, Senior Prof. Ananda Jayawardane and Ch.QS Lalith Ratnayake. Discussion centred on strengthening construction supply chain resilience and highlighted the need for closer academia-industry collaboration. The session was organized under CIB Task Group 129 and Working Commission 107 (CIB TG129 - W107) and marked the official launch of this joint working group. In addition, as guest session was led by Dr. Eziaku Rasheed and Associate Professor Mostafa Babaeian Jelodar, representing a collaboration between Massey University and the University of Moratuwa. Finally, we extend our heartfelt appreciation to our colleagues in the Organising Committee, the Symposium Secretariat, and the Department of Building Economics for their dedication and tireless efforts in ensuring the success of the 14th World Construction Symposium 2026.

*Editors*
The 14th World Construction Symposium
Colombo, Sri Lanka
July 2026

# PREFACE

The 14th World Construction Symposium (WCS 2026), jointly organised by the Ceylon Institute of Builders (CIOB) and the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, was held on the 10th and 11th of July 2026. The symposium was organised in partnership with the Adelaide University, Australia, Centre for Smart Modern Construction, Western Sydney University, Australia, Deakin University, Australia, Indian Institute of Technology Madras (IIT Madras), India, Massey University, New Zealand, MKSSS's Dr B. N. College of Architecture for Women, Pune, India, Colombo School of Construction Technology (CSCT), Sri Lanka, The University of Newcastle, Australia, Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Publishing, International Council for Research and Innovation in Building and Construction (CIB).

This year marks the 14th milestone in the WCS series, which has been held annually since its inception in 2012. Through its past iterations, the symposium has grown steadily, earning recognition among academics and industry professionals, both local and foreign, as a multi-stakeholder platform to share research, practical insights, and experiences within the built environment and construction domain. This year's symposium was convened under the theme *"Towards a Regenerative Built Environment: From Foresight to Action,"* envisioning a path towards sustainable and regenerative built environment for future generations.

The symposium attracted over 150 full paper submissions, each undergoing a rigorous peer-review process as outlined below:

- All submitted full papers were reviewed by at least two independent reviewers from the symposium scientific committee through a double-blind process. Reviewers evaluated papers based on originality, significance, reliability, presentation quality, and relevance to the symposium's scope. Final decisions on acceptance or rejection were made by the Scientific Committee Co-chairs, who also serve as editors of the proceedings.
- At least one of the authors of all the accepted papers were required to register and orally present the paper in the symposium.

A total of 140 papers were accepted, with authors from South Africa, Sri Lanka, Indonesia, Australia, UK, India, Nigeria, Qatar, New Zealand, Malaysia, Vietnam, the USA and Nepal. The papers span a wide range of sub-themes among them waste management, digital twins, BIM, energy and retrofits, net-zero built environments, circular economy, building performance, data-driven innovation, inclusive housing and urban design, procurement, costing and tendering, sustainability and governance, bio-based materials, safety and well-being, climate resilience and disaster risk management, regenerative design, and nature-inspired construction approaches. A total of 136 papers were included in the symposium proceedings.

As Scientific Committee Co-chairs, we are committed to upholding the highest standards of publication ethics and scholarly quality. Accordingly, the emphasis was placed on the rigour and relevance of accepted papers rather than their quantity. The proceedings presented here reflect the dedicated efforts of authors, reviewers, the organising committee, associate partners, and sponsors. It is our sincere hope that this body of work will contribute to advancing knowledge and inspire further dialogue as we collectively strive towards shaping a regenerative built environment for future generations.

# ORGANISING COMMITTEE

| | |
|---|---|
| **Chairperson** | Prof. Chitra Weddikkara |
| **Co-Chairpersons** | Dr. Kalana Alwis<br>Mr. Ranji Hewage |
| **Advisors** | Dr. Rohan Karunaratne<br>Eng. Saliya Kaluarachchi<br>Prof. Yasangika Sandanayake |
| **Organising Committee** | Mr. Jaikish Tudawe<br>Mr. Ruwan De Silva<br>Mr. Eranda Perera<br>Eng. Asoka Randeni<br>Dr. H.L. Oberysekera |
| **Scientific Committee Co-Chairpersons** | Prof. Anuradha Waidyasekara<br>Dr. Suranga Jayasena<br>Dr. Chandanie Hadiwattege<br>Dr. Gihan Tennakoon |
| **Symposium Secretariat** | Mr. Isuru Eranga<br>Ms. Isuri Illeperuma<br>Ms. Kirushtika Thiruchelvam |
| **Symposium Support Team** | Ch. QS Dilshan Akalanka<br>Ms. Nishadi Nanayakkara<br>Mr. Lakshitha Bandaranayake<br>Mr. Charuka Deshan<br>Ms. Vithusha Aathithan<br>Mr. Kawshalya Sepalage<br>Ms. Anuki Kavirathne<br>Ms. Nawanjana Mannapperuma<br>Mr. Maneesha Ranasinghe<br>Mr. Heshan Bandara<br>Mr. Piranavan Sivasothy<br>Ms. Gheethanjali Balasubramaniyan<br>Ms. Himasha Subhasingha<br>Mr. Yasith Sandaruwan<br>Mr. Prasad Hemantha<br>Mr. Nalaka Gamage<br>Mr. Jude Perera<br>Ms. Niluka Priyangani |

# SCIENTIFIC COMMITTEE

**Co-Chairpersons**

| | |
|---|---|
| Prof. Anuradha Waidyasekara | *University of Moratuwa, Sri Lanka* |
| Dr. Suranga Jayasena | *University of Moratuwa, Sri Lanka* |
| Dr. Chandanie Hadiwattege | *University of Moratuwa, Sri Lanka* |
| Dr. Gihan Tennakoon | *University of Moratuwa, Sri Lanka* |

**Members**

| | |
|---|---|
| Dr. Akila Rathnasinghe | *Northumbria University, United Kingdom* |
| Prof. Alfred Ngowi | *Central University of Technology, United States of America* |
| Dr. Amalka Nawarathne | *University of The West of England, Bristol, United Kingdom* |
| Dr. Amruta Garud | *Dr. Bhanuben Nanavati College of Architecture, India* |
| Prof. Anishka Hettiarachchi | *University of Moratuwa, Sri Lanka* |
| Dr Anushika Chathurangi Ekanayake | *Birmingham City University, United Kingdom* |
| Dr. Anupa Manewa | *Liverpool John Moores University, United Kingdom* |
| Dr. Aparna Samaraweera | *Adelaide University, Australia* |
| Dr. Archchana Shandraseharan | *University of Hong Kong, Hong Kong* |
| Dr. Argaw Gurmu | *Deakin University, Australia* |
| Prof. Arun Chandramohan | *National Institute of Construction Management and Research, India* |
| Dr. Ashan Asmone | *University of Cambridge, United Kingdom* |
| Prof. Bingunath Ingirige | *University of Salford, United Kingdom* |
| Dr. Biyanka Ekanayake | *University of Technology, Sydney, Australia* |
| Prof. Bon-Gang | *National University of Singapore, Singapore* |
| Dr. Buddhini Ginigaddara | *University of Newcastle, Australia* |
| Prof. Chaminda Pathirage | *University of Wolverhampton, United Kingdom* |
| Dr. Chamitha Wijewickrama | *Adelaide University, Australia* |
| Dr. Chethana Illankoon | *University of New South Wales, Australia* |
| Dr. Chinthaka Atapattu | *Massey University, New Zealand* |
| Dr. Cong Yu | *University of Hong Kong, Hong Kong* |
| Dr. Daniel Oteng | *Adelaide University, Australia* |
| Dr. Devindi Geekiyanage | *University of Salford, United Kingdom* |

| | |
|---|---|
| Dr. Diani Sirimewan | *Queensland University of Technology, Australia* |
| Dr. Dilakshan Rajaratnam | *Queensland University of Technology, Australia* |
| Dr. Dilani Abeynayake | *University of Moratuwa, Sri Lanka* |
| Dr. Dumindu Soorige | *University of Moratuwa, Sri Lanka* |
| Dr. Gamini Weerasinghe | *University of Moratuwa, Sri Lanka* |
| Dr. Gayan Wedawatta | *University of Aston, United Kingdom* |
| Dr. Gayani Karunasena | *Deakin University, Australia* |
| Dr. Harshini Mallawarachchi | *University of Moratuwa, Sri Lanka* |
| Dr. Hossein Omrany | *Adelaide University, Australia* |
| Dr. Indrani Wimalaratne | *University of Moratuwa, Sri Lanka* |
| Ch. QS Indunil Seneviratne | *University of Moratuwa, Sri Lanka* |
| Dr. Ishara Rathnayake | *Adelaide University, Australia* |
| Dr. Isuri Amarasinghe | *Griffith University, Australia* |
| Senior Prof. Janaka Wijesundara | *University of Moratuwa, Sri Lanka* |
| Dr. Jessica Siva | *University of Newcastle, Australia* |
| Dr. K.A.K. Devapriya | *University of Moratuwa, Sri Lanka* |
| Dr. Kalindu Mendis | *Westford University College, UAE* |
| Senior Prof. Kanchana Perera | *University of Moratuwa, Sri Lanka* |
| Dr. Kaveesha Dewagoda | *University of Hong Kong, Hong Kong* |
| Dr. Krisanthi Seneviratne | *Western Sydney University, Australia* |
| Prof. Lalith De Silva | *University of Moratuwa, Sri Lanka* |
| Dr. Madhavee Mahinkanda | *Adelaide University, Australia* |
| Mr. Mahesh Abeynayake | *University of Moratuwa, Sri Lanka* |
| Prof. Menaha Thayaparan | *University of Moratuwa, Sri Lanka* |
| Dr. Michele Florencia Victoria | *Robert Gordon University, Scotland* |
| Dr. Mohan Siriwardena | *Liverpool John Moores University, United Kingdom* |
| Dr. Mona Salam | *University of Technology, Sydney, Australia* |
| Dr. Murali Jagannathan | *Indian Institute of Technology Madras, India* |
| Dr. Nadeeshani Wanigarathna | *Anglia Ruskin University, United Kingdom* |
| Dr. Nandun Madusanka | *University of Moratuwa, Sri Lanka* |
| Prof. Narein Perera | *University of Moratuwa, Sri Lanka* |

| | |
|---|---|
| Dr. Navodana Rodrigo | *Adelaide University, Australia* |
| Prof. Nayanthara De Silva | *University of Moratuwa, Sri Lanka* |
| Dr. Nikhil Bugalia | *Indian Institute of Technology Madras, India* |
| Dr. Nilmini Weerasinghe | *RMIT University, Australia* |
| Associate Prof. Niluka Domingo | *Massey University, New Zealand* |
| Dr. Nilupa Udawatta | *Deakin University, Australia* |
| Dr. Nimesha Jayasena | *Anglia Ruskin University, United Kingdom* |
| Dr. Nipuni Sumanarathna | *London Metropolitan University, United Kingdom* |
| Associate Prof. Nirodha Fernando | *Edinburgh Napier University, United Kingdom* |
| Dr. Nuwantha Uduwage | *University of Moratuwa, Sri Lanka* |
| Dr. Olufisayo Adedokun | *Adelaide University, Australia* |
| Dr. Pavithra Ganeshu | *University of Salford, United Kingdom* |
| Mrs. Piumi Dissanayake | *University of Moratuwa, Sri Lanka* |
| Dr. Pournima Sridarran | *University of Moratuwa, Sri Lanka* |
| Dr. Prince Antwi-Afari | *Adelaide University, Australia* |
| Dr. Ravindu Kahandawa | *Massey University, New Zealand* |
| Dr. Roshani Palliyaguru | *Oxford Brookes University, United Kingdom* |
| Dr. Ruchini Jayasinghe | *Adelaide University, Australia* |
| Dr. Ruidong Chang | *Adelaide University, Australia* |
| Dr. Sachie Gunatilake | *University of Moratuwa, Sri Lanka* |
| Prof. Sagara Jayasinghe | *University of Moratuwa, Sri Lanka* |
| Dr. Sajani Jayasuriya | *RMIT University, Australia* |
| Dr. Samudaya Nanaykkara | *Western Sydney University, Australia* |
| Dr. Savindi Perera | *Monash University, Australia* |
| Associate Prof. Sepani Senaratne | *University of Western Sydney, Australia* |
| Assistant Prof. Shavindree Nissanka | *Sri Lanka Institute of Information Technology, Sri Lanka* |
| Prof. Sherif Mohammed | *Griffith University, Australia* |
| Dr. Shyamini Rathnasabapathy | *Western Sydney University, Australia* |
| Associate Prof. Sivakumar Palaniappan | *Indian Institute of Technology, Madras, India* |
| Prof. Srinath Perera | *Western Sydney University, Australia* |
| Prof. Steve Rowlinson | *The University of Hong Kong, Hong Kong* |

| | |
|---|---|
| Prof. Sujata Karve | *Dr. Bhanuben Nanavati College of Architecture, India* |
| Assistant Prof. Thamasha Jayanetti | *Sri Lanka Institute of Information Technology, Sri Lanka* |
| Prof. Thanuja Ramachandra | *University of Moratuwa, Sri Lanka* |
| Dr. Tharusha Ranadewa | *University of Moratuwa, Sri Lanka* |
| Prof. Thayaparan Gajendran | *University of Newcastle, Australia* |
| Dr. Thilini Jayawickrama | *Adelaide University, Australia* |
| Prof. Udayangani Kulatunga | *University of Moratuwa, Sri Lanka* |
| Dr. Udara Ranasinghe | *Adelaide University, Australia* |
| Dr. Uthapala Rathnayake | *University of Moratuwa, Sri Lanka* |
| Associate Prof. Vaishali Anagal | *Dr. Bhanuben Nanavati College of Architecture, India* |
| Ch. QS Vijitha Disaratna | *University of Moratuwa, Sri Lanka* |
| Prof. Yasangika Sandanayake | *University of Moratuwa, Sri Lanka* |

# SYMPOSIUM INFORMATION

**IMPORTANT:** To ensure the proper execution of WCS 2026 hybrid symposium, please pay special attention to the instructions below. If you have any questions or difficulties following the guidelines, please contact the WCS 2026 Secretariat (info@ciobwcs.com) who will be happy to help.

## How will WCS 2026 hybrid symposium work?

- The conference is delivered physically at Hilton, Colombo, Sri Lanka and virtually over a professional platform, Zoom, and is managed by a competent and experienced technical team.
- **All virtual paper presentations must be pre-recorded** to improve the quality of the delivery, avoid going over time and avoid any technical issue. However, speakers **should be virtually present for their entire session** in order to answer questions and participate in the discussion.
- The virtual conference is similar to any in-person conference. Presentations are assembled in parallel sessions according to themes. Participants can access the session of their choice by entering the WCS 2026 main meeting using the meeting ID and passcode and then selecting the breakout room for the parallel session of their choice. All registered attendees can attend all parallel sessions and switch from session to session at will.
- The symposium inauguration, panel discussion and the sum-up are held in the WCS 2026 main meeting room.
- As with in-person conferences, there will also be a dedicated period for questions and discussion after the presentations. Participants are able to use the chat or verbally ask questions during the Q&A session. The session chairperson may select a few questions, depending on the time allocated for the discussion, and read them to the presenter, who can answer verbally.
- All sessions are fully recorded. Please note that we automatically assume that presenters accept their recorded presentation to be made available to participants for post-conference streaming. In case of refusal, presenters need to notify us at info@ciobwcs.com by **08th July 2026** and the secretariat will manage the requests.

## Preparing for your Virtual Session – Instructions for Virtual Presenters

Use the instructions below when presenting your paper at WCS 2026 virtual symposium.

### *Before the symposium starts*

- Make sure that you have uploaded your pre-recorded presentation following the given instructions and have completed the registration process.
- Refer to the Symposium Programme and the Session Plan to find your presentation in the symposium programme as scheduled.
- Make sure to install Zoom on your computer and update it to the latest version (version 7.1.0 (41345) or higher).
- In preparation for the meeting, you can join a test meeting via https://support.zoom.us/hc/en-us/articles/115002262083-Joining-a-test-meeting. For the best experience, please use your webcam and test your audio.

- Test your internet speed, we recommend an Internet connection download speed of at least 1.5Mbps.
- A microphone is recommended as well as a quiet place cut off from ambient noise for better interactions.

***Before your session starts***

- Please make sure to join your assigned virtual session **10 minutes prior to the session start time** in case there are any issues that need to be worked out. Each session is conducted in a breakout room within the main Zoom meeting.
- When entering the session, make sure to identify yourself with **your name as it appears on your paper** to help the technical staff and the session chair to find you easily.
- Test your audio and video as you join; Mute your microphone when not speaking; Position your webcam at eye level and make eye contact as much as possible.

***During the session***

- As with a physical meeting, each session will proceed in the order identified and maintain the schedule.
- Each parallel session comprises of paper presentations (via playback of pre-recorded presentations) and a subsequent Q&A session.
- **Speakers should be virtually present for their entire session** in order to answer questions and participate in the discussion.
- A session chair is assigned to each session to introduce the presenters, facilitate and oversee time, and the Q&A period. A session coordinator is also assigned to each parallel session to manage the order of the presentations, initiate playback of the pre-recorded presentations and ensure smooth transitions between presentations.
- Pre-recorded presentations are managed by the session coordinator according to the established schedule (see Session Plan).
- A common Q&A session will follow the presentations in each session. The session chair will lead the Q&A period and time allotted.
- Please ensure that **your webcam is on during the Q&A session** so that attendees can view you.
- The participants may submit their questions verbally (You can use the **Raise Hand** tool to inform the session chair if you want to raise a question verbally) or via **Chat**. The session chair will choose the most relevant ones to read for presenters to answer during the Q&A period.
- The **Chat** tool can also be used by session chair and session coordinator to privately contact the presenters if needed. If you need technical assistance, you can inform the session coordinator using this tool.

## To Access WCS 2026 Hybrid Symposium

To access the symposium virtually:

**Join the 14th World Construction Symposium**
https://zoom.us/j/93208449801?pwd=xAUUv3nhPAggV3ggRaDPWBvHp2lf0e.1

**Meeting ID:** 932 0844 9801
**Passcode:** WCS2026

- Make sure to install Zoom on your computer or update it to the latest version (version 7.1.0 (41345) or higher).
- Use the Meeting ID and passcode provided by the Symposium Secretariat to log on to the Main Meeting Room of the symposium. (The symposium inauguration, panel discussion and the sum-up are held in the WCS2026 main meeting room).
- Parallel paper presentation sessions are held in breakout rooms within the main meeting room. Once the breakout rooms are opened, you will be able to select and enter a breakout room of your choice. All registered attendees can attend all parallel sessions and switch from session to session at will. [Note: Participants not joined with the desktop or mobile app (version 7.1.0 (41345) or higher) may not be able to self-select a breakout room and will need to be assigned by the Host].
- To join the parallel session of your choice:
  (1) Click **Breakout Rooms** in your meeting controls.
  (2) This will display the list of open breakout rooms (i.e. parallel sessions) created by the host.
  (3) Hover your pointer over the number to the right of breakout room you wish to join, click **Join**, then confirm by clicking Join.
  (4) Repeat as necessary to join other breakout rooms.
  (5) You can leave the breakout room and return to the main meeting room at any time, or you can leave the meeting entirely from the breakout room.
  (6) To leave the breakout room click **Leave Breakout Room** and choose if you want to leave the breakout room or the entire meeting (if you want to switch to a different parallel session, make sure to use the 'Leave Room' option to re-enter the main meeting room and join a different parallel session).
  (7) When the host ends the breakout rooms, you will be notified and given the option to return to the main room immediately, or in 60 seconds.

## Virtual Background for Zoom

- You can use an optional virtual background with your university/company logo to hide or standardize your backstage during your parallel session and/or symposium group photo (refer Symposium Agenda).
- We recommend that you do a test beforehand to see which background works better for you, depending on your environment.

## Language

- The official language of the symposium is English. There will be no simultaneous translations.

## Dress Code

- For the symposium: business, lounge or national attire
- For the fellowship and awards night: formal attire

## Awards

- CIOB Best Paper Award
- CIOB – Highly Commended Paper Award
- BEPAM Best Paper award – with a certificate and a prize of free access to Emerald Insight for a period of 90 days and 40 free downloads for the author(s) of this Best paper
- Two (02) BEPAM Highly Commended Paper awards – with a certificate for the author(s) of each Highly Commended Paper

## Certificate of Attendance

- A certificate of attendance will be issued to all authors, after the respective parallel sessions. The authors who participated in the symposium virtually will receive the e-certificates in due course.

## Disclaimer

- Whilst every attempt being made to ensure that all aspects of the symposium mentioned in this announcement will take place as scheduled, the Organizing Committee reserves the prerogative to make last-minute changes should the need arise without prior notice.

# MESSAGE FROM THE SYMPOSIUM CHAIRPERSON


## Prof. Chitra Weddikkara

**Chairperson**
**The 14th World Construction Symposium 2026**

It is my honour and privilege to welcome you to the 14th World Construction Symposium, a flagship event in Sri Lanka's academic and professional calendar. Over the past fourteen years, this symposium has evolved into a leading platform that unites scholars, practitioners, and industry leaders to exchange ideas, share innovations, and explore pathways to address the challenges and opportunities in the construction sector. Organized under the patronage of the Ceylon Institute of Builders (CIOB) and the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, it serves as a unique forum for reflection, engagement, and collaboration.

This year's theme, "Towards a Regenerative Built Environment: From Foresight to Action," highlights the crucial role of the construction industry in steering global efforts towards sustainability. Our responsibility extends beyond meeting immediate infrastructural needs. It is about translating foresight into tangible action, ensuring resilience, inclusivity, and prosperity for generations to come.

I extend my sincere appreciation to our sponsors, partners, and the organising committee, whose commitment and dedication have been instrumental in making this event a success. Their efforts ensure that the symposium continues to foster meaningful conversations that inspire actionable outcomes.

As we embark on this year's sessions, let us seize the opportunity to exchange knowledge, challenge conventional thinking, and co-create solutions that will move us from foresight to action in shaping a more sustainable and regenerative built environment. Thank you for joining us at the 14th World Construction Symposium and I look forward to the stimulating discussions and fruitful collaborations to follow.

.

# MESSAGE FROM THE PRESIDENT, CIOB


## Dr. Rohan Karunaratne

**President**
**The Ceylon Institute of Builders (CIOB)**

On behalf of the Ceylon Institute of Builders (CIOB), we take great pleasure in welcoming you to the 14th World Construction Symposium, to be held on the 10th and 11th of July 2026 in Colombo. This annual symposium has been jointly organized by the Ceylon Institute of Builders and the Department of Building Economics, University of Moratuwa, since the year 2012. The theme for the symposium is "Towards a Regenerative Built Environment: From Foresight to Action," in keeping with the global position and the sustainable goals of the construction industry.

As you know, CIOB's initiatives with the University of Moratuwa through this highly acknowledged event, the WCS, play a leading role in the sustainable development process for the construction industry. This has further strengthened integrated multidisciplinary teams to develop a number of appropriate technologies in the field of research and development. Recognition of such outstanding research achievements among researchers is a great motivating factor, and achievements by academic and professional bodies together are also a great encouragement for the industry and for further research. Furthermore, gaining Scopus-indexed status over the years has been a significant achievement for the WCS and the University of Moratuwa.

As in the past, this symposium has been greatly supported by construction industry stakeholders and professional institutions in its organization. I wish to record my special thanks to all our sponsors and well-wishers for their generous contribution to making this symposium a success.

While congratulating and appreciating the work done by the global and local contributors to the 14th WCS for the development of the construction industry through this significant international event, we wish WCS 2026 every success in all its accomplishments.

# MESSAGE FROM THE HON. SECRETARY, CIOB


## Eng. Saliya Kaluarachchi

**Hon. Secretary**
**The Ceylon Institute of Builders (CIOB)**

I am delighted to welcome you to the 14th World Construction Symposium 2026, scheduled for the 10th and 11th of July 2026 in Colombo. It gives me immense pleasure to share that the Ceylon Institute of Builders has been able to host the World Construction Symposium annually since 2012. The symposium has become a well-received event for both academics and professionals in the construction industry in Sri Lanka, and I am sure that this year's symposium too will live up to expectations and enable participants to gain valuable knowledge from the presentations and discussions.

The Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, Sri Lanka, is the joint organizer of this symposium. I would like to express my gratitude to them for their firm commitment and patronage. I am also thankful to the Associate Partners of the symposium, including BEPAM.

It is indeed an honour to have a renowned team of academics and researchers serving on the scientific committee, providing comprehensive reviews of the submissions. The extensive technical programme developed by the scientific committee includes five concurrent sessions/presentation tracks, giving professionals in the construction industry the opportunity to work towards their Continuing Professional Development targets.

My best wishes to our sponsors, the organizing committee, and everyone who worked tirelessly to make this event a reality. Let's make this a productive, inspiring, and unforgettable experience together.

# MESSAGE FROM THE SYMPOSIUM CO-CHAIRPERSONS

**Dr. Kalana Alwis**

**Eng. Ranji Hewage**

**Co-Chairpersons**
**Organizing Committee**
**The 14th World Construction Symposium 2026**

We take great pleasure in welcoming all delegates to the 14th World Construction Symposium 2026, on the theme "Towards a Regenerative Built Environment: From Foresight to Action," to be held on the 10th and 11th of July 2026 in Colombo. CIOBWCS is an exciting annual event in the Sri Lankan construction industry, organized jointly by the Ceylon Institute of Builders (CIOB) and the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, Sri Lanka.

The purpose and vision of this symposium is the promotion of academic and research activities in the field of sustainable construction. The symposium brings together like-minded individuals on a single platform to confer on new trends and challenges in sustainable construction. During the symposium, Sri Lankan academics, research scholars, and practitioners will have the opportunity to interact with eminent experts from overseas on sustainable construction and new developments in the global built environment.

Whilst thanking our special guests, speakers, professionals, academics, paper presenters, sponsors, and everyone here today for making this event a reality, we wish the symposium every success, with your continued participation and the commitment of the University of Moratuwa, along with the generous support of all from the Sri Lankan construction industry.

.

# MESSAGE FROM HEAD, DEPARTMENT OF BUILDING ECONOMICS, UNIVERSITY OF MORATUWA


## Ch. QS. Dr Suranga Jayasena

**Head of the Department**
**Department of Building Economics**
**University of Moratuwa**

I extend my warmest wishes for the 14th World Construction Symposium 2026. This international event is jointly organized by the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics, University of Moratuwa, Sri Lanka and the Ceylon Institute of Builders (CIOB). The symposium brings together several esteemed national and international partners, including Adelaide University, Australia, Centre for Smart Modern Construction, Western Sydney University, Australia, Deakin University, Australia, Indian Institute of Technology Madras (IIT Madras), India, Massey University, New Zealand, MKSSS's Dr B. N. College of Architecture for Women, Pune, India, Colombo School of Construction Technology (CSCT), Sri Lanka, The University of Newcastle, Australia, Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Publishing, International Council for Research and Innovation in Building and Construction (CIB).

The global construction industry is moving towards a more regenerative and resilient future, responding to pressing challenges such as climate change, resource scarcity, economic uncertainty, and the need for sustainable development. The 14th World Construction Symposium is themed *"Towards a Regenerative Built Environment: From Foresight to Action"*, highlighting the importance of translating forward-looking knowledge, research, and innovation into practical actions that can shape a sustainable and regenerative built environment for future generations.

This year's symposium provides an excellent platform for local and international delegates to share knowledge, exchange experiences, and present sustainable solutions and research findings that address contemporary challenges in the construction industry. I encourage all participants to make the most of this opportunity to engage in meaningful discussions, build networks, and contribute to the collective advancement of our industry.

I wish the 14th World Construction Symposium 2026 every success and look forward to its continued contribution towards shaping a sustainable and innovative construction future.

# CONTENTS


| | |
|---|---|
| SYMPOSIUM ORGANISERS | iii |
| ASSOCIATE PARTNERS | iv |
| ACKNOWLEDGEMENT | viii |
| PREFACE | ix |
| ORGANISING COMMITTEE | x |
| SCIENTIFIC COMMITTEE | xi |
| SYMPOSIUM INFORMATION | xv |
| MESSAGE FROM THE SYMPOSIUM CHAIRPERSON | xix |
| MESSAGE FROM THE PRESIDENT, CIOB | xx |
| MESSAGE FROM THE HON. SECRETARY, CIOB | xxi |
| MESSAGE FROM THE SYMPOSIUM CO-CHAIRPERSONS | xxii |
| MESSAGE FROM HEAD, DEPARTMENT OF BUILDING ECONOMICS, UNIVERSITY OF MORATUWA | xxiii |
| CONTENTS | xxiv |
| SYMPOSIUM PROGRAMME | xxv |
| SYMPOSIUM SESSION PLAN AT-A-GLANCE | xxvii |
| DETAILED SESSION PLAN | xxix |
| KEYNOTE SPEAKERS | liv |
| ROUNDTABLE BRAINSTORMING | lv |
| SESSION BY THE CIB STUDENT CHAPTER | lxii |
| CONTENTS OF PAPERS | lxiii |
| PAPERS | 1 |

# SYMPOSIUM PROGRAMME

| FRIDAY, 10 JULY 2026 – DAY ONE<br>AT HILTON, COLOMBO. | |
|---|---|
| 08.30 am | Symposium Registration |
| 09.00 am | Symposium Inauguration |
| 09.10 am - 09.20 am | Welcome address by President, CIOB<br>**Dr. Rohan Karunaratne** |
| 09.20 am - 09.30 am | Address by Conference Chairperson<br>**Prof. Chitra Weddikkara** |
| 09.30 am - 09.40 am | Address by Head of the Department<br>**Ch.QS Dr. Suranga Jayasena** |
| 09.40 am - 09.50 am | Address by Guest of Honour, Deputy Vice Chancellor, University of Moratuwa<br>**Prof. Dileeka Dias** |
| 09.50 am -10.05 am | Address by the Chief Guest<br>**Chief Guest, Hon. Mr. Anton Jayakody**<br>Deputy Minister of Environment, Sri Lanka |
| 10.05 am - 10.35am | Keynote Address<br>***"From Extraction to Circulation: Rethinking Cities as Sources of Building Materials"***<br>**Dr Josephine Vaughan, University of Newcastle, Australia** |
| 10.35 am- 10.40 am | Sponsors Video |
| 10.40 am- 11.00 am | Refreshments |
| 11.00 am – 11.10 am<br><br>11.10 am – 12.00 noon | Guest Talks organised by the CIB Student Chapters of Massey University, New Zealand, and the University of Moratuwa, Sri Lanka<br>**Speaker 1:**<br>**Dr. Eziaku Rasheed, Massey University, NZ**<br>*"Connect, Learn, Lead: What the CIB Student Chapter Can Do for You"*<br>**Speaker 2:**<br>**Associate Professor Mostafa Babaeianjelodar, Massey University, NZ**<br>*"Advancing Sustainability in the Built Environment through Modern Methods of Construction and Automation"* |
| 12.00 noon – 12.15 pm | Address by Editor-in-Chief, Built Environment Project and Asset Management (BEPAM) Journal<br>*"Mobilising Urban-Rural Linkages for an Integrated Built-Natural Environment"*<br>**Prof. Mohan Kumaraswamy** |
| 12.15 am - 12.20 am | Sponsors Video |
| 12.20 pm -12.30 pm | Vote of Thanks by the Hon. Secretary, CIOB<br>**Eng. Saliya Kaluarachchi** |
| 12.30 pm - 01.30 pm | Lunch Break |
| 01.30 pm - 03.30 pm | **Parallel Sessions 1** |
| 03.30 pm - 04.00 pm | Refreshments |
| 04.00 pm - 06.00 pm | **Parallel Sessions 2** |
| 06.00 pm | End of Day 1 |

# SYMPOSIUM PROGRAMME

| SATURDAY, 11 JULY 2026 – DAY TWO<br>AT HILTON, COLOMBO. | |
|---|---|
| 08.00 am | Symposium Registration |
| 08.30 am - 10.30 am | **Parallel Sessions 3** |
| 10.30 am - 11.00 am | Refreshments |
| 11.00 am - 12.30 pm | **Parallel Sessions 4** |
| 12.30 pm - 01.30 pm | Lunch Break |
| 01.30 pm - 03.00 pm | **Parallel Sessions 5** |
| 03.00 pm - 03.10 pm | **Launching New CIB Task Group TG129: Urban-Rural Built and Natural Environment Synergies (URBANES)**<br>**Ch.QS Dr. Suranga Jayasena (**TG129 Lead Coordinator) |
| 03.10 pm - 04.40 pm | **CIB TG129-W107 - WCS Roundtable Brainstorming on:**<br>*"Sustainable Supply Chains for Resilient Construction Industries in Developing Countries"*<br>Expert Panellists: **Prof. Hemanta Doloi** (W107 Lead Coordinator)<br>**Dr. Josephine Vaughan**<br>**Senior Prof. Ananda Jayawardena**<br>**Ch.QS. Lalith Rathnayake**<br>Moderator : **Prof. Mohan Kumaraswamy**<br>Rapporteur : **Dr. Suranga Jayasena** (TG129 Lead Coordinator)<br>Coordinator : **Dr. Dilani Abeynayake** (TG129 Early Career Researcher-ECR) |
| 04.40 pm - 05.10 pm | Refreshments |
| 05.10 pm - 05.20 pm | Announcing the Award Winners<br>**Prof. Mohan Kumaraswamy**<br>**Prof. Anuradha Waidyasekara** |
| 05.20 pm - 05.30 pm | Vote of Thanks by Scientific Committee Co-Chairperson<br>**Dr. Gihan Tennakoon** |
| 05.30 pm | End of Programme |
| 07.00 pm Onwards | Awards Ceremony and Symposium Dinner at the Hilton Colombo |

# SYMPOSIUM SESSION PLAN AT-A-GLANCE

| SYMPOSIUM SESSION PLAN AT-A-GLANCE | | | | | |
|---|---|---|---|---|---|
| **Friday, 10th July 2026 - Day One** | | | | | |
| 08.30 am | **Symposium Registration** | | | | |
| 09.00 am - 12.30 pm | **Symposium Inauguration** | | | | |
| 12.30 pm - 02.00 pm | **Lunch Break** | | | | **Hybrid** |
| 02.00 pm - 03.30 pm | **Session 1A** | **Session 1B** | **Session 1C** | **Session 1D** | **Session 1E** |
| | S18034 | S18002 | S18025 | S18008 | S18058 |
| | S18084 | S18030 | S18047 | S18009 | S18020 |
| | T18119 | S18067 | S18121 | S18045 | S18024 |
| | S18125 | S18141 | S18068 | S18109 | T18062 |
| | S18158 | S18016 | S18116 | S18056 | S18102 |
| | S18111 | S18157 | S18151 | S18117 | S18015 |
| | Q&A | Q&A | Q&A | Q&A | Q&A |
| 03.30 pm - 04.00 pm | **Break** | | | | **Hybrid** |
| 04.00 pm - 05.30 pm | **Session 2A** | **Session 2B** | **Session 2C** | **Session 2D** | **Session 2E** |
| | S18128 | S18061 | S18017 | S18143 | S18101 |
| | S18099 | S18162 | S18043 | T18087 | S18040 |
| | T18103 | S18127 | S18044 | T18096 | T18081 |
| | S18074 | S18134 | S18050 | S18114 | T18093 |
| | S18149 | S18133 | S18052 | S18145 | S18019 |
| | S18113 | S18088 | S18085 | T18136 | S18167 |
| | Q&A | Q&A | Q&A | Q&A | S18039 |
| | | | | | Q&A |
| 05.30 pm | **End of Day 1** | | | | |
| **Saturday, 11th July 2026 - Day Two** | | | | | |
| 08.30 am | **Symposium Registration** | | | | **Hybrid** |
| 09.00 am - 10.30 am | **Session 3A** | **Session 3B** | **Session 3C** | **Session 3D** | **Session 3E** |
| | S18023 | S18120 | S18059 | S18097 | S18003 |
| | S18031 | S18110 | S18126 | S18038 | S18021 |
| | S18094 | S18115 | S18135 | S18161 | S18032 |
| | T18078 | S18132 | S18079 | S18046 | S18036 |
| | T18108 | S18138 | S18169 | S18142 | S18083 |
| | T18076 | S18163 | Q&A | S18075 | S18168 |
| | Q&A | Q&A | | Q&A | S18130 |
| | | | | | Q&A |
| 10.30 am - 11.00 am | **Break** | | | | **Hybrid** |
| 11.00 am - 12.30 pm | **Session 4A** | **Session 4B** | **Session 4C** | **Session 4D** | **Session 4E** |
| | S18129 | S18035 | S18089 | S18070 | S18004 |
| | S18006 | S18154 | S18164 | S18100 | S18095 |
| | S18106 | S18131 | S18092 | T18071 | S18165 |
| | S18077 | S18139 | S18148 | S18066 | S18147 |
| | S18160 | S18069 | S18054 | S18170 | S18150 |
| | Q&A | Q&A | Q&A | Q&A | Q&A |
| 12.30 pm - 01.30 pm | **Lunch Break** | | | | **Hybrid** |
| 1.30 pm - 2.50 pm | **Session 5A** | **Session 5B** | **Session 5C** | **Session 5D** | **Session 5E** |
| | S18018 | S18001 | S18105 | S18073 | S18010 |
| | S18028 | S18064 | S18155 | S18080 | T18027 |
| | S18049 | S18156 | S18166 | S18123 | S18029 |

# SYMPOSIUM SESSION PLAN AT-A-GLANCE

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| | S18051 | S18026 | S18152 | S18112 | S18005 |
| | S18072 | Q&A | S18137 | S18107 | S18053 |
| | Q&A | | Q&A | Q&A | Q&A |
| 02.50 pm | **End of Parallel Sessions** | | | | |
| 03.00 pm - 03.10 pm | **Launching New CIB Task Group TG129: Urban-Rural Built and Natural Environment Synergies (URBANES)** | | | | |
| 03.10 pm - 04.40 pm | **WCS Roundtable Brainstorming on: "Sustainable Supply Chains for Resilient Construction Industries in Developing Countries"** | | | | |
| 04.40 pm - 05.00 pm | **Symposium Sum-Up** | | | | |
| 05.00 pm - 05.30 pm | **Refreshments** | | | | |
| 05.30 pm | **End of Programme** | | | | |
| 07.00 pm onwards | **Fellowship and Awards Night at the Hilton, Colombo** | | | | |

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 1A**

| | |
|---|---|
| **Theme** | **Waste Management for Regenerative Built Environment** |
| **Session Chair** | **Prof. (Mrs.) Udayangani Kulatunga** |
| **Venue/Time** | **Tanzanite 1 / 02.00 PM - 03.30 PM** |
| **Virtual** | **Breakout Room - Session A** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 02.00 PM - 02.10 PM | **S18034: Pivot Strategies for Lean Construction Implementation: A Sri Lankan Perspective**<br>*S.A.A.B. Senevirarhne, C. Allis, K. Guruge* |
| 02.10 PM - 02.20 PM | **S18084: Contractual Provisions Inducing Construction Waste Generation: An Analysis of Sri Lankan Standard Forms of Contract**<br>*R.D.L. Fernando, R.M.H.R Bandara., M. Thayaparan.* |
| 02.20 PM - 02.30 PM | **T18119: From Waste to Use: Plywood Usage and Wastage in Slab and Beam Construction**<br>*W.M.P.M. Bandara, K.G.A.S. Waidyasekara, P.H.G.M.A. Ranasinghe* |
| 02.30 PM - 02.40 PM | **S18125: Robotics Systems for Closed Loop Construction: A Bibliometric Analysis of Construction Demolition Waste Management**<br>*M.K.L.I.C Fernando, P.L.I Wimalaratne* |
| 02.40 PM - 02.50 PM | **S18158: From Waste to Worth: Digitalizing Secondary Materials Market in Construction**<br>*K. Arthigan, B.A.I Eranga* |
| 02.50 PM - 03.00 PM | **S18111: Data Requirements for a Material Passport in the Sri Lankan Construction Industry**<br>*H.S Jayasena, S. Piranavan, H.G.G. Nawarathna* |
| 03.00 PM - 03.30 PM | **Q&A** |

*Session Coordinator: Ms. Anuki Kavirathne*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 1B**

| | |
|---|---|
| **Theme** | **Technological Transformation through Digital Twins & BIM** |
| **Session Chair** | **Assistant Professor Dr Ranju kumari Shiwakoti** |
| **Venue/Time** | **Tanzanite 2 / 02.00 PM - 03.30 PM** |
| **Virtual** | **Breakout Room - Session B** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 02.00 PM - 02.10 PM | **S18002: From BIM 6D/7D to Operational Digital Twins Closing the Building Energy Performance Gap in Tropical Buildings - A Mixed-Methods Study in Sri Lanka**<br>*T.H. Madushanka, S.D.A. Soorige, H.W.N. Madhusanka* |
| 02.10 PM - 02.20 PM | **S18030: Assessing BIM Knowledge Among Construction Professionals in Sri Lanka: Challenges and Opportunities**<br>*G.K.G.S. Kosala, R.P.T Nyanathara* |
| 02.20 PM - 02.30 PM | **S18067: Prioritizing BIM-Based Safety Management Features Using the Analytic Hierarchy Process**<br>*T.N.D. Thanthirige, M.M.I.S. Mapa, G.G.N. Chandani* |
| 02.30 PM - 02.40 PM | **S18141: From Inertia to Integration: Evaluating the Challenges and Enablers of BIM in the Infrastructure Sectors of Sri Lanka and the Middle East**<br>*A. Lokuge, G.H.S.P De Silva, S. Vinoshan.* |
| 02.40 PM - 02.50 PM | **S18016: Conceptual Digital Twin Framework for Conserving Urban Cultural Heritage: A Case of Slave Island, Colombo**<br>*W.D.B.J. Jeewananda, K.S.K.N.J Kudasinghe, A.R. Rupasinghe* |
| 02.50 PM - 03.00 PM | **S18157: A Conceptual Hybrid Framework for CDE Configuration: Balancing ISO 19650 Rigidity with Agile Flexibility**<br>*B.K.C Perera, H.S. Jayasena, M. Siriwardena* |
| 03.00 PM - 03.30 PM | **Q&A** |

*Session Coordinator: Mr. Kawshalya Sepalage*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 1C**

| | |
|---|---|
| **Theme** | **Energy, Retrofits, and Net-Zero Built Environment** |
| **Session Chair** | **Associate Prof. Nirodha Fernando** |
| **Venue/Time** | **Aquamarine 1 / 02.00 PM - 03.30 PM** |
| **Virtual** | **Breakout Room - Session C** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 02.00 PM - 02.10 PM | **S18025: Exploring the Current Status of Retrofitting or Rebuilding in Construction**<br>*B.W. Madanayake, S. Nissanka* |
| 02.10 PM - 02.20 PM | **S18047: Simulation-Based Evaluation of Energy Performance in Adaptive Reuse of Historic Buildings Across Different Climatic Zones of Sri Lanka**<br>*A. Tharmitha, G.Y. Jayasinnghe, M.K.M Prabodani, K. Anojan, R.U. Halwatura* |
| 02.20 PM - 02.30 PM | **S18121: Strategies to Achieve Net-zero Carbon Goals in Construction Industry**<br>*R.M.D.D Rathnayake, B.A.K.S Perera, A.S Kavirathna* |
| 02.30 PM - 02.40 PM | **S18068: Enhancing Building Energy Data Management in Sri Lanka: Barriers, Enablers, and Strategic Pathways**<br>*R.Y. Silva, H.W.N. Madhusanka, K.A.R.V.D. Kahandawa* |
| 02.40 PM - 02.50 PM | **S18116: Conceptualising A Value Stream Mapping (VSM)-Based Decision-Making Model for Lean Energy Retrofitting of HVAC Systems in High-Rise Buildings: Literature Review Approach**<br>*H.M.D.C Gamagedara, H. Mallawaarachchi, J.A.D.K.S Jayakodi* |
| 02.50 PM - 03.00 PM | **S18151: Planning Net-Zero Energy Communities: Housing Strategies for Post-Disaster Resettlement in Sri Lanka - A Narrative Review**<br>*B.G.H.N Premasinghe, B.A.I Eranga* |
| 03.00 PM - 03.30 PM | **Q&A** |

*Session Coordinator: Ms. Gheethanjali Balasubiramaniyam*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 1D**

| | |
|---|---|
| **Theme** | **Human-Centred perspectives on Built Spaces** |
| **Session Chair** | **Prof. Lalith De Silva** |
| **Venue/Time** | **Aquamarine 2 / 02.00 PM - 03.30 PM** |
| **Virtual** | **Breakout Room - Session D** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 02.00 PM - 02.10 PM | **S18008: Unheard Stakeholder Voices: Evaluating the Functional Performance of the Manning Market Building**<br>*U. Hettithanthri, D.K.Nalaka Krishantha* |
| 02.10 PM - 02.20 PM | **S18009: Age-Related Variations in Spatial Cognition and Spatial Behavior in Royal Botanic Gardens, Peradeniya: Evidence from the Royal Botanic Gardens, Peradeniya**<br>*W.M.S.S. Dissanayake, S. Amendra* |
| 02.20 PM - 02.30 PM | **S18045: The Impact of Material Expression at Entrance Thresholds on Invitation to Access: A Comparative Study of Shopping Malls in Colombo, Sri Lanka**<br>*P.N.S Wijayarathne, S.M. Hirudini* |
| 02.30 PM - 02.40 PM | **S18109: Optimising Investment Decisions in Homestay Tourism: A Cost and Performance Analysis of Coastal Regions in Sri Lanka**<br>*Y.K.K Sampath, J.A.C.D. Jayalath, S. Piranavan, H.S. Jayasena* |
| 02.40 PM - 02.50 PM | **S18056: The Influence of Visibility on Personal Space Creation in Urban Public Spaces: A Case Study of the Arcade at Independence Square**<br>*Y.R. Dissanayake, S.M. Hirudini* |
| 02.50 PM - 03.00 PM | **S18117: Revisiting Methodological Taxonomy: Locating Design Science Research within Research Design Hierarchies**<br>*W.M.I.H. Wijesundara., P.L.I Wimalaratne., U. Kulatunga* |
| 03.00 PM - 03.30 PM | **Q&A** |

*Session Coordinator: Ms. Nawanjana Mannapperuma*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 1E (Hybrid)**

| | |
|---|---|
| **Theme** | **Operationalising Circular Economy and Emission Reduction** |
| **Session Chair** | **Associate Prof. Sivakumar Palaniappan and Dr. Prince Antwi-Afari** |
| **Venue/Time** | **Jade / 02.00 PM - 03.30 PM** |
| **Virtual** | **Breakout Room - Session E** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 02.00 PM - 02.10 PM | **S18058: A Conceptual Framework for the Adoption of a Life Cycle Assessment-Based Emissions Trading Scheme in the Australian Construction Sector**<br>*P. Yang, B.T.H. Lim, B.L. Oo* |
| 02.10 PM - 02.20 PM | **S18020: Appropriateness of Commonly Used Methods for Assessing the Impacts of Circular Economy Practices**<br>*I. Gamage, S. Senaratne, S. Perera, X. Jin* |
| 02.20 PM - 02.30 PM | **S18024: Circular Economy Knowledge Management Initiatives in the Australian Construction and Demolition Waste Management Sector**<br>*M. Nadeetharu, N. Udawatta, G.P. Costin, G. Karunasena* |
| 02.30 PM - 02.40 PM | **T18062: Risk Perceptions in Circular Economy Adoption in the Australian Construction Industry**<br>*I.R. Kadirappulige, G. Karunasena, N. Udawatta, A. Grumu* |
| 02.40 PM - 02.50 PM | **S18102: Operationalizing Circular Economy in Mega Infrastructure Projects: A Data-Driven Analysis**<br>*P. Maneesha, S. Loganathan, D. Mouli* |
| 02.50 PM - 03.00 PM | **S18015: Analysing Key Process Areas in Developing the Circular Economy Maturity Model for Construction Organisations**<br>*S. Jayakodi, S. Senaratne, S. Perera, K. Bamdad* |
| 03.00 PM - 03.30 PM | **Q&A** |

*Session Coordinator: Mr. Yasith Sandaruwan*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 2A**

| | |
|---|---|
| **Theme** | **User-Centred Building Performance and Design** |
| **Session Chair** | **Associate Professor Sepani Senaratne** |
| **Venue/Time** | **Tanzanite 1 / 04.00 PM - 05.30 PM** |
| **Virtual** | **Breakout Room - Session A** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 04.00 PM - 04.10 PM | **S18128: Integration of Post Occupancy Evaluation into Government Office Buildings to Enhance User Satisfaction**<br>*H.D. Subhasingha., P.A.P.V.D.S Disaratna* |
| 04.10 PM - 04.20 PM | **S18099: Ergonomic Performance Indicators for Evaluating Office Workstation Arrangements**<br>*T.A. Kasthuriarachchi, M.M.I.S. Mapa, G.G.N Chandani* |
| 04.20 PM - 04.30 PM | **T18103: Puzzleglaze: A User-Driven Window System to Maximize User Comfort**<br>*S.S. Shaikh, A.Garud* |
| 04.30 PM - 04.40 PM | **S18074: Workplace Design and Gen Z Retention: A Social Sustainability Perspective in Sri Lanka**<br>*S.N. Ranathunga., P. Dissanayake., W.N.K.B.N.A Sathsarani* |
| 04.40 PM - 04.50 PM | **S18149: Beyond The Envelope: Examining Project Management as a Catalyst for High-Performance Building Design**<br>*H. Deheragoda, G.H.S.P. De Silva, M. Jinthusan* |
| 04.50 PM - 05.00 PM | **S18113: Temperature and Humidity Control in Operating Theatres: BMS Vs. Thermostat Systems**<br>*K.S. Ramasingha, D.A. Soorige, K. A. D.M. Natasha* |
| 05.00 PM - 05.30 PM | **Q&A** |

*Session Coordinator: Mr. Charuka Deshan*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 2B**

| | |
|---|---|
| **Theme** | **Data-Driven Innovations in the Built Environment** |
| **Session Chair** | **Dr. Chandanie Hediwattage** |
| **Venue/Time** | **Tanzanite 2 / 04.00 PM - 05.30 PM** |
| **Virtual** | **Breakout Room - Session B** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 04.00 PM - 04.10 PM | **S18061: From Reactive Reporting to Regenerative Control: Rethinking Construction Progress Monitoring in Sri Lanka through IOT Enabled Real-time Practices**<br>*T.M.A.Y.B. Malvila, R.M.H.R. Bandara, M. Thayaparan* |
| 04.10 PM - 04.20 PM | **S18162: Applicability of Artificial Intelligence for improving Infrastructure Resilience**<br>*S.A.L. Wimalasuriya, U. Kulatunga, D. Munasinghe, N. Dias* |
| 04.20 PM - 04.30 PM | **S18127: Integrating Computer Vision into Quality Assurance of Structural Concrete in Sri Lankan Construction Industry**<br>*V. Krishan, I. Seneviratne, B. Gheethanjali, S. Sivanraj* |
| 04.30 PM - 04.40 PM | **S18134: Macroeconomic Driven Cement Price Forecasting in Sri Lanka Using Econometric and Deep Learning Models**<br>*H.H.A.P. Hemantha, D.N.L.S. Uduwage, R.K. Shiwakoti, K.G.A.S. Waidyasekara* |
| 04.40 PM - 04.50 PM | **S18133: Impact of Digital Payment Methods on Greenhouse Gas Emissions: Evidence from Asian Economies**<br>*K.G.H.M. Senevirathna, N.P.Y.R. Kumarasiri, A.P.H.D.C.I. Minirankotuwa, P.D.P.S. Pallewela, W.Weerathunga, D.D.Silva* |
| 04.50 PM - 05.00 PM | **S18088: FPM Sentinel: A Data-Driven Facility Performance Management Dashboard for The Sri Lankan Built Environment**<br>*M.N.S. De Silva, H.W.N. Madhusanka, K.A.D.M. Natasha* |
| 05.00 PM - 05.30 PM | **Q&A** |

*Session Coordinator: Ms. Nishadi Nanayakkara*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 2C**

| | |
|---|---|
| **Theme** | **Housing, Urban Space Designs for Inclusive Communities** |
| **Session Chair** | **Prof. Hemanta Doloi** |
| **Venue/Time** | **Aquamarine 1 / 04.00 PM - 05.30 PM** |
| **Virtual** | **Breakout Room - Session C** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 04.00 PM - 04.10 PM | **S18017: Resilient and Culturally Responsive Plantation Housing: Socio-Spatial Adaptation in Dunsinane Estate, Sri Lanka**<br>*K. Krishanth, V. Vidhushan* |
| 04.10 PM - 04.20 PM | **S18043: The Effect of House Plan Types on House Plan Transition Patterns in Upper Middle-Class Residences: Case in Aniwatte, Kandy**<br>*H.M.P.M.K. Wijerathne, S.M. Hirudini* |
| 04.20 PM - 04.30 PM | **S18044: The Impact of Location on Threshold Space Architectural Character: Study of Egoda Uyana, Sri Lanka**<br>*S.I. Rajapakse, M. Hirudini* |
| 04.30 PM - 04.40 PM | **S18050: Influence of Personal Space on Privacy-Related Psychological Comfort in Migratory Settlements: A Case Study of Muththettugala, Kurunegala**<br>*W.M.S.S. Dissnayake, S. M. Hirudini* |
| 04.40 PM - 04.50 PM | **S18052: Harnessing Socio-Cultural Practices of Shanty Dwellers for Inclusive Urban Development in Sri Lanka: Evidence from Wattala**<br>*H.M.O.V Herath, M.W.R. Thathsara* |
| 04.50 PM - 05.00 PM | **S18085: Incremental Retrofitting and Material - Space Adaptation in Plantation Line Housing: Evidence from a Wet-Zone Settlement in Sri Lanka**<br>*M.S.M. Senarathna, A. Hettiarachchi* |
| 05.00 PM - 05.30 PM | **Q&A** |

*Session Coordinator: Ms. Vithusha Aathithan*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 2D**

| | |
|---|---|
| **Theme** | **Construction Business, Entrepreneurship & Project Delivery** |
| **Session Chair** | **Prof. (Mrs.) Thanuja Ramachandra** |
| **Venue/Time** | **Aquamarine 2 / 04.00 PM - 05.30 PM** |
| **Virtual** | **Breakout Room - Session D** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 04.00 PM - 04.10 PM | **S18143: The Mind Behind the Machine: Mapping Personality-Based Traits to Entrepreneurial Decision-Making in Construction SMEs**<br>*K.M. Pulasinghe, G.H.S.P. De Silva, A.A.D.A.T. Vihindhuni, A.O. Lokuge* |
| 04.10 PM - 04.20 PM | **T18087: A Conceptual Management Framework for Resource and Financial Optimisation of Construction SMES in Sri Lanka**<br>*A.W.G.S.B. Amaradiwakara, K.A.K. Devapriya* |
| 04.20 PM - 04.30 PM | **T18096: Significance of Joint Venture Enterprises for the Development of Construction Industry of Sri Lanka**<br>*Y.M.W.H.M.R.R.L.J.B Kiridana, M.D.T.E Abenayake* |
| 04.30 PM - 04.40 PM | **S18114: Early Contractor Involvement in a Developing Country Context: Public - Private Sector Differences and Emerging Variants**<br>*H.D.A.S Kumari, D.N. Abeynayake, S. Piranavan* |
| 04.40 PM - 04.50 PM | **S18145: Building Resilience: Navigating the Barriers of Innovation in Construction SMEs of Sri Lanka**<br>*N.L.A. Nissanka, G.H.S.P. De Silva, R. Ahila* |
| 04.50 PM - 05.00 PM | **T18136: Digital Transformation in Large-scale Construction: A Real-world Implementation**<br>*S.I. Mahawatta, K.G.A.S Waidyasekara, P.H.G.M.A Ranasinghe* |
| 05.00 PM - 05.30 PM | **Q&A** |

*Session Coordinator: Ms. Gheethanjali Balasubiramaniyam*

# DETAILED SESSION PLAN

## FRIDAY, 10 JULY 2026

**SESSION 2E (Hybrid)**

| | |
|---|---|
| **Theme** | **Digital Transformation for Regenerative Construction** |
| **Session Chairs** | **Dr. Mohan Siriwardhana and Dr. Michele Florencia Victoria** |
| **Venue/Time** | **Jade / 04.00 PM - 05.40 PM** |
| **Virtual** | **Breakout Room - Session E** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 04.00 PM - 04.10 PM | **S18101: BIM Consultancy Cost Formation in Design-Stage Public Projects: Evidence from Vietnam**<br>*M.L. Vu, T.Q. Nguyen* |
| 04.10 PM - 04.20 PM | **S18040: A Theoretical Framework for the Adoption of Artificial Intelligence Technologies in the Construction Industry**<br>*R. Li, B.L. Oo, B.T.H. Lim* |
| 04.20 PM - 04.30 PM | **T18081: A Framework for the Parametric BIM Implementation and Design Automation in Transportation Infrastructure Projects in India**<br>*M. Kumar, S. Loganathan* |
| 04.30 PM - 04.40 PM | **T18093: Development of A Blockchain-Enabled Smart Contract Framework for Linear Construction Projects**<br>*A.A. Nair, P. Prabu* |
| 04.40 PM - 04.50 PM | **S18019: A Review of Building Information Modelling (BIM) Research in New Zealand Academia from 2010–2025**<br>*M.A. Rahman* |
| 04.50 PM - 05.00 PM | **S18167: A Methodology for Selecting a Digital Twin Platform for Application Development in Construction**<br>*B.P. Arsecularatne, N. Rodrigo, R. Chang* |
| 05.00 PM - 05.10 PM | **S18039: Digitalising Urban Drainage Systems: Barriers and Implications for Vietnam**<br>*V. Mai, T.Q. Nguyen* |
| 05.10 PM - 05.40 PM | **Q&A** |

*Session Coordinator: Mr. Lakshitha Bandaranayake*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 3A**

| | |
|---|---|
| **Theme** | **Bio-based and alternative Construction Materials** |
| **Session Chair** | **Dr. Tharusha Ranadewa** |
| **Venue/Time** | **Tanzanite 1 / 09.00 AM - 10.30 AM** |
| **Virtual** | **Breakout Room - Session A** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 09.00 AM - 09.10 AM | **S18023: Comparative Field Performance of Organic and Commercial Preservatives Against Blue Stain Fungi in Pinewood**<br>*L.R. Rathuge, I.S. Hewage, M.S. Mendis, R.U. Halwatura* |
| 09.10 AM - 09.20 AM | **S18031: Integrating Material Performance and Pedestrian Experience in Sri Lanka: A Review of Bio-Based Wood-Clay Composites in Landscape Architecture**<br>*K.P.S. Amandi, A.A. Hettiarachchi, U.P. Nawagamuwa* |
| 09.20 AM - 09.30 AM | **S18094: Performance Evaluation of Wood-Based Additives in Asphalt Binder: A Comparative Study**<br>*P.K.V.M. Senevirathne, J.M. D. Ashen, T. D. Perera, R. L. H. Gunawardena* |
| 09.30 AM - 09.40 AM | **T18078: Material Innovation as a Cultural Material Practice: Coconut Based Product Design for Regenerative Futures**<br>*C.P. De Silva* |
| 09.40 AM - 09.50 AM | **T18108: Iron Slag Substitution in Soil-Based Geopolymers: A Comparative Study with Coal Fly Ash for Non-Load Bearing Applications**<br>*R.K.N.P. Piyasena, M.F.F. Farha, I.S. Hewage, S.M. Young, R.U. Halwatura* |
| 09.50 AM - 10.00 AM | **T18076: Applicability Of Autoclaved Aerated Concrete (AAC) Blocks Compared to Conventional Bricks and Blocks Within the Sri Lankan Context**<br>*N.T. Pawani, J.K.D.D.T. Jayanetti, D.P. J.D. Ranasinghe* |
| 10.00 AM - 10.30 AM | **Q&A** |

*Session Coordinator: Mr. Charuka Deshan*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 3B**

| | |
|---|---|
| **Theme** | **Circular Economy Governance and Implementation** |
| **Session Chair** | **Ch.QS Indunil Seneviratne** |
| **Venue/Time** | **Tanzanite 2 / 09.00 AM - 10.30 AM** |
| **Virtual** | **Breakout Room - Session B** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 09.00 AM - 09.10 AM | **S18120: Enhancing Circularity in Steel Structures Through Design for Deconstruction: Information Needs**<br>*K. Guruge, K.G.A.S. Waidyasekara, R.M. A.S. Manewa, H.S. Jayasena* |
| 09.10 AM - 09.20 AM | **S18110: Convergence of Circular Economy Strategies for Sustainable Timber Usage in Sri Lanka**<br>*T. Wijesinghe, Y.G. Sandanayake, J.K.D.D.T. Jayanetti, B.A.K.S. Perera* |
| 09.20 AM - 09.30 AM | **S18115: Legislation Provisions for Circular Economy Implementation in the Construction Industry in the Sri Lankan Jurisdiction**<br>*M.D.T.E. Abeynayake, B.A.K.S. Perera, T.B. Abeysekara, P. Mahanamahewa* |
| 09.30 AM - 09.40 AM | **S18132: Role of Regulations and Governance in the Circular Economy for Construction: A Comparative Analysis**<br>*S.M.S.S. Attanayaka, I.E. Illeperuma, M.D.T.E. Abeynayake* |
| 09.40 AM - 09.50 AM | **S18138: Stakeholder Influence and Roles on Circular Economy Adoption in the Sri Lankan Construction Industry**<br>*H.D.T Jayasinghe, D.N Abenayake, V. Aathithan* |
| 09.50 AM - 10.00 AM | **S18163: Cost Impacts of Circular Applications to Construction Activities: A Case of Sri Lanka**<br>*M.A.A. Udayangani, T.Ramachandra, S. Piranavan* |
| 10.00 AM - 10.30 AM | **Q&A** |

*Session Coordinator: Mr. Heshan Bandara*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 3C**

| | |
|---|---|
| **Theme** | **Procurement in Construction** |
| **Session Chair** | **Dr. Dilani Abeynayake** |
| **Venue/Time** | **Aquamarine 1 / 09.00 AM - 10.20 AM** |
| **Virtual** | **Breakout Room - Session C** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 09.00 AM - 09.10 AM | **S18059: Beyond Functionality: The Gap Between Materiality and Compensatory Expectations in Eprocurement**<br>*Y.K. Delpachitra, H.S. Jayasena, C. Wijekoon* |
| 09.10 AM - 09.20 AM | **S18126: Identifying Corruption Risks in Public Construction Procurement: A Stage-ased Framework Aligned with the RIBA Plan of Work**<br>*M.M.H. Chanuka, P.L.I. Wimalaratne* |
| 09.20 AM - 09.30 AM | **S18135: Identifying Factors Influencing Construction Material Procurement Performance Through Latent Dirichlet Allocation Analysis**<br>*H.H.A.P. Hemantha, K.G.A.S. Waidyasekara, D.N.L.S Uduwage* |
| 09.30 AM - 09.40 AM | **S18079: Barriers To Smart Procurement Implementation in the Sri Lankan Construction Sector: An Empirical Investigation**<br>*G.C.K. Wijayawardhana, K. Thiruchelvam, D.N.L.S Uduwage* |
| 09.40 AM - 09.50 AM | **S18169: Exploring Cost Estimation Accuracy and Its Implications for Cost Overruns and Delays in Small-Scale Construction Projects: Evidence from Sri Lanka**<br>*J.W. Mesthrige, L.H.U.W. Abeydeera, T. Maqsood, G.G.N Chandani* |
| 09.50 AM - 10.20 AM | **Q&A** |

*Session Coordinator: Mr. Maneesha Ranasinghe*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 3D**

| | |
|---|---|
| **Theme** | **Construction Costing & Tendering** |
| **Session Chairs** | **Snr. Prof. Kanchana Perera** |
| **Venue/Time** | **Aquamarine 2 / 09.00 AM - 10.30 AM** |
| **Virtual** | **Breakout Room - Session D** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 09.00 AM - 09.10 AM | **S18097: A Systematic Review to Investigate the Root Causes for variations in Infrastructure Developments**<br>*E. Kithulgodage, U. Kulatunga* |
| 09.10 AM - 09.20 AM | **S18038: Factors Influencing the Probability of Winning a Bid in the Sri Lankan Construction Tendering Process**<br>*S. Sayanthan, K. Thiruchelvam, D.N.L.S. Uduwage* |
| 09.20 AM - 09.30 AM | **S18161: Critical Criteria Influencing the Selection of Bid Evaluation Mechanisms under the Most Economically Advantageous Tender (MEAT)**<br>*D.N.L.S. Uduwage, K. Thiruchelvam, H.H.A.P Hemantha, K. Panuwatwanich* |
| 09.30 AM - 09.40 AM | **S18046: Typological Synthesis of Cost Overrun Determinants in Road Construction Using "K-Means": A Narrative Synthesis**<br>*K.N. Hettiarachchi, U. Kulatunga, D.N.L.S. Uduwage* |
| 09.40 AM - 09.50 AM | **S18142: Industry Readiness for Inflation Adjusted Data Driven Cost Estimation in Sri Lankan Construction Industry**<br>*H.M.S.P. Herath, K. Thiruchelvam, D.N.L.S. Uduwage* |
| 09.50 AM - 10.00 AM | **S18075: Assessment Of Material Wastage and Material Reconciliation Practices in Sri Lankan Road Construction Projects**<br>*G.H.D. Thamodhya, C. Handiwattage, H.D. Subhasingha* |
| 10.00 AM - 10.30 AM | **Q&A** |

*Session Coordinator: Mr. Lakshitha Bandaranayake*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 3E (Hybrid)**

| | |
|---|---|
| **Theme** | **Governance, Procurement and Construction Business Innovation** |
| **Session Chair** | **Prof. Thayaparan Gajendran and Dr. Navodana Rodrigo** |
| **Venue/Time** | **Jade / 09.00 AM - 10.40 AM** |
| **Virtual** | **Breakout Room - Session E** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 09.00 AM - 09.10 AM | **S18003: Key Issues and Root Causes in Pre-project Property Selling: A Comparative Analysis Between Indonesia and Malaysia**<br>*S. Hansen, N. Shaqman, L. Darmiyanti* |
| 09.10 AM - 09.20 AM | **S18021: Statutory Good Faith as a Governance Tool: Reforming Infrastructure Delivery and Curbing Corruption in Africa**<br>*A. Aderibigbe, N. Umeokafor, Y. Upadhyay, T. Umar* |
| 09.20 AM - 09.30 AM | **S18032: Managing Foreign Labour in Malaysia's Construction Sector: Practices and Constraints**<br>*S. Sanmargaraja, A. Olanrewaju, M.A. Ali, H.C. Chu, S.C. Khor, V. Ponniah, G. Kanniyapan* |
| 09.30 AM - 09.40 AM | **S18036: From Strategy to Practice: Implementing Sustainable Procurement in Construction SMEs – A Systematic Review**<br>*A. Sivakumar, A. Staal, I. Piri* |
| 09.40 AM - 09.50 AM | **S18083: Mapping Infrastructure Finance Research in Africa's Built Environment: A Bibliometric Review**<br>*M.A. Ogungbe, C.O. Aigbavboa, A.E. Oke, M. Ikuabe, G.T. Aregbesola, T.V. Ogunade* |
| 09.50 AM - 10.00 AM | **S18168: Value Creation in the Construction Industry: A Scoping Review**<br>*P.Y. Weerakoon, M.K.C.S. Wijewickrama, A. Samaraweera, J.J. Ochoa* |
| 10.00 AM - 10.10 AM | **S18130: Reimagining Procurement for Domestic Construction Clients**<br>*P.J. Gamage, C. Hadiwattege* |
| 10.10 AM - 10.40 AM | **Q&A** |

*Session Coordinator: Ch. QS. Dilshan Akalanka*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 4A**

| | |
|---|---|
| **Theme** | **Sustainability Transitions in Construction** |
| **Session Chair** | **Dr. Sachie Gunathilaka** |
| **Venue/Time** | **Tanzanite 1 / 11.00 AM - 12.20 PM** |
| **Virtual** | **Breakout Room - Session A** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 11.00 AM - 11.10 AM | **S18129: Theft and Vandalism in Infrastructure Construction-A Review of Sustainability Impacts**<br>*P.L.T.T. Thilakasiri, K.G.A.S. Waidyasekaraa, P.H.G.A. Ranasinghehe* |
| 11.10 AM - 11.20 AM | **S18006: Circular Economy Policy Framework for Promoting Sustainable Construction Practices in Sri Lankan Construction Industry; Stakeholder Perception**<br>*K. Karunarathna, S. Perera, C. Kalugala* |
| 11.20 AM - 11.30 AM | **S18106: Exploring Porcelain Tableware Waste as a Sustainable Material for Interior Construction in Sri Lanka**<br>*W.M.N.D.Ranasinghe, M. M. Samitha, R. Poovahiya* |
| 11.30 AM - 11.40 AM | **S18077: Prioritising Construction Procurement Decision Factors for Achieving Sustainable Development**<br>*K. D. S. De Abrew, H. Chandanie, P.H.G.M.A. Ranasinghe* |
| 11.40 AM - 11.50 AM | **S18160: Sustainability Impacts of Industry 4.0 In Construction Project Management**<br>*W.K.R. Prasadinee, C. Hadiwattege, N.B. Nanayakkara* |
| 11.50 PM - 12.20 PM | **Q&A** |

*Session Coordinator: Ms. Anuki Kavirathne*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 4B**

| | |
|---|---|
| **Theme** | **Construction Governance & Project Administration** |
| **Session Chair** | **Ch.QS Vijitha Disaratna** |
| **Venue/Time** | **Tanzanite 2 / 11.00 AM - 12.20 PM** |
| **Virtual** | **Breakout Room - Session B** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 11.00 AM - 11.10 AM | **S18035: Understanding The Status Quo of Consultant Selection in Sri Lankan Public Construction Projects**<br>*S. Uthayakumar, K. Thiruchelvam, D.N.L.S. Uduwage* |
| 11.10 AM - 11.20 AM | **S18154: Withstanding Supply Chain Vulnerabilities in Off-Site Construction Logistics: A Narrative Review and 3D Visualisation**<br>*W.M D.Y. Sandaruwan, Y.G. Sandanayake, E.M.C. Ekanayake, G.A. Tennakoon* |
| 11.20 AM - 11.30 AM | **S18131: Adoption of Plain Language to Sri Lankan Construction Contracts: A Narrative Review**<br>*K. Thiruchelvam, D.N.L.S. Uduwage* |
| 11.30 AM - 11.40 AM | **S18139: Effectiveness of Tax Administration with Respect to the Construction Industry in Sri Lanka**<br>*R. Siriwardhana, N. Gunarathana, S. Vivek* |
| 11.40 AM - 11.50 AM | **S18069: A Bibliometric Analysis of Dynamic Organisational Capabilities and Hybrid Project Management Research in the Construction Industry**<br>*S.N. Perera, L.V.K. Jayatilake, U. Kulatunga* |
| 11.50 PM - 12.20 PM | **Q&A** |

*Session Coordinator: Ms. Vithusha Aathithan*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 4C**

| | |
|---|---|
| **Theme** | **Green implications in Built Environment** |
| **Session Chair** | **Mr. Mahesh Abeynayake** |
| **Venue/Time** | **Aquamarine 1 / 11.00 AM - 12.20 PM** |
| **Virtual** | **Breakout Room - Session C** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 11.00 AM - 11.10 AM | **S18089: The Need for Reforming Green Rating Systems for Hospitals in Sri Lanka**<br>*H.W.A.G. Madhuwantha, P. Sridarran., M.N.U. Maddakandage* |
| 11.10 AM - 11.20 AM | **S18164: Enhancing Green Achievement: An Emphasis on Design Features**<br>*S.A.C. Kavindi, T. Ramachandra, B. Gheethanjali* |
| 11.20 AM - 11.30 AM | **S18092: Physicochemical Characterisation of Polyester and Nylon Synthetic Fibres as Potential Plant Growth Substrates for Green Roof Systems: A Preliminary Study**<br>*I.S. Hewage, H. K. P. Ruwanthika, R.K.N.P. Piyasena, T.A. Perera, A. Satharasinghe, A. Gunawardena, R.U. Halwatura* |
| 11.30 AM - 11.40 AM | **S18148: Barriers to Use of LeAgile Project Management for Stakeholder Collaboration in Green Building Constructions in Sri Lanka**<br>*H.V.D. Perera, B.A.K.S. Perera, M.M.N. Mannapperuma* |
| 11.40 AM - 11.50 AM | **S18054: Cognitive Framework for Lighting Design: Perceptions from Contemporary Sri Lankan Architects**<br>*L.P. Balapitiya, N.G.R. Perera* |
| 11.50 PM - 12.20 PM | **Q&A** |

*Session Coordinator: Ch. QS. Dilshan Akalanka*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 4D**

| | |
|---|---|
| **Theme** | **Research and Education in the Built Environment** |
| **Session Chairs** | **Prof. Menaha Thayaparan** |
| **Venue/Time** | **Aquamarine 2 / 11.00 AM - 12.20 PM** |
| **Virtual** | **Breakout Room - Session D** |

| **Time** | **Paper ID, Title and Author(s)** |
|---|---|
| 11.00 AM - 11.10 AM | **S18070: Operationalising Community-Based Research Through Photovoice**<br>*W.S.D. Perera, U. Kulatunga, D. Ranasinghe, R. Mahamood, N. Kangana, C. De Silva* |
| 11.10 AM - 11.20 AM | **S18100: Reframing The Inclusive Classroom as a Designed Learning Environment: An Integrative Literature Review**<br>*A.I. Sewwandi, S. Samarawickrama* |
| 11.20 AM - 11.30 AM | **T18071: Digital System for Effective End-User Engagement in Higher Education Building Design**<br>*F.S. Nazeer, I. Kamardeen, A. Hasan* |
| 11.30 AM - 11.40 AM | **S18066: Academic Workload and Mental Wellbeing: Perspectives of First-Year Quantity Surveying students at higher education institutions in Sri Lanka**<br>*J.D.R.A. Jayakody, K. Thiruchelvam, D.N.L.S. Uduwage* |
| 11.40 AM - 11.50 AM | **S18170: A Scientometric Analysis of Construction Value Management Research: A 25-Year Review**<br>*L.H.U.W. Abeydeera, W.M. Jayantha, T. Maqsood, G.G.N Chandani* |
| 11.50 PM - 12.20 PM | **Q&A** |

*Session Coordinator: Ms. Himasha Subhasingha*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 4E (Hybrid)**

| | |
|---|---|
| **Theme** | **Capacity Building for a Regenerative Built Environment** |
| **Session Chairs** | **Dr. Gayani Karunasena** |
| **Venue/Time** | **Jade / 11.00 AM - 12.20 PM** |
| **Virtual** | **Breakout Room - Session E** |

| **Time** | **Paper ID, Title and Author(s)** |
|---|---|
| 11.00 AM - 11.10 AM | **S18004: Relationship Model of Mindfulness Practice and Construction Workers' Performance: An Exploratory Study in Indonesia**<br>*S. Hansen* |
| 11.10 AM - 11.20 AM | **S18095: Distance Is No Barrier: Drivers of the Deployment of Remote Construction Management for Project Delivery in South Africa**<br>*M. Ikuabe, C. Aigbavboa, M. Ogungbe, T. Aregbesola, T. Ogunade* |
| 11.20 AM - 11.30 AM | **S18165: Enhancing High-performance Computing (HPC) Adoption in the Built Environment: A User-centred Approach to Inclusive Digital Innovation**<br>*T. Umar, K. Chun, J. Smith* |
| 11.30 AM - 11.40 AM | **S18147: International Students' Decision-Making and Learning Experience in Construction Management Coursework Master's Degree**<br>*B.L. Oo, R. Li, B.T.H. Lim* |
| 11.40 AM - 11.50 AM | **S18150: Integrating Life Cycle Assessment and Emissions Trading Scheme in the Australian Construction Sector: A Preliminary Study**<br>*P. Yang, B.T.H. Lim, B.L. Oo* |
| 11.50 PM - 12.20 PM | **Q&A** |

*Session Coordinator: Mr. Kawshalya Sepalage*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 5A**

| | |
|---|---|
| **Theme** | **Regenerative Design, Culture & Community-Based Built Environments** |
| **Session Chair** | **Dr Amruta Garud** |
| **Venue/Time** | **Tanzanite 1 / 01.30 PM - 2.50 PM** |
| **Virtual** | **Breakout Room - Session A** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 01.30 PM - 01.40 PM | **S18018: Schoolyards As Built Infrastructure: A Feasibility Framework for Closing Environmental Education Implementation Gaps**<br>*E. Mendis, M. Thayaparan, D. Lellupitiya* |
| 01.40 PM - 01.50 PM | **S18028: Temporary Built Environments in Sri Lankan Film Production Design**<br>*S. Fernando, S. Samarawickrama* |
| 01.50 PM - 02.00 PM | **S18049: Landscape as a Signifier of Rural Social Class Inequality in Contemporary Sri Lankan Cinema: An Analytical Study of Three Selected Films**<br>*P.T. Kolamunna, U.G.D. Weerasinghe, S.M. Hirudini* |
| 02.00 PM - 02.10 PM | **S18051: Maritime Infrastructure Impacts on Marine Socio-Ecological Systems: A Literature Review**<br>*S.J.L. Madhushani, K.A.T.O. Ranadewa, B.A.K.S. Perera* |
| 02.10 PM - 02.20 PM | **S18072: Regional Identity and Regenerative Architecture: Reinterpreting Buddhist Philosophy in Contemporary Built Environments**<br>*G.R.K.A.G. Menike, K. Perera* |
| 02.20 PM - 02.50 PM | **Q&A** |

*Session Coordinator: Mr. Maneesha Ranasinghe*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 5B**

| | |
|---|---|
| **Theme** | **Construction Safety and Well-being** |
| **Session Chair** | **Dr. Uthpala Rathnayaka** |
| **Venue/Time** | **Tanzanite 2 / 01.30 PM - 2.40 PM** |
| **Virtual** | **Breakout Room - Session B** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 01.30 PM - 01.40 PM | **S18001: The Financial and Social Implications of Construction Site Accidents in Sri Lanka**<br>*H.R. Fernando, U. Kulatunga, B. Gheethanjali, N. Gunawardhana* |
| 01.40 PM - 01.50 PM | **S18064: Artificial Intelligence (AI)-Powered Gesture Recognition for Occupational Safety Improvement in the Sri Lankan Construction Industry: A Conceptual Framework**<br>*R. Thathsara, H. Mallawaarachchi* |
| 01.50 PM - 02.00 PM | **S18156: Occupational Stressors among Sri Lankan Construction Professionals**<br>*S.D.N.B. Peiris, S. Gunatilake, I.W.M.A.D. Ilangakoon* |
| 02.00 PM - 02.10 PM | **S18026: Remote Work for Female Professionals in Sri Lankan Construction Industry: Challenges and Expectations**<br>*Y.B.M.C.S. Kumarihami, K. Thiruchelvam, D.N.L.S. Uduwage* |
| 02.10 PM - 02.40 PM | **Q&A** |

*Session Coordinator: Ms. Nawanjana Mannapperuma*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 5C**

| | |
|---|---|
| **Theme** | **Climate Resilience & Disaster Risk Management** |
| **Session Chair** | **Dr. Kapila Devapriya** |
| **Venue/Time** | **Aquamarine 1 / 01.30 PM - 2.50 PM** |
| **Virtual** | **Breakout Room - Session C** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 01.30 PM - 01.40 PM | **S18105: Microclimate Aware Urban Planning in Tropical Climates**<br>*J.S. Nimesha, U. Kulatunga, H.D. Subhasingha* |
| 01.40 PM - 01.50 PM | **S18155: Deep Learning-based Flood Mapping in Monsoon Climates Using SENTINEL-1 SAR**<br>*A. Bhattarai, R.K. Shiwakoti, D.N.L.S. Uduwage* |
| 01.50 PM - 02.00 PM | **S18166: What Enables Climate-responsive and Resource-efficient Office Buildings in a Small Island Developing State? A Stakeholder-weighted Readiness Gap Analysis**<br>*S.B. Nahullah, N. Fernando, M. Jowkar* |
| 02.00 PM - 02.10 PM | **S18152: Optimizing Community Participation in Post-Disaster Crisis Response: Evidence From the "Ditwah" Cyclone, Sri Lanka**<br>*J.A.C.D Jayalath, U. Kulatunga* |
| 02.10 PM - 02.20 PM | **S18137: Nature-based Solutions for Flood Mitigation: A Systematic Review of Evidence, Performance Mechanisms, and Implementation Conditions**<br>*R.V.A.D. Rahubadda, B. Ingirige, U. Kulatunga* |
| 02.20 PM - 02.50 PM | **Q&A** |

*Session Coordinator: Ms. Himasha Subhasingha*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 5D**

| | |
|---|---|
| **Theme** | **Nature-Inspired Approaches in Construction** |
| **Session Chairs** | **Dr. Nuwantha Uduwage** |
| **Venue/Time** | **Aquamarine 2 / 01.30 PM - 2.50 PM** |
| **Virtual** | **Breakout Room - Session D** |

| Time | Paper ID, Title and Author(s) |
|---|---|
| 01.30 PM - 01.40 PM | **S18073: Exploring Multi-Level Biomimicry in Building Façade Construction**<br>*M.D.K.S. Bandara, U. Kulatunga, H.D. Subhasingha* |
| 01.40 PM - 01.50 PM | **S18080: Learning from Nature: Biomimicry Inspired Daylighting Design for Reducing Artificial Lighting in Urban Buildings**<br>*P.A.D.D.J. Weeranayaka, R.M.H.R Bandara, M. Thayaparan* |
| 01.50 PM - 02.00 PM | **S18123: Performance Indicators for Biomimicry-based Construction Materials and their Operationalization through Augmented Reality: A Systematic Literature Review**<br>*W.M.I.H. Wijesundara., U. Kulatunga, P.L.I. Wimalaratne* |
| 02.00 PM - 02.10 PM | **S18112: A Conceptual Biomimicry-Inspired Model for Enhancing Energy Efficiency in High-Rise Buildings in Sri Lanka.**<br>*S.B.N.S.W. De Silva, P. Sridarran, M.N.U. Maddakandage* |
| 02.10 PM - 02.20 PM | **S18107: Managing End-of-Life Impacts of Solar Photovoltaic Systems: A Sri Lankan Perspective**<br>*U. Jayanandana, G.A. Tennakoon, D. Kodituwakku, M. Chan* |
| 02.20 PM - 02.50 PM | **Q&A** |

*Session Coordinator: Ms. Nishadi Nanayakkara*

# DETAILED SESSION PLAN

## SATURDAY, 11 JULY 2026

**SESSION 5E (Hybrid)**

| | |
|---|---|
| **Theme** | **Sustainable Constructions and Climate-Responsive Designs** |
| **Session Chair** | **Associate Prof. Niluka Domingo** |
| **Venue/Time** | **Jade / 01.30 PM - 2.50 PM** |
| **Virtual** | **Breakout Room - Session E** |

| **Time** | **Paper ID, Title and Author(s)** |
|---|---|
| 01.30 PM - 01.40 PM | **S18010: Smart Building Technologies in Qatar: Challenges and Opportunities for Sustainable Development**<br>*A.R. Rauff, R. Sofar* |
| 01.40 PM - 01.50 PM | **T18027: Evaluating the Thermal Performance of Various Vernacular Roofing Systems in Contemporary Buildings**<br>*T.S. Prakash, K. Murugkar* |
| 01.50 PM - 02.00 PM | **S18029: Conceptualising an Inclusive Compliance Approach to Sustain Energy Efficiency of New Single-Family Homes**<br>*N.D. Hulathdoowage, G. Karunasena, N. Udawatta, P. Harrington, C. Liu* |
| 02.00 PM - 02.10 PM | **S18005: Bridging the Gap: Professional Perceptions and Adoption of Mud Construction Techniques in Nigerian Urban Architecture**<br>*A.O. Comfort, G. Emmanuel* |
| 02.10 PM - 02.20 PM | **S18053: Microclimate-Driven Spatial Patterns for Adaptive Urban Design: Evidence from Kotahena, Sri Lanka**<br>*D. Kumar, N. Perera* |
| 02.20 PM - 02.50 PM | **Q&A** |

*Session Coordinator: Mr. Heshan Bandara*

# KEYNOTE SPEAKER

## Dr Josephine Vaughan

### Keynote on 'From Extraction to Circulation: Rethinking Cities as Sources of Building Materials'

Dr Josephine Vaughan is a Senior Lecturer in the built environment and a recognised leader in sustainable and regenerative construction research. Her work sits at the intersection of circular economy, embodied carbon, low impact building materials and industry engaged innovation, with a strong focus on translating foresight into practical, scalable action. Dr Vaughan has led more than 15 major industry funded research projects in collaboration with government, industry and international partners, producing academic and industry publications that inform policy, practice and education. She co leads the Circular Economy and Sustainable Construction Research Group at the University of Newcastle, Australia and is a co chair of Materials and Assemblies in the Materials and Embodied Carbon Leaders' Alliance (MECLA), supporting interdisciplinary collaboration across the built environment sector. Her research and leadership have been recognised through multiple awards, including the Trailblazer for Recycling and Clean Energy (TRaCE) Fellowship, Global Engagement Awards and UNITAR CIFAL United Nations certifications, reflecting her commitment to capacity building and systemic change in construction practices worldwide. She is also actively involved in international knowledge exchange initiatives across Asia–Pacific, including climate resilient and net zero infrastructure programs.

# ROUNDTABLE BRAINSTORMING

## CIB TG129–W107 WCS ROUNDTABLE BRAINSTORMING

### *Sustainable Supply Chains for Resilient Construction Industries in Developing Countries*

| | | |
|---|---|---|
| **Panel Members** | : | **Associate Prof. Hemanta Doloi** (W107 Lead Coordinator) – Construction Management & Technology, Faculty of Architecture, Building and Planning, University of Melbourne, Australia<br>**Senior Prof. Ananda Jayawardane** – Faculty of Engineering, University of Moratuwa, Sri Lanka<br>**Dr Josephine Vaughan** – College of Engineering, Science and Environment, The University of Newcastle, Australia<br>**Ch.QS. Lalith Rathnayake** – Chartered Quantity Surveyor, Contract Management Consultant, Director - VFORM Consultants Private Ltd and PROMAP Private Ltd, Sri Lanka |
| **Panel Moderator** | : | **Prof**. **Mohan Kumaraswamy** – Honorary Professor, University of Hong Kong and Honorary Professor, University of Moratuwa |
| **Thematic Summary Contributor** | : | **Dr. Suranga Jayasena** (TG129 Lead Coordinator) – Head of the Department, Department of Building Economics, University of Moratuwa, Sri Lanka |

# Panel Member

## Associate Prof. Hemanta Doloi

**PhD (Sydney), Grad. Cert. (Melbourne), MSc (AIT), BSc Hons (Dibrugarh)**

**Associate Professor and Lead Investigator (Assam Project)**

**Director and Project Leader (Smart Villages Lab)**

**Lead Coordinator- CIB Working Commission W107 on Construction in Developing Countries**

Associate Prof. Hemanta Doloi is an Associate Professor specialising in Project and Construction Management, with internationally recognised expertise in project management, infrastructure planning and policy, and construction economics and management. He has an outstanding research record, publishing extensively in leading international journals. He established a new research facility, Smart Villages Lab (SVL) at the University of Melbourne, supporting sustainable rural development in partnership with the Government of Assam. His work integrates governance, construction management, and technology to improve rural communities. In recognition of his excellence in research and teaching, he received the prestigious AIQS Infinite Value Award in 2012.

# Panel Member

## Senior Prof. Ananda Kithsiri Wijenayaka Jayawardane

**BSc Eng Hons (Moratuwa), MSc (Loughborough, UK),**

**PhD (Loughborough, UK), MSSE (SL), FNASSL, FIPM (SL),**

**CEng, FIE(SL), Int.PEng (SL), M (SLAAS), GSLID**

Professor Ananda Jayawardane is currently a Senior Professor in Civil Engineering at the University of Moratuwa and a Director of Bank of Ceylon, HNB Life PLC, Prime Land Residencies PLC and Mother Lanka Foundation. He is the former Chairman of the Commercial Bank of Ceylon PLC, a past Vice-Chancellor of the University of Moratuwa, a past Chairman of the Committee of Vice-Chancellors, a past Director General of the National Science Foundation, a past Commission Member of the University Grants Commission, past NDB Bank Endowed Professor in Entrepreneurship at the University of Moratuwa, and a Past President of the Institution of Engineers, Sri Lanka.

He is a Chartered Engineer, an International Professional Engineer, and a Fellow of several other professional and scientific bodies.

He has served as a member of the governing Councils/Boards of several other private and public institutions including ICTAD, CIDA, State Engineering Corporation, Engineering Council and Green Building Council of Sri Lanka. He is a recipient of several awards for his research, contribution to education including the “eminence in the practice of engineering” the most prestigious lifetime award given by the IESL.

# Panel Member

## Dr Josephine Vaughan

**PhD Architecture (Newcastle 2017), B.Arch (Newcastle 1999), Grad. Cert. ESD (TAFE NSW 2009), BSc Architecture (Sydney 1998)**

**Senior Lecturer**

**College of Engineering, Science and Environment**

**The University of Newcastle on Awabakal land: Callaghan, Australia**

Dr Josephine Vaughan is a Senior Lecturer in the built environment and a recognised leader in sustainable and regenerative construction research. Her work sits at the intersection of circular economy, embodied carbon, low-impact building materials and industry-engaged innovation, with a strong focus on translating foresight into practical, scalable action. Dr Vaughan has led more than 15 major industry-funded research projects in collaboration with government, industry and international partners, producing over academic and industry publications that inform policy, practice and education. She co-leads the Circular Economy and Sustainable Construction Research Group at the University of Newcastle, Australia and is a co-chair of Materials and Assemblies in the Materials and Embodied Carbon Leaders' Alliance (MECLA), supporting interdisciplinary collaboration across the built environment sector. Her research and leadership have been recognised through multiple awards, including the Trailblazer for Recycling and Clean Energy (TRaCE) Fellowship, Global Engagement Awards and UNITAR-CIFAL United Nations certifications, reflecting her commitment to capacity-building and systemic change in construction practices worldwide. She is also actively involved in international knowledge exchange initiatives across the Asia–Pacific, including climate-resilient and net-zero infrastructure programs.

# Panel Member

## Ch. QS. Lalith Ratnayake

**Senior Chartered Quantity Surveyor**

**Contract Management Consultant**

**Director, VFORM Consultants Private Ltd. and PROMAP Private Ltd.**

Ch.QS Lalith Ratnayake obtained the B.Sc. (Hons) QS degree in 1992 and M.Sc. in Project Management in 2012 from the University of Moratuwa. He is an Accredited Mediator of the Singapore International Mediation Institute (SIMI) (Level 01).

Mr Lalith Ratnayake has his own professional practice providing specialist services in Quantity Surveying, Contracts Management and Dispute Mediation.

He is a Fellow member of the Institute of Quantity Surveyors, Sri Lanka (IQSSL) and the Past President of IQSSL during 2019-2021. He is a visiting lecturer at the University of Moratuwa for M.Sc. Degree in Construction Law & Dispute Resolution. His contribution to the build environment sector includes serving as a resource person at construction industry forums, industry regulatory bodies, faculty boards at state and non-state universities, and local and overseas professional bodies. Further, he has published many technical papers related to the built environment and contributed to research.

# Panel Moderator

## Eng. Prof. Mohan Kumaraswamy

**DSc (UK), PhD (UK), MSc (UK), BSc Engineering (Hons) Civil Eng**

**Honorary Professor, University of Hong Kong and Honorary Professor, University of Moratuwa**

Eng. Prof. Mohan M. Kumaraswamy is now an Honorary Professor at HKU and also at the University of Moratuwa, Sri Lanka. His B.Eng. (Civil) is from Sri Lanka, while his M.Sc., Ph.D. and D.Sc. are from the UK. He was in full-time academia for 21 years at the University of Hong Kong.

Before joining full-time academia, apart from part-time teaching, he worked in a client's design & project management office, as well as with contractors in Sri Lanka and Nigeria. He then joined the first construction project management company in Sri Lanka, was Construction Manager, and then a Director, also leading construction management, training package development and consultancy projects, some funded by international organisations.

He is a Fellow of relevant professional bodies in Sri Lanka, UK and Hong Kong and a member of others in Australia, UK and USA. He has actively contributed and held high offices in professional bodies and industry link bodies in Sri Lanka and Hong Kong. He launched CICID (Centre for Innovation in Construction & Infrastructure Development) in Hong Kong in 2002. Being its first Executive Director, he now assists as its Founder Director.

In academia, he has won awards for research, teaching and research supervision. he has also led many research projects including; and publishes widely in international journals, books and conferences, He also plays leading roles in international research bodies and editorial boards. e.g., as one of three Joint Co-ordinators of the CIB Working Commission W122 on Public Private Partnership; and also as Editor-in-Chief of the Emerald Journal of Built Environment Project and Asset Management (BEPAM) which he launched in 2010; and as Editor-in-Chief of the Book Series on Domain-Specific Bodies of Knowledge in Project Management, which he launched in 2020.

# Thematic Summary Contributor

## Ch. QS. Dr. Suranga Jayasena

**PhD, MSc (Building), BSc (Hons) QS, FIQSSL**

**Senior Lecturer, Department of Building Economics, University of Moratuwa**


Ch. QS. Dr. Suranga Jayasena is the current head of the Department of Building Economics, University of Moratuwa and currently serving as a Senior Lecturer of the Department. He obtained a B.Sc. (Hons) degree in Quantity Surveying from the University of Moratuwa and an M.Sc. in Building from the National University of Singapore. In 2023, Dr. Jayasena completed his PhD at the University of Moratuwa, Sri Lanka. While his primary teaching area is Building Procurement, his research interests span a broader landscape, encompassing Building Economics, Procurement Systems, Dispute Resolution, and Construction Information Technology, all of which are intertwined with Building Procurement and enrich his teaching. He is a Fellow, a member of the governing council, and a Committee Chair of the Institute of Quantity Surveyors Sri Lanka (IQSSL).

# SESSION BY THE CIB STUDENT CHAPTER

## SESSION IN COLLABORATION BY THE CIB STUDENT CHAPTERS OF MASSEY UNIVERSITY AND THE UNIVERSITY OF MORATUWA

***Towards a Regenerative Built Environment: From Foresight to Action***

## Speakers

### Dr. Eziaku Rasheed

**SFHEA, PhD (Arch), MSc (Proj.Mgt), BSc (Arch), CerBIM (Proj.Mgt)**

*Session Title: Connect, Learn, Lead: What the CIB Student Chapter Can Do for You*

Senior Lecturer in Sustainable Built Environment; Coordinator, CIB Task Group 125: Creating an Inclusive Built Environment for Diverse Users; Massey's CIB Student Advisor (since 2020); School of Built Environment, Massey University

### Associate Professor Mostafa Babaeian Jelodar

**PhD (Civil.En; Const.Mng), MSc(Proj.Mgt), BEng (Civil)**

*Session Title: Advancing Sustainability in the Built Environment through Modern Methods of Construction and Automation*

Modern Methods of Construction and Automation in Built Environment (MOCABE); Team Lead at CanConstructNZ; Associate Professor in Construction Engineering and Management; Academic Lead, School of Built Environment, Massey University

# CONTENTS OF PAPERS

A Bibliometric Analysis of Dynamic Organisational Capabilities and Hybrid Project Management Research in the Construction Industry ..... 1
*S.N. Perera, L.V.K. Jayatilake & U. Kulatunga*

A Conceptual Biomimicry-Inspired Model for Enhancing Energy Efficiency in High-Rise Buildings in Sri Lanka ..... 16
*S.B.N.S.W. De Silva, P. Sridarran & M.N.U. Maddakandage*

A Conceptual Framework for the Adoption of a Life Cycle Assessment-Based Emissions Trading Scheme in the Australian Construction Sector ..... 30
*P. Yang, B.T.H. Lim & B.L. Oo*

A Conceptual Hybrid Framework for CDE Configuration: Balancing ISO 19650 Rigidity with Agile Flexibility ..... 44
*B.K.C Perera, H.S. Jayasena & M. Siriwardena*

A Conceptual Management Framework for Resource and Financial Optimisation of Construction SMEs in Sri Lanka ..... 58
*A.W.G.S.B. Amaradiwakara & K.A.K. Devapriya*

A Framework for the Parametric BIM Implementation and Design Automation in Transportation Infrastructure Projects in India ..... 71
*M. Kumar & S. Loganathan*

A Methodology for Selecting a Digital Twin Platform for Application Development in Construction ..... 85
*B.P. Arsecularatne, N. Rodrigo & R. Chang*

A Review of Building Information Modelling (BIM) Research in New Zealand Academia from 2010-2025 ..... 99
*M.A. Rahman*

A Systematic Review to Investigate the Root Causes for Variations in Infrastructure Developments ..... 110
*E. Kithulgodage & U. Kulatunga*

A Theoretical Framework for the Adoption of Artificial Intelligence Technologies in the Construction Industry ..... 121
*R. Li, B.L. Oo & B.T.H. Lim*

Academic Workload and Mental Wellbeing: Perspectives of First-Year Quantity Surveying Students at Higher Education Institutions in Sri Lanka ..... 135
*J.D.R.A. Jayakody, K. Thiruchelvam & D.N.L.S. Uduwage*

Adoption of Plain Language to Sri Lankan Construction Contracts: A Narrative Review ..... 149
*K. Thiruchelvam & D.N.L.S. Uduwage*

Age-Related Variations in Spatial Cognition and Spatial Behavior in Botanic Gardens: Evidence from the Royal Botanic Gardens, Peradeniya ..... 161
*W.M.S.S. Dissanayake & S. Amendra*

Analysing Key Process Areas in Developing the Circular Economy Maturity Model for Construction Organisations ..... 176
*S. Jayakodi, S. Senaratne, S. Perera & K. Bamdad*

Applicability of Artificial Intelligence for Improving Infrastructure Resilience ..... 191
*S.A.L. Wimalasuriya, U. Kulatunga, D. Munasinghe & N. Dias*

Applicability of Autoclaved Aerated Concrete (AAC) Blocks Compared to Conventional Bricks and Blocks within the Sri Lankan Context ..... 205
*N.T. Pawani, J.K.D.D.T. Jayanetti & D.P. J.D. Ranasinghe*

Appropriateness of Commonly Used Methods for Assessing the Impacts of Circular Economy Practices ..... 220
*I. Gamage, S. Senaratne, S. Perera & X. Jin*

Artificial Intelligence (AI)-Powered Gesture Recognition for Occupational Safety Improvement in the Sri Lankan Construction Industry: A Conceptual Framework ..... 235
*R. Thathsara & H. Mallawaarachchi*

Assessing BIM Knowledge among Construction Professionals in Sri Lanka: Challenges and Opportunities ..... 249
*G.K.G.S. Kosala & R.P.T Nyanathara*

Assessment of Material Wastage and Material Reconciliation Practices in Sri Lankan Road Construction Projects ..... 263
*G.H.D. Thamodhya, C. Handiwattage & H.D. Subhasingha*

Barriers to Smart Procurement Implementation in the Sri Lankan Construction Sector: An Empirical Investigation ..... 278
*G.C.K. Wijayawardhana, K. Thiruchelvam & D.N.L.S Uduwage*

Barriers to Use of LeAgile Project Management for Stakeholder Collaboration in Green Building Constructions in Sri Lanka ..... 292
*H.V.D. Perera, B.A.K.S. Perera & M.M.N. Mannapperuma*

Beyond Functionality: The Gap between Materiality and Compensatory Expectations in Eprocurement ..... 306
*Y.K. Delpachitra, H.S. Jayasena & C. Wijekoon*

Beyond the Envelope: Examining Project Management as a Catalyst for High-Performance Building Design ..... 320
*H. Deheragoda, G.H.S.P. De Silva & M. Jinthusan*

BIM Consultancy Cost Formation in Design-Stage Public Projects: Evidence from Vietnam ..... 334
*M.L. Vu & T.Q. Nguyen*

Building Resilience: Navigating the Barriers of Innovation in Construction SMEs of Sri Lanka... 349
*N.L.A. Nissanka, G.H.S.P. De Silva & R. Ahila*

Circular Economy Knowledge Management Initiatives in the Australian Construction and Demolition Waste Management Sector ..... 364

*M. Nadeetharu, N. Udawatta, G.P. Costin & G. Karunasena*

Circular Economy Policy Framework for Promoting Sustainable Construction Practices in Sri Lankan Construction Industry; Stakeholder Perception..... 377
*K. Karunarathna, S. Perera & C. Kalugala*

Cognitive Framework for Lighting Design: Perceptions from Contemporary Sri Lankan Architects ..... 391
*L.P. Balapitiya & N.G.R. Perera*

Comparative Field Performance of Organic and Commercial Preservatives against Blue Stain Fungi in Pinewood ..... 405
*L.R. Rathuge, I.S. Hewage, M.S. Mendis & R.U. Halwatura*

Conceptual Digital Twin Framework for Conserving Urban Cultural Heritage: A Case of Slave Island, Colombo..... 419
*W.D.B.J. Jeewananda, K.S.K.N.J Kudasinghe & A.R. Rupasinghe*

Conceptualising a Value Stream Mapping (VSM)-Based Decision-Making Model for Lean Energy Retrofitting of HVAC Systems in High-Rise Buildings: Literature Review Approach ..... 433
*H.M.D.C Gamagedara, H. Mallawaarachchi & J.A.D.K.S Jayakodi*

Conceptualising an Inclusive Compliance Approach to Sustain Energy Efficiency of New Single-Family Homes..... 445
*N.D. Hulathdoowage, G. Karunasena, N. Udawatta, P. Harrington & C. Liu*

Contractual Provisions Inducing Construction Waste Generation: An Analysis of Sri Lankan Standard Forms of Contract..... 459
*R.D.L. Fernando, R.M.H.R Bandara & M. Thayaparan*

Convergence of Circular Economy Strategies for Sustainable Timber Usage in Sri Lanka..... 471
*T. Wijesinghe, Y.G. Sandanayake, J.K.D.D.T. Jayanetti & B.A.K.S. Perera*

Cost Impacts of Circular Applications to Construction Activities: A Case of Sri Lanka ..... 485
*M.A.A. Udayangani, T. Ramachandra & S. Piranavan*

Critical Criteria Influencing the Selection of Bid Evaluation Mechanisms under the Most Economically Advantageous Tender (MEAT) ..... 499
*D.N.L.S. Uduwage, K. Thiruchelvam, H.H.A.P Hemantha & K. Panuwatwanich*

Data Requirements for a Material Passport in the Sri Lankan Construction Industry ..... 513
*H.G.G. Nawarathna, H.S Jayasena & S. Piranavan*

Deep Learning-Based Flood Mapping in Monsoon Climates using SENTINEL-1 SAR ..... 527
*A. Bhattarai, R.K. Shiwakoti & D.N.L.S. Uduwage*

Development of a Blockchain-Enabled Smart Contract Framework for Linear Construction Projects ..... 539
*A.A. Nair & P. Prabu*

Digital System for Effective End-User Engagement in Higher Education Building Design..... 552
*F.S. Nazeer, I. Kamardeen & A. Hasan*

Digital Transformation in Large-Scale Construction: A Real-World Implementation..... 565
*S.I. Mahawatta, K.G.A.S Waidyasekara & P.H.G.M.A Ranasinghe*

Digitalising Urban Drainage Systems: Barriers and Implications for Vietnam ..... 578
*V. Mai & T.Q. Nguyen*

Distance Is No Barrier: Drivers of the Deployment of Remote Construction Management for Project Delivery in South Africa ..... 592
*M. Ikuabe, C. Aigbavboa, M. Ogungbe, T. Aregbesola & T. Ogunade*

Early Contractor Involvement in a Developing Country Context: Public - Private Sector Differences and Emerging Variants ..... 601
*H.D.A.S Kumari, D.N. Abeynayake & S. Piranavan*

Effectiveness of Tax Administration with Respect to the Construction Industry in Sri Lanka ..... 615
*R. Siriwardhana, N. Gunarathana & S. Vivek*

Enhancing Building Energy Data Management in Sri Lanka: Barriers, Enablers, and Strategic Pathways ..... 628
*R.Y. Silva, H.W.N. Madhusanka & K.A.R.V.D. Kahandawa*

Enhancing Circularity in Steel Structures through Design for Deconstruction: Information Needs 642
*K. Guruge, K.G.A.S. Waidyasekara, R.M. A.S. Manewa & H.S. Jayasena*

Enhancing Green Achievement: An Emphasis on Design Features ..... 657
*S.A.C. Kavindi, T. Ramachandra & B. Gheethanjali*

Enhancing High-Performance Computing (HPC) Adoption in the Built Environment: A User-Centred Approach to Inclusive Digital Innovation ..... 672
*T. Umar, K. Chun & J. Smith*

Ergonomic Performance Indicators for Evaluating Office Workstation Arrangements ..... 686
*T.A. Kasthuriarachchi, M.M.I.S. Mapa & G.G.N Chandani*

Evaluating the Thermal Performance of Various Vernacular Roofing Systems in Contemporary Buildings ..... 702
*T.S. Prakash & K. Murugkar*

Exploring Cost Estimation Accuracy and Its Implications for Cost Overruns and Delays in Small-Scale Construction Projects: Evidence from Sri Lanka ..... 714
*J.W. Mesthrige, L.H.U.W. Abeydeera, T. Maqsood & G.G.N Chandani*

Exploring Multi-Level Biomimicry in Building Façade Construction ..... 729
*M.D.K.S. Bandara, U. Kulatunga & H.D. Subhasingha*

Exploring Porcelain Tableware Waste as a Sustainable Material for Interior Construction in Sri Lanka ..... 740
*W.M.N.D. Ranasinghe, M. M. Samitha & R. Poovahiya*

Exploring the Current Status of Retrofitting or Rebuilding in Construction ..... 754
*B.W. Madanayake & S. Nissanka*

Factors Influencing the Probability of Winning a Bid in the Sri Lankan Construction Tendering Process ..... 768
*S. Sayanthan, K. Thiruchelvam & D.N.L.S. Uduwage*

FPM Sentinel: A Data-Driven Facility Performance Management Dashboard for the Sri Lankan Built Environment ..... 782

*M.N.S. De Silva, H.W.N. Madhusanka & K.A.D.M. Natasha*

From BIM 6D/7D to Operational Digital Twins Closing the Building Energy Performance Gap in Tropical Buildings - a Mixed-Methods Study in Sri Lanka ..... 796
*T.H. Madushanka, S.D.A. Soorige & H.W.N. Madhusanka*

From Inertia to Integration: Evaluating the Challenges and Enablers of BIM in the Infrastructure Sectors of Sri Lanka and the Middle East ..... 814
*A. Lokuge, G.H.S.P De Silva & S. Vinoshan*

From Reactive Reporting to Regenerative Control: Rethinking Construction Progress Monitoring in Sri Lanka through IOT Enabled Real-Time Practices ..... 828
*T.M.A.Y.B. Malvila, R.M.H.R. Bandara & M. Thayaparan*

From Strategy to Practice: Implementing Sustainable Procurement in Construction SMEs - a Systematic Review ..... 842
*A. Sivakumar, A. Staal & I. Piri*

From Waste to Use: Plywood Usage and Wastage in Slab and Beam Construction ..... 855
*W.M.P.M. Bandara, K.G.A.S. Waidyasekara & P.H.G.M.A. Ranasinghe*

From Waste to Worth: Digitalizing Secondary Materials Market in Construction ..... 870
*K. Arthigan & B.A.I Eranga*

Harnessing Socio-Cultural Practices of Shanty Dwellers for Inclusive Urban Development in Sri Lanka: Evidence from Wattala ..... 884
*H.M.O.V Herath, M. Wijesinghe & M.W.R. Thathsara*

Identifying Factors Influencing Construction Material Procurement Performance through Latent Dirichlet Allocation Analysis ..... 897
*H.H.A.P. Hemantha, K.G.A.S. Waidyasekara & D.N.L.S Uduwage*

Incremental Retrofitting and Material - Space Adaptation in Plantation Line Housing: Evidence from a Wet-Zone Settlement in Sri Lanka ..... 911
*M.S.M. Senarathna & A. Hettiarachchi*

Industry Readiness for Inflation Adjusted Data Driven Cost Estimation in Sri Lankan Construction Industry ..... 924
*H.M.S.P. Herath, K. Thiruchelvam & D.N.L.S. Uduwage*

Influence of Personal Space on Privacy-Related Psychological Comfort in Migratory Settlements: A Case Study of Muththettugala, Kurunegala ..... 936
*W.M.S.S. Dissnayake & S. M. Hirudini*

Integrating Computer Vision into Quality Assurance of Structural Concrete in Sri Lankan Construction Industry ..... 951
*V. Krishan, I. Seneviratne, B. Gheethanjali & S. Sivanraj*

Integrating Life Cycle Assessment and Emissions Trading Scheme in the Australian Construction Sector: A Preliminary Study ..... 965
*P. Yang, B.T.H. Lim & B.L. Oo*

Integrating Material Performance and Pedestrian Experience in Sri Lanka: A Review of Bio-Based Wood-Clay Composites in Landscape Architecture ..... 979
*K.P.S. Amandi, A.A. Hettiarachchi & U.P. Nawagamuwa*

Integration of Post Occupancy Evaluation into Government Office Buildings to Enhance User Satisfaction..... 993
*H.D. Subhasingha & P.A.P.V.D.S Disaratna*

International Students' Decision-Making and Learning Experience in Construction Management Coursework Master's Degree..... 1008
*B.L. Oo, R. Li & B.T.H. Lim*

Iron Slag Substitution in Soil-Based Geopolymers: A Comparative Study with Coal Fly Ash for Non-Load Bearing Applications..... 1022
*R.K.N.P. Piyasena, M.F.F. Farha, I.S. Hewage, S.M. Young & R.U. Halwatura*

Key Issues and Root Causes in Pre-Project Property Selling: A Comparative Analysis between Indonesia and Malaysia..... 1037
*S. Hansen, N. Shaqman & L. Darmiyanti*

Landscape as a Signifier of Rural Social Class Inequality in Contemporary Sri Lankan Cinema: An Analytical Study of Three Selected Films ..... 1050
*P.T. Kolamunna, U.G.D. Weerasinghe & S.M. Hirudini*

Learning from Nature: Biomimicry Inspired Daylighting Design for Reducing Artificial Lighting in Urban Buildings..... 1065
*P.A.D.D.J. Weeranayaka, R.M.H.R Bandara & M. Thayaparan*

Legislation Provisions for Circular Economy Implementation in the Construction Industry in the Sri Lankan Jurisdiction..... 1079
*M.D.T.E. Abeynayake, B.A.K.S. Perera, T.B. Abeysekara & P. Mahanamahewa*

Macroeconomic Driven Cement Price Forecasting in Sri Lanka using Econometric and Deep Learning Models..... 1094
*H.H.A.P. Hemantha, D.N.L.S. Uduwage, R.K. Shiwakoti & K.G.A.S. Waidyasekara*

Managing End-of-Life Impacts of Solar Photovoltaic Systems: A Sri Lankan Perspective..... 1109
*U. Jayanandana, G.A. Tennakoon, D. Kodituwakku & M. Chan*

Managing Foreign Labour in Malaysia's Construction Sector: Practices and Constraints..... 1123
*S. Sanmargaraja, A. Olanrewaju, M.A. Ali, H.C. Chu, S.C. Khor, V. Ponniah & G. Kanniyapan*

Mapping Infrastructure Finance Research in Africa's Built Environment: A Bibliometric Review ..... 1136
*M.A. Ogungbe, C.O. Aigbavboa, A.E. Oke, M. Ikuabe, G.T. Aregbesola & T.V. Ogunade*

Maritime Infrastructure Impacts on Marine Socio-Ecological Systems: A Literature Review ..... 1150
*S.J.L. Madhushani, K.A.T.O. Ranadewa & B.A.K.S. Perera*

Material Innovation as a Cultural Material Practice: Coconut Based Product Design for Regenerative Futures ..... 1166
*C.P. De Silva*

Microclimate-Aware Urban Planning in Tropical Climates: A Literature Review ..... 1180
*J.S. Nimesha, U. Kulatunga & H.D. Subhasingha*

Microclimate-Driven Spatial Patterns for Adaptive Urban Design: Evidence from Kotahena, Sri Lanka ..... 1195
*D. Kumar & N. Perera*

Nature-Based Solutions for Flood Mitigation: A Systematic Review of Evidence, Performance Mechanisms, and Implementation Conditions ..... 1208
*R.V.A.D. Rahubadda, B. Ingirige & U. Kulatunga*

Occupational Stressors among Sri Lankan Construction Professionals ..... 1223
*S.D.N.B. Peiris, S. Gunatilake & I.W.M.A.D. Ilangakoon*

Operationalising Community-Based Research through Photovoice ..... 1236
*W.S.D. Perera, U. Kulatunga, D. Ranasinghe, R. Mahamood, N. Kangana & C. De Silva*

Operationalizing Circular Economy in Mega Infrastructure Projects: A Data-Driven Analysis ... 1251
*P. Maneesha, S. Loganathan & D. Mouli*

Optimising Investment Decisions in Homestay Tourism: A Cost and Performance Analysis of Coastal Regions in Sri Lanka ..... 1265
*Y.K.K Sampath, J.A.C.D. Jayalath, S. Piranavan & H.S. Jayasena*

Optimizing Community Participation in Post-Disaster Crisis Response: Evidence from the "Ditwah" Cyclone, Sri Lanka ..... 1278
*J.A.C.D Jayalath & U. Kulatunga*

Performance Evaluation of Wood-Based Additives in Asphalt Binder: A Comparative Study .... 1292
*P.K.V.M. Senevirathne, J.M. D. Ashen, T. D. Perera & R. L. H. Gunawardena*

Performance Indicators for Biomimicry-Based Construction Materials and Their Operationalization through Augmented Reality: A Systematic Literature Review ..... 1303
*W.M.I.H. Wijesundara, U. Kulatunga & P.L.I. Wimalaratne*

Physicochemical Characterisation of Polyester and Nylon Synthetic Fibres as Potential Plant Growth Substrates for Green Roof Systems: A Preliminary Study ..... 1315
*I.S. Hewage, H. K. P. Ruwanthika, R.K.N.P. Piyasena, T.A. Perera, A. Satharasinghe, A. Gunawardena & R.U. Halwatura*

Pivot Strategies for Lean Construction Implementation: A Sri Lankan Perspective ..... 1328
*S. A. A. B. Senevirarhne, C. Allis & K. Guruge*

Planning Net-Zero Energy Communities: Housing Strategies for Post-Disaster Resettlement in Sri Lanka - a Narrative Review ..... 1344
*B.G.H.N Premasinghe & B.A.I Eranga*

Prioritising Construction Procurement Decision Factors for Achieving Sustainable Development ..... 1359
*K. D. S. De Abrew, H. Chandanie & P.H.G.M.A. Ranasinghe*

Prioritizing BIM-Based Safety Management Features using the Analytic Hierarchy Process ..... 1373
*T.N.D. Thanthirige, M.M.I.S. Mapa & G.G.N. Chandani*

PuzzleGlaze: A User-Driven Window System to Maximize User Comfort ..... 1387
*S.S. Shaikh & A. Garud*

Reframing the Inclusive Classroom as a Designed Learning Environment: An Integrative Literature Review ..... 1398
*A.I. Sewwandi & S. Samarawickrama*

Regional Identity and Regenerative Architecture: Reinterpreting Buddhist Philosophy in Contemporary Built Environments ..... 1414
*G.R.K.A.G. Menike & K. Perera*

Reimagining Procurement for Domestic Construction Clients ..... 1427
*P.J. Gamage & C. Hadiwattege*

Relationship Model of Mindfulness Practice and Construction Workers' Performance: An Exploratory Study in Indonesia ..... 1440
*S. Hansen*

Remote Work for Female Professionals in Sri Lankan Construction Industry: Challenges and Expectations ..... 1455
*Y.B.M.C.S. Kumarihami, K. Thiruchelvam & D.N.L.S. Uduwage*

Resilient and Culturally Responsive Plantation Housing: Socio-Spatial Adaptation in Dunsinane Estate, Sri Lanka ..... 1470
*K. Krishanth & V. Vidhushan*

Revisiting Methodological Taxonomy: Locating Design Science Research within Research Design Hierarchies ..... 1484
*W.M.I.H. Wijesundara, P.L.I Wimalaratne & U. Kulatunga*

Risk Perceptions in Circular Economy Adoption in the Australian Construction Industry ..... 1498
*I.R. Kadirappulige, G. Karunasena, N. Udawatta & A. Grumu*

Robotics Systems for Closed Loop Construction: A Bibliometric Analysis of Construction Demolition Waste Management ..... 1512
*M.K.L.I.C Fernando & P.L.I Wimalaratne*

Role of Regulations and Governance in the Circular Economy for Construction: A Comparative Analysis ..... 1527
*S.M.S.S. Attanayaka, I.E. Illeperuma & M.D.T.E. Abeynayake*

Schoolyards as Built Infrastructure: A Feasibility Framework for Closing Environmental Education Implementation Gaps ..... 1541
*E. Mendis, M. Thayaparan & D. Lellupitiya*

Significance of Joint Venture Enterprises for the Development of Construction Industry of Sri Lanka ..... 1556
*Y.M.W.H.M.R.R.L.J.B Kiridana & M.D.T.E Abenayake*

Simulation-Based Evaluation of Energy Performance in Adaptive Reuse of Historic Buildings across Different Climatic Zones of Sri Lanka ..... 1569
*A. Tharmitha, G.Y. Jayasinnghe, M.K.M Prabodani, K. Anojan & R.U. Halwatura*

Stakeholder Influence and Roles on Circular Economy Adoption in the Sri Lankan Construction Industry ..... 1583
*H.D.T Jayasinghe, D.N Abenayake & V. Aathithan*

Statutory Good Faith as a Governance Tool: Reforming Infrastructure Delivery and Curbing Corruption in Africa ..... 1597
*A. Aderibigbe, N. Umeokafor, Y. Upadhyay & T. Umar*

Strategies to Achieve Net-Zero Carbon Goals in Construction Industry ..... 1611

*R.M.D.D Rathnayake, B.A.K.S Perera & A.S Kavirathna*

Sustainability Impacts of Industry 4.0 in Construction Project Management..... 1624
*W.K.R. Prasadinee, C. Hadiwattege & N.B. Nanayakkara*

Temperature and Humidity Control in Operating Theatres: BMS vs. Thermostat Systems..... 1637
*K.S. Ramasingha, S.D.A. Soorige & K. A. D.M. Natasha*

Temporary Built Environments in Sri Lankan Film Production Design..... 1651
*S. Fernando & S. Samarawickrama*

The Effect of House Plan Types on House Plan Transition Patterns in Upper Middle-Class Residences: Case in Aniwatte, Kandy ..... 1664
*H.M.P.M.K. Wijerathne & S.M. Hirudini*

The Financial and Social Implications of Construction Site Accidents in Sri Lanka ..... 1679
*H.R. Fernando, U. Kulatunga, B. Gheethanjali & N. Gunawardhana*

The Impact of Location on Threshold Space Architectural Character: Study of Egoda Uyana, Sri Lanka ..... 1693
*S.I. Rajapakse & M. Hirudini*

The Impact of Material Expression at Entrance Thresholds on Invitation to Access: A Comparative Study of Shopping Malls in Colombo, Sri Lanka ..... 1707
*P.N.S Wijayarathne & S.M. Hirudini*

The Influence of Visibility on Personal Space Creation in Urban Public Spaces: A Case Study of the Arcade at Independence Square ..... 1721
*Y.R. Dissanayake & S.M. Hirudini*

The Mind behind the Machine: Mapping Personality-Based Traits to Entrepreneurial Decision-Making in Construction SMEs..... 1735
*K.M. Pulasinghe, G.H.S.P. De Silva, A.A.D.A.T. Vihindhuni & A.O. Lokuge*

The Need for Reforming Green Rating Systems for Hospitals in Sri Lanka ..... 1747
*H.W.A.G. Madhuwantha, P. Sridarran & M.N.U. Maddakandage*

Theft and Vandalism in Infrastructure Construction-a Review of Sustainability Impacts ..... 1761
*P.L.T.T. Thilakasiri, K.G.A.S. Waidyasekara & P.H.G.M.A. Ranasinghe*

Typological Synthesis of Cost Overrun Determinants in Road Construction using “K-Means”: A Narrative Synthesis ..... 1774
*K.N. Hettiarachchi, U. Kulatunga & D.N.L.S. Uduwage*

Understanding the Status Quo of Consultant Selection in Sri Lankan Public Construction Projects ..... 1788
*S. Uthayakumar, K. Thiruchelvam & D.N.L.S. Uduwage*

Unheard Stakeholder Voices: Evaluating the Functional Performance of the Manning Market Building ..... 1802
*U. Hettithanthri & D.K. Nalaka Krishantha*

Value Creation in the Construction Industry: A Scoping Review ..... 1816
*P.Y. Weerakoon, M.K.C.S. Wijewickrama, A. Samaraweera & J.J. Ochoa*

What Enables Climate-Responsive and Resource-Efficient Office Buildings in a Small Island Developing State? A Stakeholder-Weighted Readiness Gap Analysis..... 1829
*S.B. Nahullah, N. Fernando & M. Jowkar*

Withstanding Supply Chain Vulnerabilities in Off-Site Construction Logistics: A Narrative Review and 3D Visualisation..... 1843
*W. M. D. Y. Sandaruwan, Y. G. Sandanayake, E. M. C. Ekanayake & G. A. Tennakoon*

Workplace Design and Gen Z Retention: A Social Sustainability Perspective in Sri Lanka..... 1857
*S.N. Ranathunga, P. Dissanayake & W.N.K.B.N.A Sathsarani*

A Scientometric Analysis of Construction Value Management Research: A 25-Year Review..... 1871
*L.H.U.W. Abeydeera, W.M. Jayantha, T. Maqsood & G.G.N Chandani*

Perera, S., Jayatilake, L.V.K. and Kulatunga, U., 2026. A bibliometric analysis of dynamic organisational capabilities and hybrid project management research in the construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1-15. DOI: https://doi.org/10.31705/WCS.2026.1. Available from: https://ciobwcs.com/papers/

# A BIBLIOMETRIC ANALYSIS OF DYNAMIC ORGANISATIONAL CAPABILITIES AND HYBRID PROJECT MANAGEMENT RESEARCH IN THE CONSTRUCTION INDUSTRY

**Shehan Perera[1], Lakmini V.K. Jayatilake[2] and U. Kulatunga[3]**

## *ABSTRACT*

*The increasing volatility, uncertainty, complexity, and ambiguity (VUCA) of environments in which the construction industry operates has created interest in Hybrid Project Management (HPM) strategies that integrate predictive and Agile methods. Whilst general organisational capabilities refer to the broad operational and functional competencies of a firm, dynamic organisational capabilities represent a higher-order subset specifically the capacity to sense environmental changes, seize emerging opportunities, and transform internal configurations and are increasingly recognised as the critical enabler for successful HPM adoption. However, this distinction remains under-explored in the construction literature, and it is unclear how dynamic organisational capabilities specifically moderate HPM implementation in firms facing institutional rigidity and strategic inertia a question that future empirical inquiry must address. As the necessary first step, this intersection has not been systematically explored through bibliometric analysis to date, leaving researchers without a structured overview of publication trends, geographic concentrations, and thematic frontiers. The purpose of this bibliometric analysis is to provide that foundational mapping by uncovering publication trends, key players, and thematic structures relating to dynamic organisational capabilities and HPM within the construction sector. 79 peer-reviewed articles published in 2020–2025 were analysed using PRISMA guidelines, with parameters from Bibliometrix and VOSviewer. The results offer a framework for conceptually organising the material, reveal that developing economies, especially Sri Lanka, are significantly underrepresented geographically, and call for a more focused empirical study.*

***Keywords:*** *Bibliometric Analysis; Construction Industry; Dynamic Organisational Capabilities; Hybrid Project Management; Organisational Capabilities.*

## 1. INTRODUCTION

The construction sector is fundamental to economic advancement, marked by significant technical intricacy, extended project durations, and a variety of stakeholders (Bastos et

[1] Researcher, Faculty of Graduate Studies, University of Moratuwa, Sri Lanka, shehan@innowaveltd.com
[2] Senior Professor, Department of Commerce & Financial Management, University of Kelaniya, Sri Lanka, lakminij@kln.ac.lk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

al., 2025; Wang et al., 2025). In today's uncertain, rapidly changing world, there is strong demand for the construction sector to become more efficient, sustainable, and compliant with stringent standards and regulations (Bastos et al., 2025; Khaled & Alshalal, 2025). This is especially applicable to project-driven firms in emerging nations such as Sri Lanka, where industrial operations must contend with considerable environmental variability and institutional transformations (Samsuden et al., 2024).

In response to these challenges, hybrid project management models have been developed that combine the advantages of predictive and Agile methods, such as iterative cycles and flexibility, while maintaining the structure of predictive models (Bastos et al., 2025; Mirzaei et al., 2025). According to large-scale surveys, Hybrid models have been gaining ground, with over 50% of projects globally using them (Mirzaei et al., 2025). Hybrid models are known for mitigating some of the challenges of traditional models, offering a balance between operational flexibility and predictability, but they face institutional hurdles and strategic inertia (Bastos et al., 2025; Khaled & Alshalal, 2025). This situation requires, in addition to the methodological adoption, the development of resilient organisational capacities for strategic renewal to be successful (Weiss & Kanbach, 2022).

It is important to distinguish between two related but distinct concepts: general organisational capabilities, which encompass the broad operational and functional competencies of a firm, and dynamic organisational capabilities, which represent the higher-order capacity to sense environmental changes, seize opportunities, and transform internal configurations in response to shifting conditions (Teece, 2012; Teece et al., 1997). Dynamic organisational capabilities are built through sustained experience, deliberate investment, and accumulated project-to-project learning, and are classified into sensing, seizing, and transforming abilities that enable businesses to detect market changes, reallocate resources, and adjust business models in real time (Khaled & Alshalal, 2025; Prayag et al., 2024). Despite their recognised importance, prior studies have repeatedly called for empirical investigation of the moderating role of dynamic organisational capabilities in Hybrid Project Management adoption, particularly in developing-economy construction contexts such as Sri Lanka (Leonidou et al., 2025; Mikalef et al., 2021; Samsuden et al., 2024). Designing such empirical inquiry, however, first requires a consolidated understanding of the existing body of knowledge, and to date no bibliometric study has systematically mapped the intersection of dynamic organisational capabilities and HPM in construction. This study therefore addresses this knowledge-mapping gap by charting publication trajectories, influential contributors, geographic concentrations, and thematic frontiers, providing the structured foundation upon which subsequent empirical investigation of the moderating role of dynamic organisational capabilities can be built.

This study seeks to respond to this challenge by conducting a comprehensive bibliometric study to address the following questions:

RQ1: What are the publication trends and research growth patterns in relation to dynamic organisational capabilities and hybrid project management in construction?

RQ2: Which countries and journals have made the most influential contributions to this area of research?

RQ3: What themes are most prominent and how do they cluster, along with what evolutionary path do they take?

## 2. LITERATURE REVIEW

Volatility, uncertainty, complexity and ambiguity (VUCA) now define the modern business environment and necessitate that businesses develop higher skills to preserve their competitiveness (Weiss & Kanbach, 2022; Witschel et al., 2022). Companies in the construction industry are characterised by long cycles, instability, and high technical complexity, which are typical of project-oriented businesses (Bastos et al., 2025). In response, organisations have adopted Agile methodologies, such as Scrum, that prioritise incremental development, communication, and quick iteration based on user feedback (Bastos et al., 2025; Wang et al., 2025). The Hybrid model is a dual communication model to reconcile these conflicting management philosophies. This allows macro-level governance to ensure contractual compliance and operational agility in execution (Bastos et al., 2025). From the literature, two types of HPM application are distinguished: "Hybrid-by-Phases", where different methodologies are used in different phases of projects and "Hybrid-by-Methods", where specific Agile and Plan-driven approaches are integrated in the same phase (Mirzaei et al., 2025).

The Dynamic Capabilities View (DCV), an evolution of the Resource-Based View (RBV), identifies the ability of a company to combine, build and reconfigure its internal and external capabilities as the key source of Sustainable Competitive Advantage (SCA) (Leonidou et al., 2025; Mikalef et al., 2021). These skills can usually be classified into three basic skill sets: sensing (spotting opportunities and threats), seizing (mobilising resources to seize opportunities), and transformation (a process of continuous revitalisation of the organisation) (Chasapi et al., 2024; García-Valenzuela et al., 2023). Institutional rigidity, also known as strategic inertia, is one of the most significant barriers to adopting new methods and approaches (Khaled & Alshalal, 2025). Often this is the result of centralised decision-making, structural stagnation, and risk-averse cultures (Khaled & Alshalal, 2025). In the construction sector, inertia can manifest as a "design-implementation gap," in which firms may identify new business models as needed but struggle to implement them effectively (Coffay et al., 2024). Dynamic organisational capabilities are the main means to combat this inertia, foster adaptive awareness, promote flexible leadership, and minimise bureaucratic inefficiencies (Khaled & Alshalal, 2025).

Ozanne et al. (2022) and Samsuden et al. (2024) find that organisational capabilities moderate the relationship between HPM implementation and project success outcomes. Strategic planning's impact on performance is amplified by high levels of financial and human resources and mitigated by high environmental volatility and competition (Leonidou et al., 2025). Effective adoption of Hybrid models relies on the match between project goal (success-oriented versus management-oriented) and the team type (stable versus transient) and depends on the overall capabilities' configuration of the organisation (Mirzaei et al., 2025).

Collectively, the literature establishes that dynamic organisational capabilities are a critical yet insufficiently explored mediating force between environmental volatility and HPM effectiveness in construction. Three specific gaps motivate this study. First, no prior bibliometric analysis has systematically mapped the intersection of dynamic organisational capabilities and HPM within construction, leaving the intellectual boundaries of this emerging domain undefined. Second, geographic representation is skewed overwhelmingly toward European and East Asian contexts, rendering developing-economy settings particularly South Asia near-invisible in the evidence base.

Third, the thematic frontiers of the field, including digital transformation and organisational resilience, have not been formally charted, preventing researchers from identifying where emerging inquiry should concentrate. This study addresses these three gaps through a structured bibliometric analysis designed to provide the foundational mapping that subsequent empirical investigation requires.

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN

In this study, researchers applied bibliometric analysis to the literature on dynamic organisational capabilities and hybrid project management in the construction industry. Bibliometric analysis was selected for three reasons: (1) the intersection of dynamic organisational capabilities and HPM in construction is an emerging research domain with no prior systematic mapping, making quantitative structural analysis the appropriate first-step method; (2) bibliometric methods objectively reveal patterns in scientific output publication trends, citation structures, and thematic clusters at a scale that individual reading cannot achieve; and (3) the Scopus corpus of 184 initial records provides a sufficient sample size for statistically meaningful mapping (Donthu et al., 2021). The author followed the PRISMA guidelines to ensure that the methods of article selection were transparent and could be duplicated (Liberati et al., 2009).

## 3.2 CHOICE OF DATABASE AND SEARCH STRATEGY

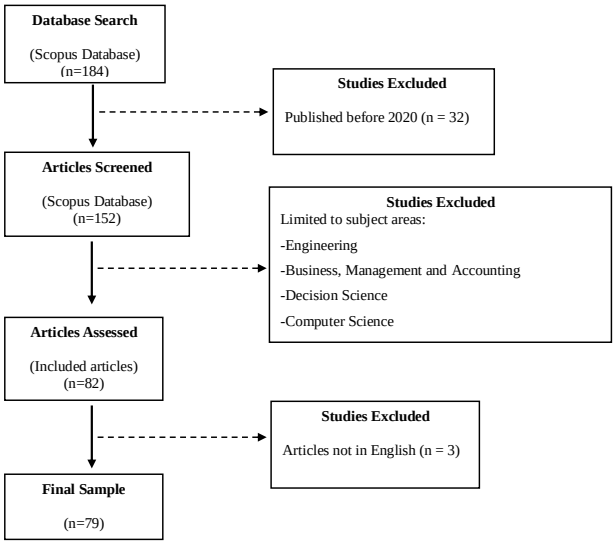



*Figure 1: Article selection strategy*

The comprehensiveness of the peer-reviewed literature in construction management and organisational studies (Ametepey et al., 2024) is behind the choice of the Scopus database. Although more articles in general are available in Web of Science and Google Scholar, Scopus offers better-structured metadata and an export function for Bibliometrix, so it was chosen for this analysis. Sri Lanka was not used as a search term; the analysis was conducted on the global construction management literature. The suitability of these global findings to the Sri Lankan context is validated on two grounds: first, the geographic gap analysis confirms that developing economies including Sri

Lanka are substantially underrepresented, meaning that globally derived frameworks have not yet been contextualised for the Sri Lankan environment; and second, the Sri Lankan construction sector is a VUCA-exposed, emerging-economy industry with limited hybrid project management maturity, and its institutional characteristics therefore closely parallel those of the developing-economy contexts identified as research frontiers in this literature. The search string used was: (Organisational Capabilities OR Dynamic Capabilities) AND (Hybrid Project Management OR Agile Project Management) AND (Construction OR Construction Industry). Only publications from 2020 to 2025 are analysed. This time period was chosen to reflect the current surge in digital and agile transformation in construction, accelerated by COVID-19, and the growing use of the Dynamic Capabilities View in project management literature. Pre-2020 foundational work is systematically captured through backward citation analysis of the 79 retained articles. Seminal contributions such as Teece et al. (1997) on dynamic capabilities and Liberati et al. (2009) on PRISMA reporting appear as high-frequency anchor citations within the retained corpus, confirming that the intellectual influence of foundational pre-2020 scholarship is preserved within the analytical boundary rather than excluded by it. No major pre-2020 publication is therefore omitted from the analysis; rather, its influence is measured through the citation patterns of the 79 articles that post-date the consolidation period.

## 3.3 CRITERIA OF PRISMA AND INCLUSION PROTOCOLS

In compliance with the PRISMA framework (Liberati et al., 2009), the selection criteria were developed in four steps as illustrated in Figure 1.

Identification: The first round of searching yielded 184 articles

Screening: Inclusion criteria: Articles were published in peer-reviewed journals, written in English, from 2020 to 2025. 152 articles were retained after screening, given recent developments in a dynamic, rapidly changing environment.

Exclusion criteria: Articles were published as conference proceedings, book chapters, editorials, or if the articles were published in languages other than English

Eligibility: The author assessed the article's full text to determine its relevance to dynamic organisational capabilities, hybrid project management, and construction contexts. Eligibility verification resulted in 79 articles being retained.

Inclusion: Within the scope of the bibliometric analysis, the final sample consisted of 79 articles.

As illustrated in Figure 1, the initial search yielded 184 articles, which were reduced to 152 after screening, 82 after eligibility assessment, and finally 79 for analysis.

## 3.4 ANALYTICAL TOOLS AND TECHNIQUES

Bibliometric assessment was performed using a dual software approach: first, the Bibliometrix package (version 4.0) in RStudio, and second, VOSviewer (version 1.6.18). The Scopus dataset was exported to CSV format to ensure the search snapshot is fixed and reproducible. The analytical framework was organised into two main levels: one quantitative and one qualitative, to achieve depth of understanding. First, a performance analysis was carried out using Bibliometrix's biblioAnalysis function to assess the productivity and impact of the field, including analysis of annual scientific production

trends, identification of leading journals and scientific sources by country, and examination of journals and outlets using Bradford's Law implemented via the Bradford function to differentiate between core journals and peripheral outlets. Second, the science-mapping phase used VOSviewer to visualise the thematic and relational structure of the research area. For keyword co-occurrence network analysis, a minimum co-occurrence threshold of two was applied to author keywords, producing the eligible term set for network mapping; the association strength normalisation method was used with a resolution value of 1.0 and a minimum cluster size of two for community detection. Thematic mapping of these findings was generated in Bibliometrix using the thematicMap function with default centrality and density parameters, with the point where centrality and density scores intersected creating four strategic quadrants that positioned the research areas. This classification approach enabled mapping topics into motor themes (well-developed and central), basic themes (well-founded but less developed), niche themes (specialised), and emerging and declining themes, providing an overview of the evolutionary development of dynamic organisational capabilities and HPM research in the construction field.

# 4. KEY FINDINGS

## 4.1 ANNUAL SCIENTIFIC PRODUCTION

As illustrated in Figure 2, the construction industry shows a V-shaped growth trajectory in scientific production from 2021 to 2025 in the research on dynamic organisational capabilities and Hybrid Project Management (HPM). The number of publications increased from 15 in 2021 to 17 in 2022, then declined to 14 in 2023, recovered to fifteen in 2024, and is expected to increase to 18 in 2025, representing a 28% recovery from the 2023 low point and 20% overall growth from 2021.

Such a pattern of growth illustrates that the field has entered an expansion phase after consolidation, demonstrating the recognition that the success of a project relies on the combination of dynamic organisational capabilities and the HPM, rather than the HPM methodology alone. The trajectory of growth and increase in publications post-2023 demonstrates the relevance of conducting research on how local construction firms in Sri Lanka develop and utilise sensing, seizing, and transforming capabilities to execute hybrid methodologies, particularly in the pronounced VUCA (volatile, uncertain, complex, and ambiguous) environment. With the anticipated peak in publication volume by 2025, this research extends recognition of the field's expansion phase, allowing the construction project management literature to refine its theory and applications as contextual studies from developing countries emerge.

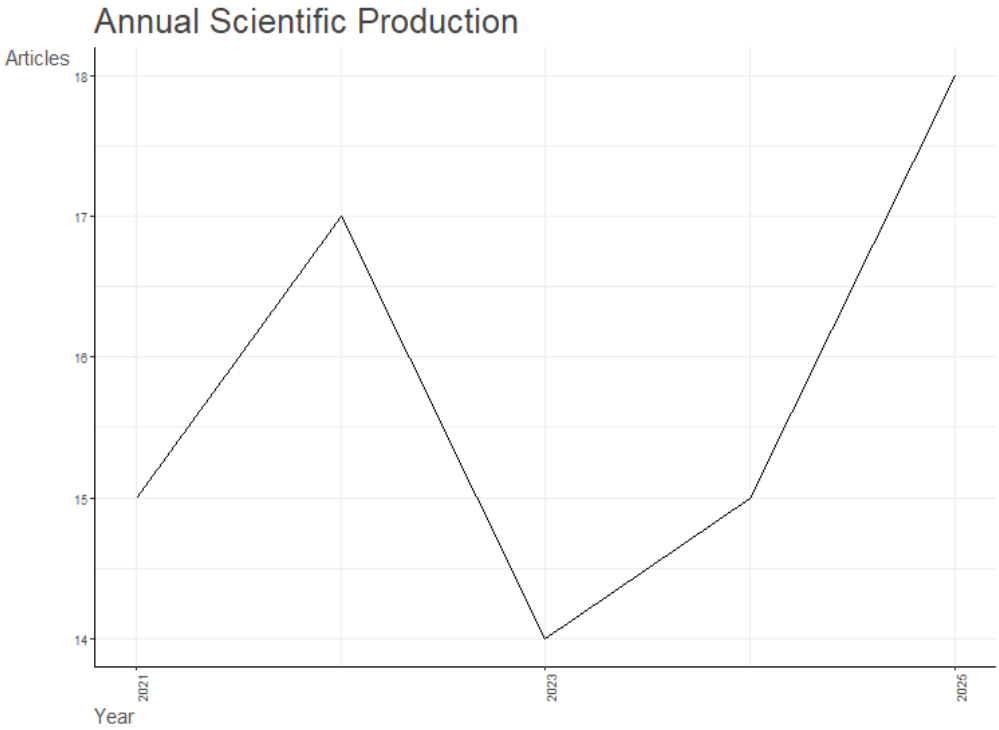



*Figure 2: Annual scientific production*

## 4.2 COUNTRY ANALYSIS

The chart (Figure 3) provides a comparative analysis of total citation counts across the ten most cited countries, with countries listed on the vertical axis and the number of citations on the horizontal axis. The horizontal lollipop format, with the citation count marked at the end of each line, facilitates direct country-to-country comparison and clarifies differences in citation frequency.

Germany is the glaring leader with 369 citations, far exceeding all other countries. This dominance indicates that German research is highly productive and globally acknowledged. New Zealand comes second with 217 citations, a remarkable figure considering its small population. This shows that the nation has made significant contributions in particular domains. France and Norway follow with 198 and 181 citations, respectively. These figures reveal that they remain relevant in global research. Italy, with 149 citations, maintains an influential presence, while China, with 143 citations, demonstrates its increasing significance in global academia, however falling short of expectations considering its extensive research community.

India records the lowest count among the ten, with 54 citations. Notably, Italy belongs to the European geographic cluster and is not geographically proximate to the South/South-East Asian cluster comprising India, Malaysia, and Sri Lanka. Overall, research in this field is concentrated primarily in European and Asia-Pacific institutions; Sri Lanka's geographic invisibility and the limited representation of similar South Asian economies, such as India, point to the geographical void that motivates this study.

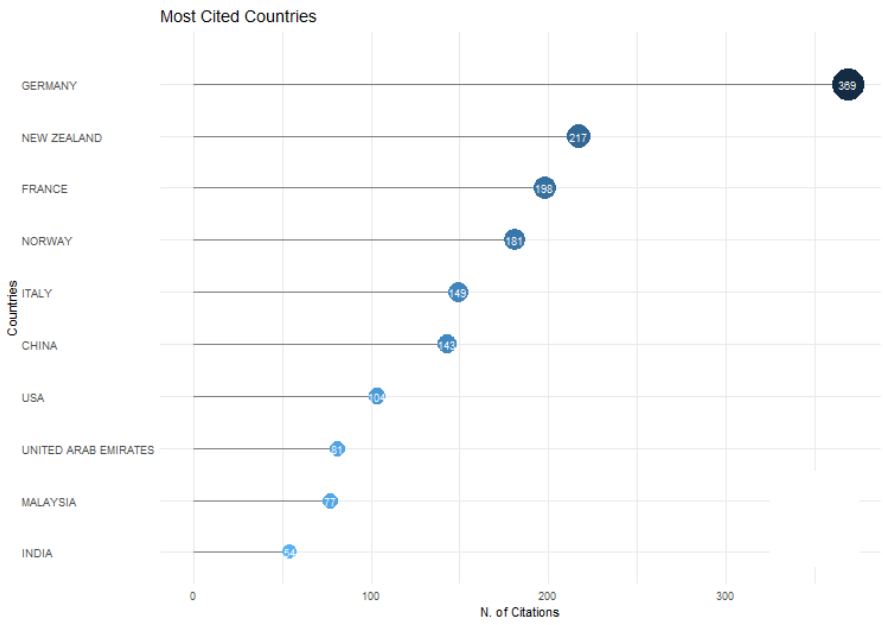



*Figure 3: Most cited countries*

## 4.3 SOURCE ANALYSIS

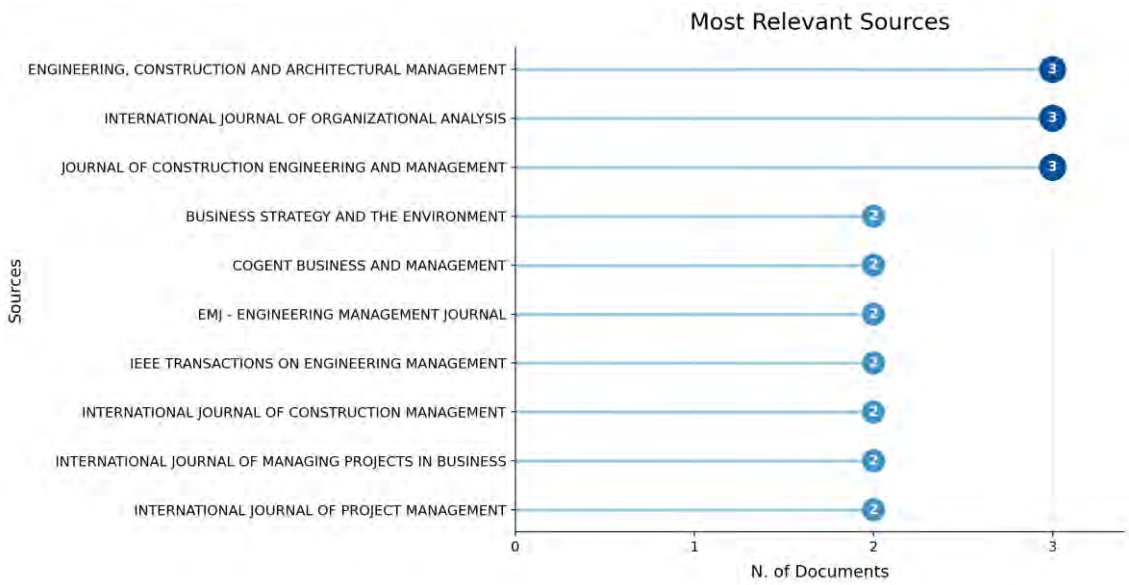



*Figure 4: Most relevant sources*

Figure 4 shows three core journals with three articles each: “Engineering, Construction and Architectural Management,” “International Journal of Organisational Analysis," and "Journal of Construction Engineering and Management”. This spread of journals spans construction engineering, project management, organisational studies, and business strategy, confirming the field’s cross-boundary nature.

## 4.4 BRADFORD'S LAW DISTRIBUTION

In reference to Figure 5, Bradford's Law holds: scholarly production is concentrated in core journals and scattered across many peripheral outlets. The core sources (Zone 1)

publish at most 3 articles, while Zone 2 journals publish 2 articles, and Zone 3 journals publish 1 article each.

This distribution shows that not all important research exists in high-quality journals, and that it is dispersed across journals that make only a small contribution to the knowledge base. For newcomers to this research area, the three core journals are a must, and the more than 20 peripheral journals are essential for understanding the niche and emerging uses of the subject.

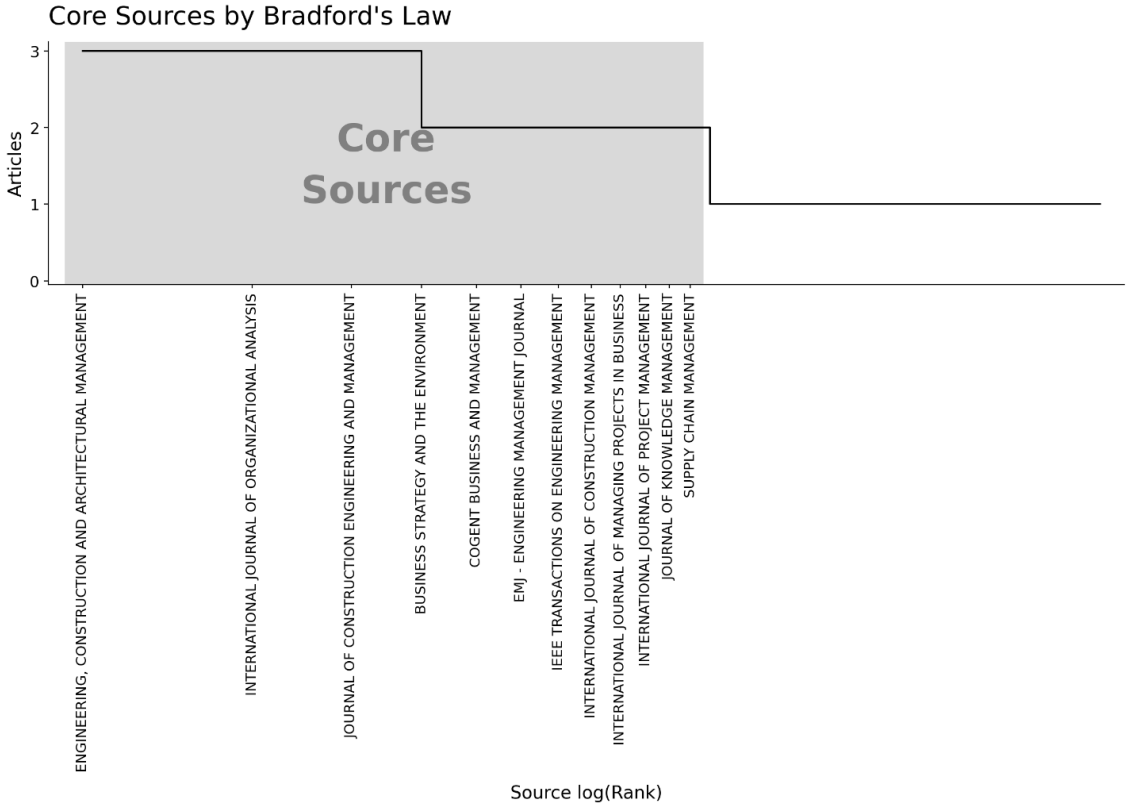



*Figure 5: Core sources by Bradford's Law*

## 4.5 KEYWORDS ANALYSIS

Figure 6 shows the number of times each keyword appears in the sample. By analysing co-occurring keywords, it is possible to understand the structure of research on Hybrid Project Management (HPM) and dynamic organisational capabilities, revealing not only the frequency of occurrence of certain keywords but also their relationships with one another. Keywords such as HPM, dynamic organisational capabilities, and project performance, when used as primary keywords, are considered hubs. The majority of research studies examine the extent to which the organisational sensing, seizing, and transforming capabilities are used to support hybrid management and the extent to which these capabilities improve project management outcomes.

Figure 6 shows three thematic clusters, marked on the network. Cluster 1 (Project Management and Decision Processes) is centered on the dominant project management node and links decision making, risk management, program (project) management, environmental management, strategic management, and construction projects, reflecting the operational and process-level core of the field. Cluster 2 (Knowledge and Capability

Management) connects knowledge management, dynamic capabilities, industrial management, manufacturing firms, enterprise resource management, and structural equation modelling, representing the stream through which organisational capabilities are theorised and empirically measured. Cluster 3 (Construction Industry and Dynamic Capabilities) groups construction industry, organizational flexibility, and dynamic capabilities, situating capability research within the industrial setting most relevant to this study. This three-cluster network shows the interconnection of core and peripheral themes, reflects a more nuanced understanding than mere frequency analysis, and reveals the structure of the research field.

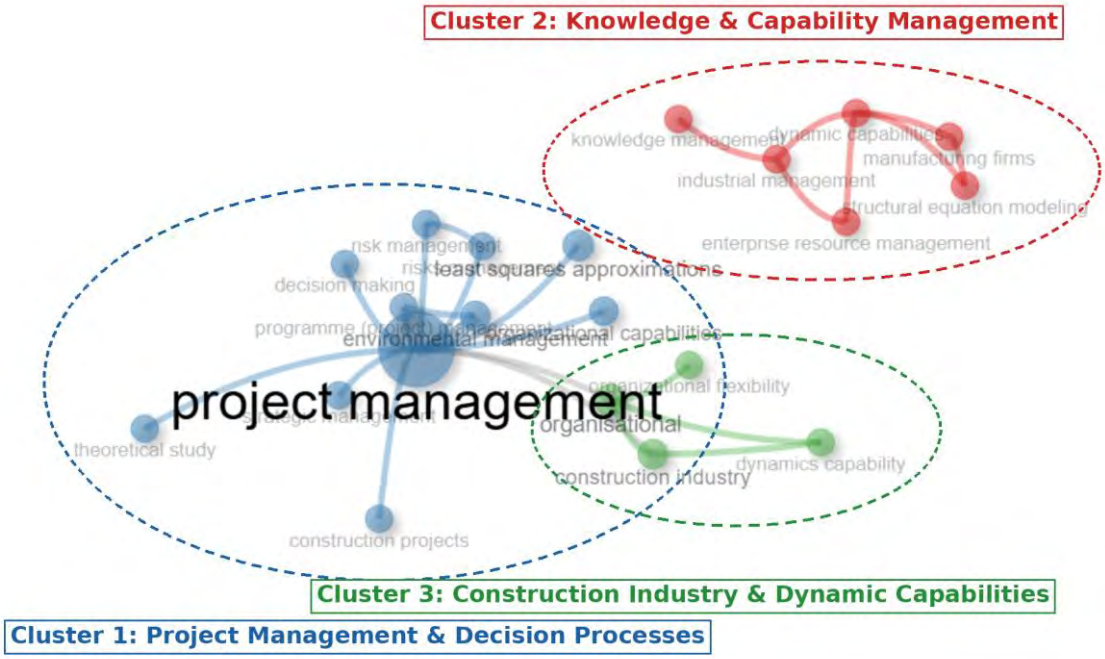



*Figure 6: Most relevant words*

The field's key discipline is the overarching concept of "project management." The second level is a second-tier cluster comprising "construction industry", "dynamic capabilities", and "organisational capabilities", which represents the two core theoretical paradigms and the industrial setting. "Decision making" and "risk management" are smaller and suggest that in addition to the more strategic capability discourse, there are also process-level concerns. The lack of geographic marks such as "Sri Lanka", "developing economy", or "emerging market" confirms the geographic gap that motivates this study.

## 4.6 WORD CLOUD

As illustrated in Figure 7, the word cloud provides a frequency-weighted visualisation of all keywords across the 79 retained articles. The dominant terms project management, dynamic capabilities, organisational capabilities, and construction confirm the conceptual core of the field and align with the principal themes identified in the keyword co-occurrence analysis. The prominence of sustainability, digital transformation, and resilience signals that the research frontier is shifting toward technology-enabled and environmentally conscious applications of dynamic capabilities in construction contexts. Notably, the relative absence of geographically specific terms such as Sri Lanka, South

Asia, or developing economy reinforces the geographic gap identified in the country analysis, further underscoring the need for contextually grounded empirical studies in underrepresented.

*Figure 7: Word cloud*

## 4.7 THEMATIC ANALYSIS

Figure 8 illustrates the relationship between centrality and density of the research themes and forms four strategic quadrants. Each quadrangle of the thematic map represents a set of keywords based on their development (density) and their relevance to the broader area (centrality).

Motor themes are well developed and central, such as Building construction, Risk analysis, Construction projects, Hybrid methodologies, etc., indicating that the motor sector is focused on Risk Management, Sustainability, and Innovation. The Basic Themes, such as project management, risk assessment, construction success, and waste management, are central but less developed, and thus can be seen as foundational. Niche themes such as completion delays, sustainable water, tunnel construction, and hydropower projects are developed to a high level on the inside but are less closely linked to other themes, indicating specialised areas of focus. Themes with low density and centrality are emerging or declining, including project scheduling, multimodal resource-constrained projects, and infrastructure projects.

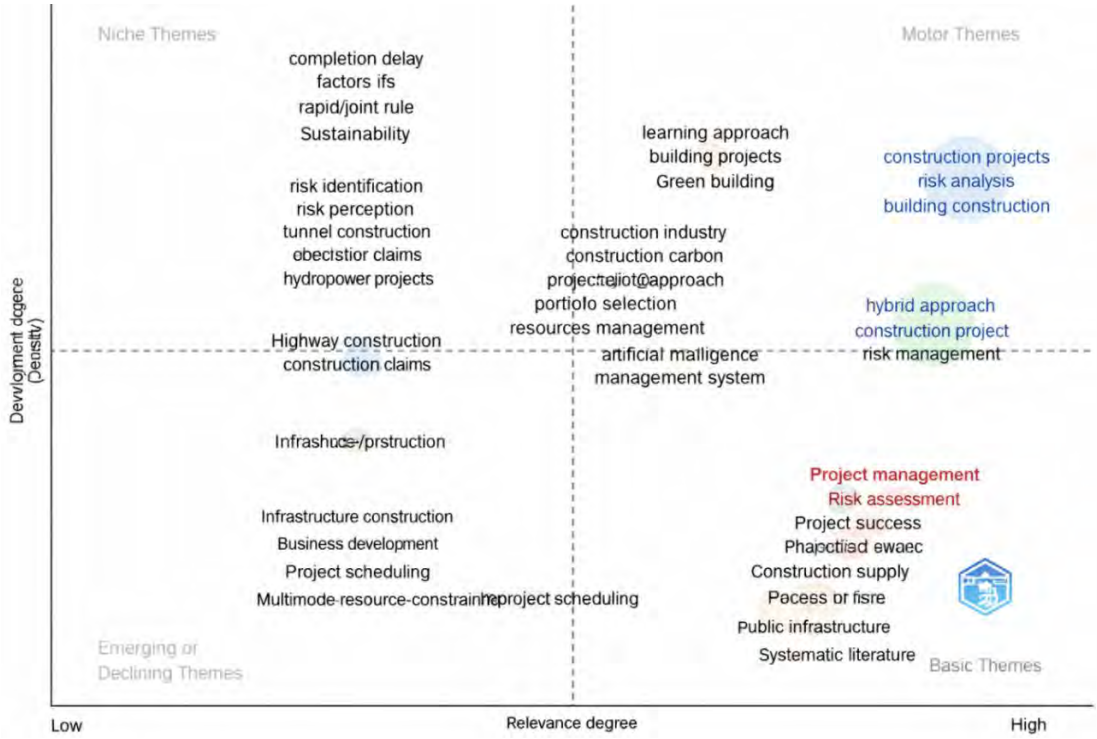



*Figure 8: Thematic analysis*

The map shows that the research field is increasingly focusing on risk management, sustainability, construction success, and technological innovation, with technical and specialised topics on the margins.

# 5. DISCUSSION

## 5.1 INTELLECTUAL STRUCTURE OF THE FIELD

The bibliometric mapping reveals the study of dynamic organisational capabilities and hybrid project management in construction as both emerging and maturing. The above-mentioned sustained academic interest aligns with the Innovation Diffusion Theory, as consolidation typically precedes renewed growth (Donthu et al., 2021). With regard to the geography of publications, the data reveals useful strategic positioning. The bibliometric mapping reveals nationally distinct research concentrations, with China as the largest contributor in terms of volume (30+ articles by 2025) and Germany as the most cited (369 citations).

## 5.2 CORE COMPETENCIES

Regarding knowledge dispersion, Bradford's Law identifies the three main journals that serve as disciplinary anchors in construction management and organisational management studies. The cross-disciplinarity of the engineering management, business management, and project management journals conveys the intricate nature of hybrid method research methodologies that integrate technical, organisational, and strategic dimensions. The pattern suggests that incoming scholars to the field should consider a wider range of journals beyond the core journals that are primary to the discipline.

Confirmation of Lotka's Law, the sharp decline in output among highly prolific authors, indicates the field has moved beyond infancy. The distribution of lead contributors (23, 19, and 15 papers respectively) alongside numerous occasional contributors reflects a maturing knowledge base with a productive core and an active periphery of emerging voices.

## 5.3 THEMATIC SHIFTS AND RESEARCH FRONTIERS

Thematic analysis reveals dynamic organisational capabilities, enterprise resource management, and industrial management as main themes for enriching the theoretical development in construction research, and project management as the specialised core cluster, in which the connections across operational, strategic, and organisational levels clearly make Hybrid Project Management (HPM) a boundary-spanning construct. Considering recent themes in digital transformation, organisational resilience, and the role of big data analytics, the focus of construction research appears to be shifting toward technology-enabled capabilities, reflecting Industry 4.0 (Wang et al., 2025), construction digitalisation, and the post-pandemic environment. The three-cluster network schema positions organisational capabilities as important integrators between the operational core and the specialised, reaffirming the Dynamic Capabilities View propositions: sensing, seizing, and transforming capabilities (Khaled & Alshalal, 2025; Mikalef et al., 2020) are streamlined and empowered. This research uniquely theorises the DOC-HPM nexus, substantiating DCV as the most relevant theory while addressing gaps in integrating environmental sustainability. For practitioners, the core capabilities and emergent themes represent a strategic differentiator and investment priority. The geographic gap analysis confirms that developing-economy construction sectors, particularly in Sri Lanka, require context-specific capability configurations, a finding that should guide construction sector policymakers in allocating R&D investment to underrepresented geographic frontiers.

## 5.4 PRACTICAL IMPLICATIONS FOR INDUSTRY PRACTITIONERS

### 5.4.1 For Construction Firms and Project Managers

The confirmation of dynamic organisational capabilities as a motor theme provides a rationale for firm-level investments in the three critical, foundational, and non-negotiable capabilities for HPM success. Firms need to: Undertake surveys to determine their levels of capability to sense (detect market shifts), seize (mobilise resources), and transform (reconfigure processes) before adopting hybrid practices. Establish organisational learning systems that reinforce project management competencies and the necessary adaptive skills (e.g., knowing when to toggle between predictive and agile methodologies within the same project).

### 5.4.2 For Strategic Decision-Makers

The prioritisation of organisational resilience and digital transformation as emergent themes illustrates their relevance to future streams of competitive advantage. This means that organisational leaders need to focus on building hybrid resilience through cross-functional, integrated units with decentralised decision-making and psychological safety to respond to emerging contradictions in the VUCA (volatility, uncertainty, complexity, and ambiguity) environment.

## 6. CONCLUSIONS

This study provides the first systematic mapping of the intellectual structure of dynamic organisational capabilities and hybrid project management (HPM) in the construction industry. The findings confirm that HPM effectiveness in construction is not merely a technical or methodological choice; it is fundamentally underpinned by dynamic organisational capabilities sensing, seizing, and transforming evidenced by a V-shaped publication trajectory peaking at 18 articles in 2025, with scholarly production anchored in specialised construction and management journals. The results of this analysis indicate the geographic concentration of knowledge today in the form of the interaction between Germany (as the highest number of citations) and China (the highest number of publications), while also revealing the significant underrepresentation of less advanced economies, especially from a South Asian perspective, with regard to the use of HPM in construction. The findings of this study plot a data-informed course from classical motor themes, such as risk analysis, towards emerging topics such as digital transformation and organisational resilience. Moving forward, this study identifies three high-priority directions for future research:

1. **Empirical studies** specifically focused on dynamic organisational capability configurations in the construction firms of **developing economies**, such as Sri Lanka, to address current geographic gaps.
2. **Longitudinal investigations** to track how organisational capability endowments evolve in tandem with increasing HPM maturity.
3. **Mixed-methods studies** that contextualise these bibliometric themes within national institutional frameworks to provide actionable guidance for policymakers.

Given the increasingly VUCA world, advancing an evidence-based understanding of how dynamic organisational capabilities shape HPM adoption is no longer a theoretical pursuit it is a practical necessity for sustaining project performance in the construction industry

## 7. REFERENCES

Ametepey, S. O., Aigbavboa, C., Addy, H., & Thwala, W. D. (2024). A bibliometric review of the trends of construction digitalization research in the past ten years. *Buildings*, *14*(9), 2729. https://doi.org/10.3390/buildings14092729

Bastos, R. A., Pierott, R. M. R., Navarro, L. L. L., Tam, V. W. Y., Najjar, M. K., & Haddad, A. N. (2025). Comparative analysis of communication in project management approaches: Waterfall, agile, and hybrid. *International Journal of Construction Management*, 25(4), 312–327. https://doi.org/10.1080/15623599.2025.2589827

Chasapi, P., Pateli, A., Mylonas, N., & Kourouthanassis, P. (2024). The impact of organisational resources on organisational agility in the hospitality industry: A dynamic capabilities approach. International Journal of Tourism Research, 26(5), e2779. https://doi.org/10.1002/jtr.2779

Coffay, M., Tveterås, R., Bocken, N., & Bogers, M. L. A. M. (2024). Sustainable business model innovation, dynamic capabilities, and organisational design: Insights from Norwegian aquaculture. *Business Strategy and the Environment*, 33(6), 5386–5404. https://doi.org/10.1002/bse.3762

Donthu, N., Kumar, S., Mukherjee, U., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

García-Valenzuela, V. M., Jacobo-Hernández, C. A., & Flores-López, J. G. (2023). Dynamic capabilities and their effect on organisational resilience in small and medium-sized commercial enterprises. *Management & Marketing*, 18(4), 496–514. https://doi.org/10.2478/mmcks-2023-0027

Khaled, O. A., & Alshalal, M. H. (2025). Mitigating strategic inertia through dynamic organisational capabilities: An analytical study of the Traffic Directorate in Nineveh. *International Journal of Operations and Quantitative Management*, 31(1), 246–264. https://doi.org/10.46970/2025.31.1.12

Leonidou, L. C., Palihawadana, D., Aykol, B., Nilssen, F., & Christodoulides, P. (2025). Dynamic capability drivers and performance outcomes of strategic import planning: The moderating role of organisational resources and market factors. *Management International Review*, 65(4), 637–672. https://doi.org/10.1007/s11575-025-00582-8

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLOS Medicine*, 6(7), e1000100. https://doi.org/10.1371/journal.pmed.1000100

Mikalef, P., van de Wetering, R., & Krogstie, J. (2021). Building dynamic capabilities by leveraging big data analytics: The role of organisational inertia. *Information & Management*, 58(6), 103412. https://doi.org/10.1016/j.im.2020.103412

Mirzaei, M., Mabin, V. J., & Zwikael, O. (2025). Customising hybrid project management methodologies. *Production Planning & Control*, 36(9), 1188–1205. https://doi.org/10.1080/09537287.2024.2349231

Ozanne, L. K., Chowdhury, M., Prayag, G., & Mollenkopf, D. A. (2022). SMEs navigating COVID-19: The influence of social capital and dynamic capabilities on organisational resilience. *Industrial Marketing Management*, 104, 116–135. https://doi.org/10.1016/j.indmarman.2022.04.009

Prayag, G., Jiang, Y., Chowdhury, M., Hossain, M. I., & Akter, N. (2024). Building dynamic capabilities and organisational resilience in tourism firms during COVID-19: A staged approach. *Journal of Travel Research*, 63(3), 713–740. https://doi.org/10.1177/00472875231164976

Samsuden, N. S., Kohar, U. H. A., Khatib, S. F. A., & Abbas, A. F. (2024). Digital capabilities and business performance: A systematic literature review. *Sustainability*, 16(24), 11108. https://doi.org/10.3390/su162411108

Teece, D. J. (2012). Dynamic capabilities: Routines versus entrepreneurial action. *Journal of Management Studies*, 49(8), 1395–1401. https://doi.org/10.1111/j.1467-6486.2012.01080.x

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, 18(7), 509–533. https://josephmahoney.web.illinois.edu/BA545_Fall%202022/Teece,%20Pisano%20and%20Shuen%20(1997).pdf

Wang, D., Huang, R., Li, K., & Shrestha, A. (2025). Organisational structure and dynamic capabilities on business model innovation in project-driven enterprises: Evidence from the construction industry. *Engineering, Construction and Architectural Management*, 32(1), 578–600. https://doi.org/10.1108/ECAM-01-2023-0090

Weiss, L., & Kanbach, D. K. (2022). Toward an integrated framework of corporate venturing for organisational ambidexterity as a dynamic capability. *Management Review Quarterly*, 72(4), 1129–1170. https://doi.org/10.1007/s11301-021-00223-y

Witschel, D., Baumann, D., & Voigt, K.-I. (2022). How manufacturing firms navigate through stormy waters of digitalisation: The role of dynamic capabilities, organisational factors and environmental turbulence for business model innovation. *Journal of Management & Organisation*, 28(3), 681–714. https://doi.org/10.1017/jmo.2022.44

De Silva, S.B.N.S.W., Sridarran, P. and Maddakandage, M.N.U., 2026. A conceptual biomimicry-inspired model for enhancing energy efficiency in high-rise buildings in Sri Lanka.. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 16-29. DOI: https://doi.org/10.31705/WCS.2026.2. Available from: https://ciobwcs.com/papers/

# A CONCEPTUAL BIOMIMICRY-INSPIRED MODEL FOR ENHANCING ENERGY EFFICIENCY IN HIGH-RISE BUILDINGS IN SRI LANKA.

**S.B.N.S.W. De Silva[1], P. Sridarran[2] and M.N.U. Maddakandage[3]**

## *ABSTRACT*

*Rapid urbanization in Sri Lanka has led to increased energy consumption in high-rise buildings, particularly due to cooling demands in tropical climates. Conventional buildings with extensive glazed facades contribute to excessive solar heat gain and high reliance on mechanical systems. This study evaluates the potential of biomimicry-inspired strategies to improve energy efficiency in high-rise buildings. Two models, a conventional building and a biomimicry-inspired model, were developed and simulated using energy analysis tools in Revit under Colombo climatic conditions. The biomimicry-inspired model incorporates envelope strategies such as external shading, textured facade surfaces, and reflective roof coatings. The results indicate a reduction of approximately 25% in cooling energy consumption in the biomimicry-inspired model, along with decreases in lighting and equipment energy use. The study concludes that biomimicry-inspired envelope strategies can effectively enhance energy efficiency in tropical high-rise buildings.*

***Keywords:*** *Biomimicry; Energy Efficiency; High-Rise Buildings; Tropical Climate.*

## 1. INTRODUCTION

Rapid urbanization and population growth have significantly transformed the urban landscape of Sri Lanka, particularly in Colombo, where limited land availability has accelerated the development of high-rise buildings. While vertical expansion offers an effective solution to urban land scarcity, it also contributes to increasing energy demand within the built environment (Jayasinghe et al., 2021). Globally, buildings account for nearly 40% of total energy consumption and a substantial proportion of greenhouse gas emissions (Christopher et al., 2023). In Sri Lanka, the building sector represents almost 60% of national electricity consumption, with a large share attributed to mechanical cooling systems used to maintain indoor thermal comfort in the tropical climate (Weerasinghe et al., 2022).

[1] Research Student, Department of Building Economics, University of Moratuwa, Sri Lanka, nirodyasandarenu@gmail.com

[2] Head of Department, Senior Lecturer, Facilities Management Department, University of Moratuwa, Sri Lanka, psridarran@uom.lk

[3] Temporary Lecturer, Facilities Management Department, University of Moratuwa, Sri Lanka, nadeeraum@uom.lk

In addition, the increasing use of glazed facades in contemporary commercial buildings intensifies solar heat gain, thereby increasing cooling loads and operational energy consumption (Qahtan, 2024). Consequently, conventional building design approaches have become increasingly inadequate in addressing the combined challenges of energy efficiency, environmental sustainability, and occupant thermal comfort.

In response to these challenges, biomimicry has emerged as a promising approach in sustainable architectural design (Vasanthanathan et al., 2020). Biomimicry involves studying and emulating strategies found in natural systems to solve complex human design problems (Dash, 2018). Many organisms have evolved efficient mechanisms to regulate temperature, airflow, and energy exchange within their environments. For instance, termite mounds maintain stable internal temperatures through natural ventilation systems, while plants such as cactus reduce heat gain through adaptive surface structures (Adarsh & Thomas, 2024). Translating such biological strategies into architectural applications presents an opportunity to develop innovative passive cooling solutions that reduce dependence on mechanical systems. Thus, this study investigates:

*How can biomimicry-inspired cooling strategies improve energy efficiency and indoor thermal comfort in high-rise buildings under tropical climatic conditions in Sri Lanka?*

Therefore, the aim of this study is to develop a biomimicry-inspired model for improving energy efficiency in high-rise buildings under tropical climatic conditions in Sri Lanka. Although biomimicry-inspired design strategies have been increasingly explored internationally, limited research has investigated their application for improving energy efficiency in high-rise buildings within the Sri Lankan tropical context. There are limited simulation-based studies evaluating biomimicry-inspired envelope strategies for commercial high-rise buildings in Sri Lanka. To address this gap, the study first reviews biomimicry principles applicable to tropical climates and suitable for architectural integration. Based on this, a conceptual biomimicry-inspired design model is developed by applying selected biomimicry strategies to an existing conventional building. Furthermore, both the conventional and biomimicry-inspired building models are simulated using energy simulation software to evaluate and compare their energy performance.

## 2. LITERATURE REVIEW

This section reviews the existing literature related to energy consumption in high-rise buildings, the role of building envelopes on energy efficiency and the use of biomimicry in sustainable building design. It also reviews the cooling strategies inspired by nature and their possible role in achieving better energy efficiency in tropical high-rise buildings.

### 2.1 ENERGY CONSUMPTION IN HIGH-RISE BUILDINGS

The building sector is one of the largest consumers of energy worldwide and plays a significant role in global greenhouse gas emissions. Studies indicate that buildings account for nearly 40% of global energy consumption and approximately one-third of total carbon emissions (Harputlugil & De Wilde, 2021; Omer, 2020). In rapidly urbanizing cities, the development of high-rise buildings has increased significantly due to limited land availability and growing population demands (Mostafavi et al., 2021). However, these buildings typically require higher energy consumption compared to low-

rise structures due to their dependence on mechanical systems for cooling, ventilation, lighting, and vertical transportation (Ge et al., 2023).

Among building systems, Heating, Ventilation, and Air Conditioning (HVAC) systems represent the largest share of energy consumption, accounting for more than 50% of total building energy use in many cases (Anarene, 2024). In tropical countries such as Sri Lanka, the demand for cooling energy is particularly high due to elevated temperatures and humidity levels. As urban areas such as Colombo continue to experience rapid vertical development, energy consumption in the building sector has increased considerably. Buildings in Sri Lanka consume a substantial portion of national electricity, with commercial high-rise buildings identified as major contributors due to their intensive cooling requirements. Total energy consumption in commercial buildings can generally be categorized in Figure 1.

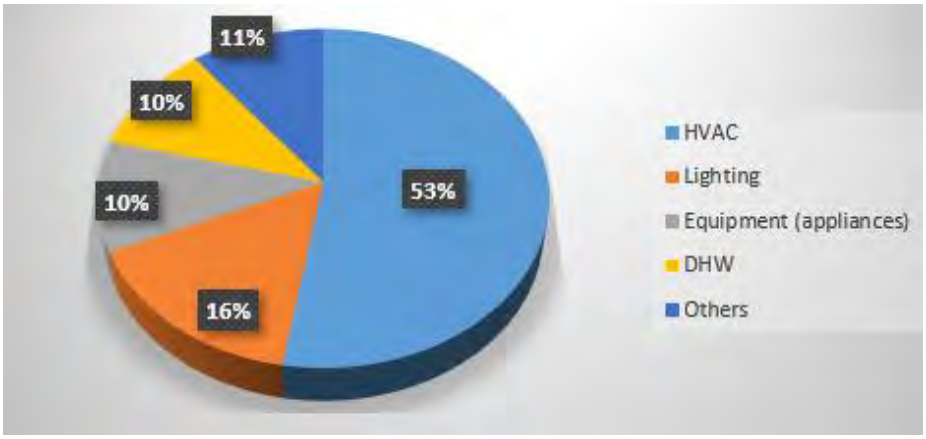



*Figure 1: Total energy consumption in commercial building*
*Source:(Gajaba & Dissanayake, 2025)*

## 2.2 ROLE OF BUILDING ENVELOPE IN ENERGY EFFICIENCY

The building envelope plays a crucial role in determining the energy performance of buildings by controlling the interaction between indoor spaces and external environmental conditions (Azima et al., 2022). Key components of the building envelope include external walls, roofs, glazing systems, shading devices, and ventilation openings. These elements collectively determine the building's ability to minimize heat gain and maintain comfortable indoor conditions. In tropical climates, poorly designed envelopes allow excessive solar radiation and heat penetration, which increases indoor temperatures and leads to higher cooling loads. Modern high-rise buildings frequently incorporate extensive glazed facades to improve daylighting and architectural aesthetics. However, large glazing areas can significantly increase solar heat gain if not properly designed, resulting in greater dependence on mechanical cooling systems such as air-conditioning (Dutta & Samanta, 2020). According to (Abdou & Reffat, 2025) the building envelope in high-rise buildings comprises physical form and orientation, external walls, roofs, glazing systems, shading devices, and ventilation elements, all of which play a critical role in controlling solar heat gain, indoor thermal comfort, and overall energy consumption in hot humid climates.

## 2.3 THE CONCEPT OF BIOMIMICRY

The concept of biomimicry involves studying natural systems, organisms, and processes to inspire solutions for human challenges. By emulating nature's strategies for adaptation, efficiency and resilience, biomimicry provides opportunities for developing environmentally responsive and energy-efficient design solutions (Araque et al., 2021). Furthermore, the approach of biomimicry, that examines and emulates the principles and mechanisms of nature to address human design challenges, with a strong emphasis on achieving sustainability (Mayank & Soumya, 2020). In addition there is increasing interest in biomimicry, as illustrated by the growing number of research studies, design projects, and sustainable innovations inspired by nature (Verbrugghe et al., 2023).

Key characteristics of biomimicry include adaptation, efficiency, resilience, and the ability of natural systems to regulate energy and resources effectively. Rather than simply copying the appearance of natural organisms, biomimicry focuses on understanding underlying functional mechanisms that enable organisms to survive in challenging environments (Tezel Ersanli & Ersanli, 2023). Biomimicry in architectural and engineering design draws inspiration from nature to foster sustainability and innovation, with two primary approaches: the top-down approach (Problem Based), and the bottom-up approach (solution-based) (Irene, 2025; Yeter et al., 2023). The problem-based approach (Design to Biology), also known as the top-down method, begins with a specific human design challenge and then seeks appropriate biological analogues to inspire solutions, whereas the solution-based approach (Biology to Design), or bottom-up method, starts by exploring biological phenomena, processes, or strategies in nature and subsequently applies these insights to address human design problems. In recent years, architects and engineers have increasingly explored biomimetic principles in building design to enhance sustainability and reduce energy consumption (Bijari et al., 2025). Nature-inspired architectural solutions have been applied in facade systems, structural forms, ventilation strategies, and shading devices. By integrating biological principles into architectural design, biomimicry enables the creation of buildings that are more adaptive, resource-efficient, and environmentally responsive.

## 2.4 BIOMIMICRY - INSPIRED COOLING STRATEGIES IN BUILDINGS

Biomimicry is the emulation of strategies seen in the living world as a basis for design and is a source of innovation, particularly in the creation of more sustainable architecture. It is the mimicry of an organism, an organism's behaviour or an entire ecosystem in terms of its form, material, construction method, process strategies or function. Research demonstrates that biomimicry can successfully address climatic challenges, with nature serving as "model, mentor and measure" for innovative architectural solutions (Cuce et al., 2019). Below Table 1 demonstrate the biological strategies provide valuable insights for developing passive cooling systems that can be adapted for architectural applications.

*Table 1: Various biomimicry strategies used in architecture*

| Design concept | Building | Biomimetic performance and building benefits |
|---|---|---|
| Termite Mounds | The Estate building in Harare, Zimbabwe | This innovative approach has resulted in a remarkable 100% reduction in energy consumption for HVAC systems. |

| Design concept | Building | Biomimetic performance and building benefits |
|---|---|---|
| | | Additionally, the building design facilitates natural ventilation and lighting, further enhancing its energy efficiency. |
| | The Council House 2, Melbourne | Towers provide a reduction of 4-13 degrees C from the top of the tower to the bottom.<br>Air is 100% filtered<br>Natural lighting and ventilation saved by 65% Maximizes natural ventilation |
| Beehive | Sinosteel International Plaza | The hexagonal windows, designed in five sizes and arranged in an energy-efficient configuration, minimize conventional energy use, eliminate the need for internal structures, and achieve 75% energy efficiency. |
| Glass sponge | Swiss Re Headquarters, London | An aerodynamic glazed facade with triangulated geometry reduces wind loads, maximizes natural light and ventilation, and cuts building energy use by up to 80%. |

Source: (Dixit et al., 2023; Rahubadda & Kulatunga, 2024; Waheeb et al., 2024)

Overall, biomimicry provides a versatile framework for developing climate-responsive architecture in tropical regions. By emulating natural systems and organisms, these strategies enhance energy efficiency, reduce reliance on mechanical cooling, and improve occupant comfort, thereby contributing to sustainable urban resilience and effective climate change adaptation (Amraoui et al., 2024).

## 2.5 BIOMIMICRY AS A SOLUTION FOR ENERGY EFFICIENCY

Improving the thermal performance of building envelopes, particularly facades, is essential for reducing operational energy consumption while maintaining indoor thermal comfort. Biomimicry provides nature-inspired strategies that can significantly reduce energy demand for heating, ventilation, and lighting by emulating efficient natural systems (Varshabi et al., 2022). Research has highlighted the potential of integrating biomimicry principles into building skins to enhance energy performance while addressing environmental aspects such as resource efficiency and material use. The Eastgate Centre in Harare demonstrates the effectiveness of biomimicry-inspired ventilation systems, achieving around 90% reduction in energy requirements compared with conventional building designs (Adarsh & Thomas, 2024). Despite these successful applications, the integration of biomimicry in high-rise residential and commercial buildings remains limited, particularly in shortage of skilled professionals. This highlights the need for further research to explore biomimicry-inspired strategies that can enhance energy efficiency in high-rise buildings (Rodriguez et al., 2024).

# 3. METHODOLOGY

This study adopted a mixed-method approach to combine qualitative insights from interviews and document reviews with quantitative energy simulation analysis, thereby providing a more comprehensive evaluation of biomimicry-inspired strategies for improving building energy efficiency. According to Nair and Prem (2020) mixed-method research enables a better understanding of complex research problems through the integration of qualitative and quantitative data. The study included a literature review, preliminary interview, document review, development of conventional and biomimicry-inspired building models, and energy simulation analysis. The overall research process is illustrated in Figure 2.

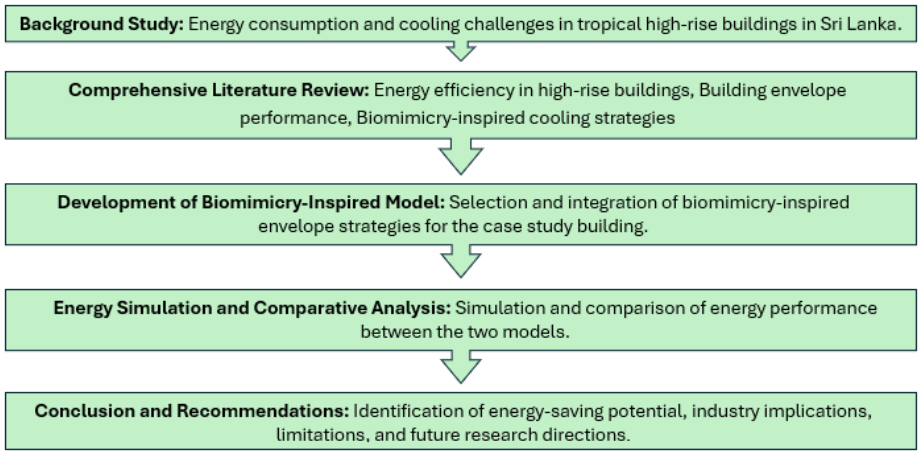



*Figure 2: Research process*

The process began with a background study and comprehensive literature review to identify relevant biomimicry principles applicable to improving energy efficiency in tropical high-rise buildings. In addition, preliminary interviews and document reviews were conducted to gather expert insights and building-related information. Based on these findings, a conventional building model and a biomimicry-inspired building model were developed. Finally, energy simulation and comparative analysis were carried out using Revit energy analysis tools to evaluate and compare the energy performance of both models, leading to the study conclusions and recommendations.

## 3.1 CASE STUDY SELECTION

A 12-storey commercial office building located in Colombo, Sri Lanka, was selected as the case study for this research. The building has a total floor area of approximately 18,805.50 m² and utilizes a reinforced concrete frame structural system. Preliminary interviews with building representatives and a review of available architectural and technical documents were conducted to collect relevant building information. The external envelope of the building primarily consists of a single-glazed tinted curtain wall facade, while secondary facade areas are constructed using 225 mm reinforced concrete walls. Figure 3 demonstrates the architectural layout of the selected building, site plan, unit layout, and ground floor design.

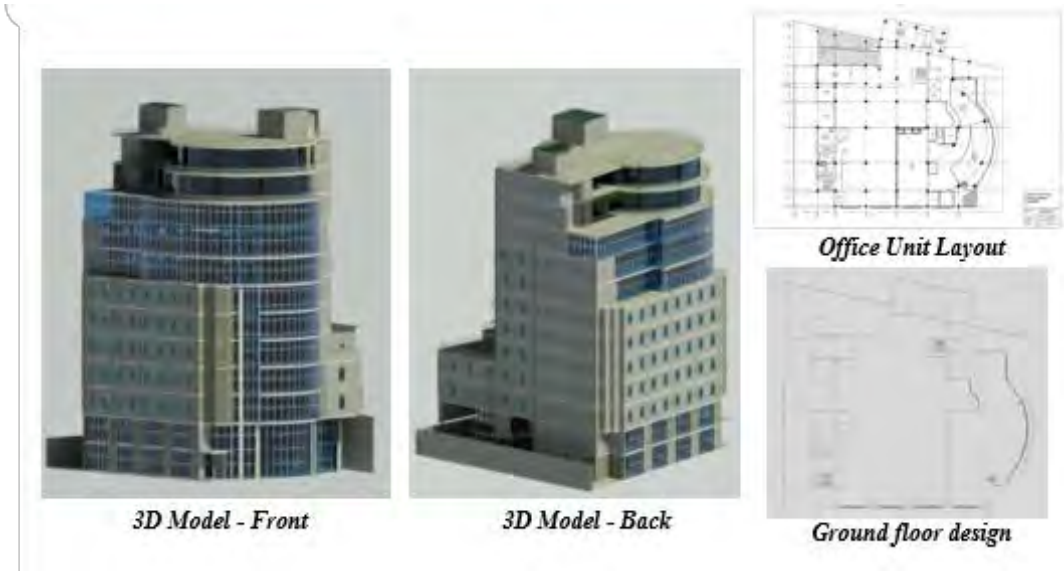



*Figure 3: Architectural layout of the selected building, site plan, unit layout, and ground floor design*

The selection of the case study building in Colombo, Sri Lanka, was guided by several key considerations. First, the building features a high glazing facade ratio of approximately 90%. Second, the building utilizes tinted glazing with a relatively high U-value, indicating lower thermal resistance and increased heat transfer through the facade. Third, the structure follows a reinforced concrete frame system with a glass curtain wall as the primary facade, representing a common typology in contemporary commercial high-rise buildings. Finally, the building provides sufficient architectural and technical information through interviews and documentation, enabling the development of a representative conventional model for evaluating biomimicry-inspired strategies aimed at improving energy efficiency.

### 3.1.1 Preliminary Interview

A preliminary interview was conducted with a participant who is highly familiar with the building. The participant is the operations manager of the building, who has 10 years of experience in the built-environment sector and sustainability. The data were analysed using a thematic analysis to identify key insights and inform the development of the model. Although only a single interview was conducted, this approach allowed the systematic extraction of meaningful observations from the participant's experience with the building.

### 3.1.2 Document Review

A document review was conducted to collect and analyse relevant building-related data. Energy consumption records and electricity bills were examined to obtain monthly energy usage patterns. Architectural layout plans were reviewed to support the development of the building model, while building handover documents were analysed to identify material specifications and usage. This document-based analysis provided reliable secondary data to inform the model development.

## 3.2 DEVELOPMENT OF THE BUILDING MODELS

To develop the conceptual biomimicry-inspired design model, Autodesk Revit, a Building Information Modelling (BIM)- platform, was used to create digital

representations of both the conventional building and the biomimicry-inspired building models. The conventional model was developed based on the collected building data and served as the baseline condition representing the existing building design. Subsequently, a biomimicry-inspired model was created by incorporating selected nature-based cooling strategies identified from the literature review. To ensure a reliable comparison between the two models, identical building functions, spatial layouts, and environmental settings were maintained across both models.

### 3.2.1 Biomimicry Model Development

In this study, the top-down (problem-based) approach was adopted, where the research first identifies the problem of high energy consumption in tropical high-rise buildings. The biomimicry-inspired model was developed by incorporating selected biomimicry-inspired envelope features derived from natural systems. A triangular parametric facade was introduced as an external shading system to minimize direct solar radiation and enhance daylight control. The concrete wall system was modified using mycelium-bound composite tiles with elephant-skin textured cladding, selected for their ability to increase surface roughness and promote heat dissipation. In addition, the rooftop was enhanced with a hexagonal ZnO microrods coating, chosen for its high reflectivity and emissivity to reduce solar absorptance. Figure 4 illustrates the development process of the biomimicry inspired building model.

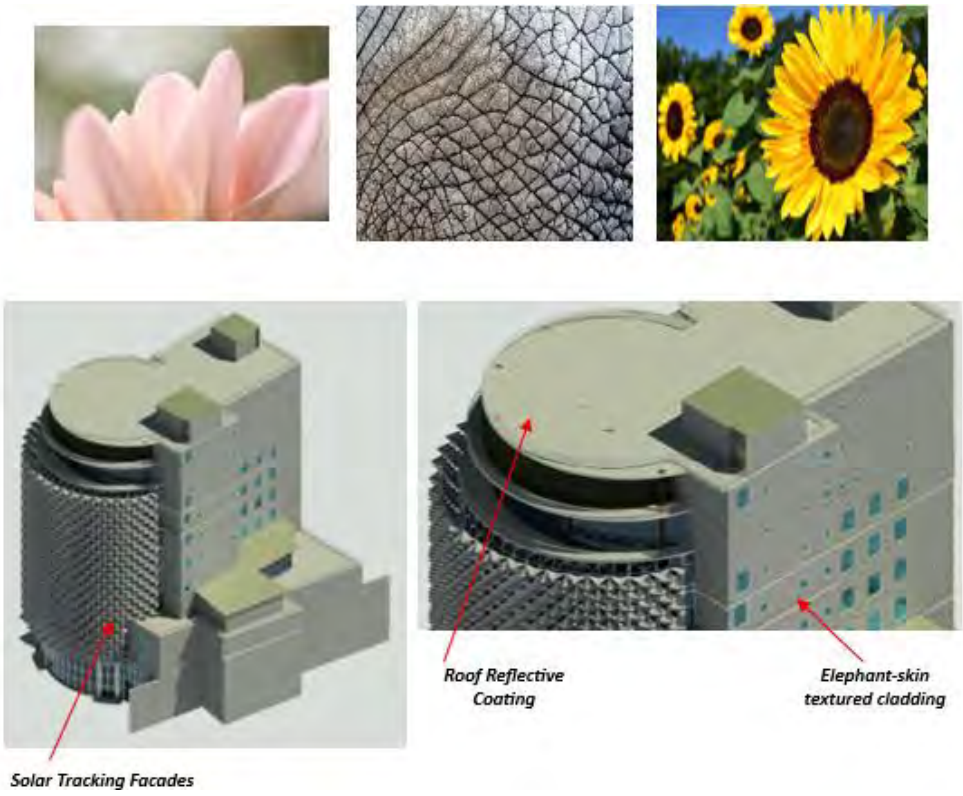



*Figure 4: Development process of the biomimicry inspired building model*

## 3.3 BUILDING ENERGY SIMULATION

Energy simulation for both the conventional and biomimicry-inspired building models was carried out using Energy Plus platform to evaluate the performance under tropical

climatic conditions. The simulation was conducted using the Colombo Bandaranaike International Airport weather file, representing local environmental conditions. The model was simulated over an annual period of 8760 hours.

The analysis focused on the Annual Building Utility Performance Summary (End Uses by Subcategory), which provides a detailed breakdown of building energy consumption. Key end-use categories considered in this study include cooling, interior lighting, and interior equipment, as well as the total energy consumption associated with heating and cooling systems. These outputs were used to establish the baseline energy performance of the conventional building and to enable comparison with the biomimicry-inspired model in terms of energy efficiency improvements.

# 4. RESEARCH FINDINGS AND DISCUSSION

## 4.1 THEMATIC ANALYSIS FOR INTERVIEW

Table 2 presents the thematic analysis conducted based on preliminary interview responses. The findings indicate that the building follows a conventional design approach with a heavy reliance on centralized HVAC systems, leading to high energy consumption, particularly due to cooling demand. The extensive use of a glass curtain wall façade contributes significantly to solar heat gain, further increasing the cooling load. According to the respondent "internal blinds are used as shading elements", advanced passive design strategies are absent. However, the interviewer revealed that "I have some general awareness of biomimicry" and highlighted their potential application, particularly in façade design, to reduce heat gain and improve energy efficiency. These insights were used to inform the development of the proposed biomimicry-based facade model.

*Table 2 - Thematic analysis of the preliminary interview*

| Theme | Code | Participant's responses and evidence |
|---|---|---|
| Building Design Characteristics | Conventional Design | No biomimicry-based features were adapted in the building |
| Energy Usage | HVAC Dependency | Centralized HVAC system operates during weekday working hours |
| | High Cooling Demand | Solar heat gain becomes a major issue in increased cooling load. |
| Facade Performance | Glazed Facade Impact | Glass curtain wall facade is a significant portion of the external envelope. |
| | Limited Passive Strategies | Internal blinds are used as a basic shading element. No advanced solutions. |
| Biomimicry Awareness | Basic Awareness | Awareness exists but is not deeply implemented. |
| Biomimicry Potential | Need for Biomimicry Solutions | Strong potential for biomimicry in improving energy performance. |

## 4.2 DOCUMENT REVIEWING

The document review of the selected building indicates a high level of annual electricity consumption (6,490,160Kwh) primarily driven by cooling demand under tropical

climatic conditions. The analysis reveals that the building is cooling-dominated, with a significant portion of total energy use attributed to the centralized HVAC system. This is largely influenced by the building's high glazing facade ratio (approximately 90% of the total facade area) and thermal properties of the envelope, which contribute to increased solar heat gain and indoor temperature rise. In addition, the roof's high solar absorptance further intensifies heat transfer into the building. The building operates during standard office hours, resulting in consistent energy demand throughout the year. Overall, the findings highlight a strong reliance on mechanical cooling and the absence of effective passive design strategies, emphasizing the need for biomimicry-inspired solutions to enhance energy efficiency.

## 4.3 COMPARISON OF ENERGY SIMULATION BETWEEN CONVENTIONAL AND THE BIOMIMICRY INSPIRED BUILDING MODELS

Figures 5 and 6 illustrate the comparison of energy simulation results between the conventional building model and the biomimicry-inspired building model.

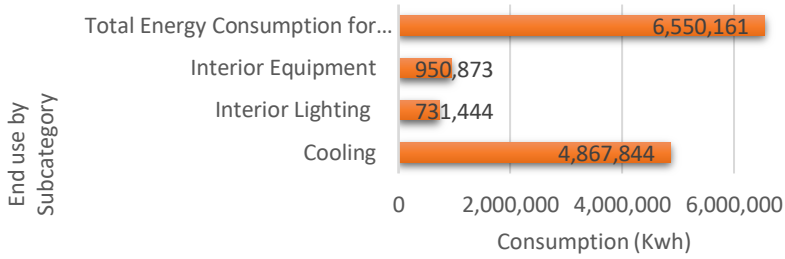



*Figure 5 - Total energy consumption (end use by subcategory) of the conventional building*

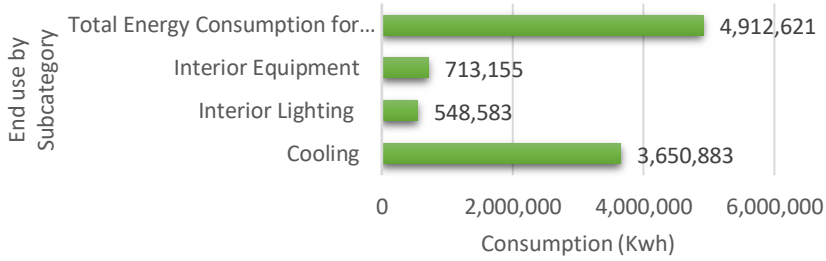



*Figure 6 - Total energy consumption (end use by subcategory) of the biomimicry inspired building*

A comparative analysis of energy consumption between the conventional and biomimicry-inspired building models, based on the End Uses by Subcategory (Cooling, Interior Lighting, and Interior Equipment) obtained from the simulation results, is presented in the following sections.

### 4.3.1 Comparison of Cooling Energy Consumption

Figure 7 illustrates the Comparison of Cooling Energy Consumption between the conventional building model and the biomimicry-inspired building model.

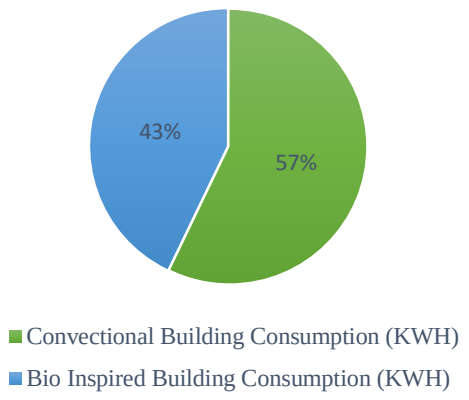



*Figure 7 - Cooling energy consumption*

The results indicate a significant reduction in cooling energy consumption in the biomimicry-inspired building model compared to the conventional building. The conventional building recorded a cooling energy consumption of 4,867,844 kWh, whereas the biomimicry-inspired model reduced this value to 3,650,883 kWh. This represents a reduction of approximately 1,216,961 kWh, equivalent to about 25% decrease in cooling energy demand.

### 4.3.2 Comparison of Interior Lighting and Equipment Energy Consumption

In addition to cooling energy, the comparison of interior lighting and interior equipment energy consumption between the conventional and biomimicry-inspired models demonstrates a noticeable reduction. The conventional building recorded 731,444 kWh for interior lighting and 950,873 kWh for interior equipment, whereas the biomimicry-inspired model reduced these values to 548,583 kWh and 713,155 kWh**,** respectively. This reduction can be attributed to the improved building envelope performance in the biomimicry-inspired model, which enhances daylight utilization and reduces dependence on artificial lighting. Furthermore, improved thermal conditions reduce internal heat gains, indirectly lowering equipment-related cooling loads. Figure 8 illustrates the Comparison of Interior Lighting and Equipment Energy Consumption between the conventional building model and the biomimicry-inspired building model.

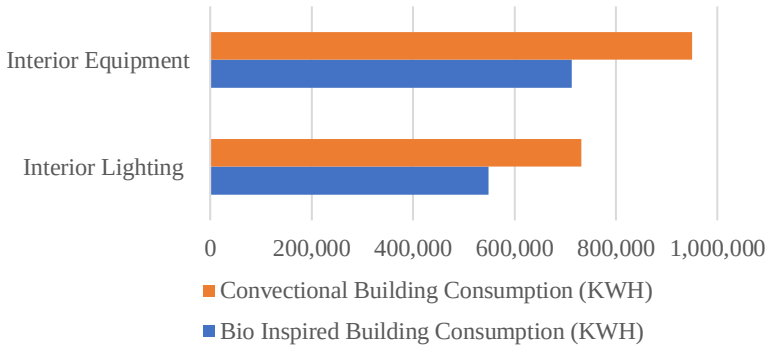



*Figure 8 : Comparison of interior lighting and equipment energy consumption*

The findings are consistent with previous studies that identified biomimicry-inspired facade systems as effective passive cooling strategies in tropical climates. For example, He et al. (2023) reported significant reductions in cooling energy demand through nature-

inspired envelope adaptations. Similarly, Shet (2026) emphasized that biomimetic facade systems improve thermal regulation and reduce dependency on mechanical cooling. Compared with previous studies, the present research specifically contributes to the Sri Lankan context by demonstrating the applicability of biomimicry-inspired envelope strategies for commercial high-rise buildings under Colombo climatic conditions. Unlike many previous conceptual biomimicry studies, this research quantified energy performance improvements through simulation modelling.

## 5. CONCLUSIONS

This study emphasizes the importance of building envelope design in improving building energy performance compared with conventional approaches that mainly rely on mechanical systems. By maintaining consistent operational and climatic conditions across both models, the findings confirm the potential of biomimicry-inspired strategies in enhancing passive energy efficiency in high-rise buildings.

The simulation results revealed a significant reduction in energy consumption in the biomimicry-inspired model compared to the conventional building. Cooling energy consumption was reduced by approximately 25%, demonstrating the effectiveness of strategies such as external shading, textured facade surfaces, and reflective roof coatings in minimizing solar heat gain and improving passive thermal regulation. These findings are consistent with previous studies highlighting the effectiveness of biomimicry-inspired façade systems in tropical climates. In addition, reductions in lighting and equipment energy consumption indicate the broader impact of improved envelope performance on overall building efficiency.

Furthermore, in industry terms, the research illustrates that the strategies in envelope design inspired by biomimicry can aid architects and developers in creating high-rise buildings in tropical climates that are more energy efficient. From a research perspective, the study contributes to the limited knowledge on biomimicry applications in Sri Lankan high-rise buildings and provides a foundation for future research on adaptive façade systems and biomimetic materials. However, this study is limited to a single case study and simulation-based analysis; therefore, the findings represent a case-specific evaluation and may not be fully generalizable. Future studies should incorporate multiple case studies, field measurements, and broader climatic comparisons to improve generalisability and validation of biomimicry-inspired design strategies. Overall, the study demonstrates that biomimicry-inspired envelope strategies can effectively reduce energy consumption in high-rise buildings under tropical climatic conditions.

## 6. REFERENCES

Abdou, A., & Reffat, R. (2025). Integrated analysis of building form, orientation and envelope factors on energy efficiency in high-rise offices in hot-humid climates. *Archnet-IJAR: International Journal of Architectural Research*, 1–26. https://doi.org/10.1108/ARCH-02-2025-0092

Adarsh, S., & Thomas, A. V. (2024). A review on the applications of biomimetic principles for sustainable construction. *IOP Conference Series: Earth and Environmental Science*, *1326*, 012154. https://doi.org/10.1088/1755-1315/1326/1/012154

Anarene, B. (2024). Revolutionizing energy efficiency in commercial and institutional buildings: A complete analysis. *International Journal of Scientific Research and Management (IJSRM)*, *12*(09), 7444–7468. https://doi.org/10.18535/ijsrm/v12i09.em12

Araque, K., Palacios, P., Mora, D., & Chen Austin, M. (2021). Biomimicry-based strategies for urban heat island mitigation: A numerical case study under tropical climate. *Biomimetics*, *6*(3), 48. https://doi.org/10.3390/biomimetics6030048

Azima, M., & Seyis, S. (2022). Evaluating the impact of building envelope on energy performance: A cooling analyses. *Journal of Construction Engineering, Management & Innovation*, *5*(1), 28–44. https://doi.org/10.31462/jcemi.2022.01028044

Bijari, M., Aflaki, A., & Esfandiari, M. (2025). Plants inspired biomimetics architecture in modern buildings: A review of form, function and energy. *Biomimetics*, *10*(2), 124. https://doi.org/10.3390/biomimetics10020124

Christopher, S., Vikram, M. P., Bakli, C., Thakur, A. K., Ma, Y., Ma, Z., Xu, H., Cuce, P. M., Cuce, E., & Singh, P. (2023). Renewable energy potential towards attainment of net-zero energy buildings status – A critical review. *Journal of Cleaner Production*, *405*, 136942. https://doi.org/10.1016/j.jclepro.2023.136942

Cuce, E., Nachan, Z., Cuce, P. M., Sher, F., & Neighbour, G. B. (2019). Strategies for ideal indoor environments towards low/zero carbon buildings through a biomimetic approach. *International Journal of Ambient Energy*, *40*(1), 86–95. https://doi.org/10.1080/01430750.2017.1372807

Dash, S. P. (2018). Application of biomimicry in building design. *International Journal of Civil Engineering and Technology (IJCIET)*, *9*(2), 644-660. _09_02_062_Cite_this_Article_Shanta_Pragyan_Dash_Application_of_Biomimicry_in_Building_Design/links/61458f8c519a1a381f691641/Article-ID-IJCIET-09-02-062-Cite-this-Article-Shanta-Pragyan-Dash-Application-of-Biomimicry-in-Building-Design.pdf

Dixit, S., Stefańska, A., & Singh, P. (2023). Manufacturing technology in terms of digital fabrication of contemporary biomimetic structures. *International Journal of Construction Management*, *23*(11), 1828–1836. https://doi.org/10.1080/15623599.2021.2015105

Dutta, A., & Samanta, A. (2020). Determining factor/s of window glazing regarding reduction in electrical energy consumption. *Journal of Energy Resources Technology*, *142*(3), 032101. https://doi.org/10.1115/1.4044888

Ge, J., Wang, Y., Zhou, D., Gu, Z., & Meng, X. (2023). Building energy demand of urban blocks in Xi'an, China: Impacts of high-rises and vertical meteorological pattern. *Building and Environment*, *244*, 110749. https://doi.org/10.1016/j.buildenv.2023.110749

Harputlugil, T., & De Wilde, P. (2021). The interaction between humans and buildings for energy efficiency: A critical review. *Energy Research & Social Science*, *71*, 101828. https://doi.org/10.1016/j.erss.2020.101828

He, Q., Tapia, F., & Reith, A. (2023). Quantifying the influence of nature-based solutions on building cooling and heating energy demand: A climate specific review. *Renewable and Sustainable Energy Reviews*, *186*, 113660. https://doi.org/10.1016/j.rser.2023.113660

Irene, N. J. (2025). Biomimicry: Designing sustainable solutions from nature. *IAA Journal of Biological Sciences*, *13*(1), 75–80. https://doi.org/10.59298/IAAJB/2025/1317580

Jayasinghe, P., Raghavan, V., & Yonezawa, G. (2021). Exploration of expansion patterns and prediction of urban growth for Colombo City, Sri Lanka. *Spatial Information Research*, *29*, 465-478. https://doi.org/10.1007/s41324-020-00364-4

Amraoui, k., Zemmouri, N., & El Bar, S. (2024). Towards resilient cities: biomimetic strategies for urban adaptation. *International Journal of Innovative Technologies in Social Science*, *4*(44). https://doi.org/10.31435/ijitss.4(44).2024.3082

Chaurasia, M., & Srivastava, S. (2020). Biomimicry and its applications - a review. *International Journal of Engineering Applied Sciences and Technology*, *4*(12), 545-549. https://doi.org/10.33564/IJEAST.2020.v04i12.098

Mostafavi, F., Tahsildoost, M., & Zomorodian, Z. (2021). Energy efficiency and carbon emission in high-rise buildings: A review (2005-2020). *Building and Environment*, *206*, 108329. https://doi.org/10.1016/j.buildenv.2021.108329

Omer, A. M. (2020). Design and operation of low energy consumption passive human comfort solutions. *Journal of Commerce and Management Thought*, *11*(1), 40-62. https://doi.org/10.5958/0976-478X.2020.00004.x

Qahtan, A. M. (2024). Aesthetic and thermal suitability of highly glazed spaces with interior roller blinds in Najran university buildings, Saudi Arabia. *Sustainability*, *16*(5), 2030. https://doi.org/10.3390/su16052030

Rahubadda, A., & Kulatunga, U. (2024). Harnessing nature's blueprint: biomimicry in urban building design for sustainable and resilient cities. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (Eds.), *Proceedings of the 12th World Construction Symposium*. (pp. 532-543). Department of Building Economics. https://doi.org/10.31705/WCS.2024.42

Rodriguez, N., Katooziani, A., & Jeelani, I. (2024). Barriers to energy-efficient design and construction practices: A comprehensive analysis. *Journal of Building Engineering*, *82*, 108349. https://doi.org/10.1016/j.jobe.2023.108349

Nair, S. S., & Prem, S. (2020). A framework for mixed-method research. *Shanlax International Journal of Management*, 8(2), 45–53. https://doi.org/10.34293/management.v8i2.3220

Shet, A. (2026). Biomimetic adaptive facades: optimizing energy efficiency through natural analogues. *International Journal for Research in Applied Science and Engineering Technology(IJRASET)*, *14*(2), 835–841. https://doi.org/10.22214/ijraset.2026.77493

Tezel Ersanli, E., & Ersanli, C. C. (2023). Biomimicry: Journey to the future with the power of nature. *International Scientific and Vocational Studies Journal*, *7*(2), 149–160. https://doi.org/10.47897/bilmes.1388402

Varshabi, N., Arslan Selçuk, S., & Mutlu Avinç, G. (2022). Biomimicry for energy-efficient building design: A bibliometric analysis. *Biomimetics*, *7*(1), 21. https://doi.org/10.3390/biomimetics7010021

Vasanthanathan, A., Siddharth, U., Vignesh, M., & Pravin, R. (2020). Biomimicry: An overview of structures, designs and materials inspired from nature. *Current Materials Science*, *13*(1), 3–15. https://doi.org/10.2174/2666145413666200212103324

Verbrugghe, N., Rubinacci, E., & Khan, A. Z. (2023). Biomimicry in architecture: A review of definitions, case studies, and design methods. *Biomimetics*, *8*(1), 107. https://doi.org/10.3390/biomimetics8010107

Waheeb, M. I., Hemeida, F. A., & Mohamed, A. F. (2024). Improving thermal comfort using biomimicry in the urban residential districts in New Aswan city, Egypt. *Environment, Development and Sustainability*, *28*, 9789-9809. https://doi.org/10.1007/s10668-024-05310-0

Weerasinghe, A. S., Ramachandra, T., & Rotimi, J. O. B. (2022). Towards sustainable commercial buildings: An analysis of operation and maintenance (O&M) costs in Sri Lanka. *Smart and Sustainable Built Environment*, *11*(3), 454–468. https://doi.org/10.1108/SASBE-04-2020-0032

Yeter, I. H., Tan, V. S. Q., & Le Ferrand, H. (2023). Conceptualization of biomimicry in engineering context among undergraduate and high school students: An international interdisciplinary exploration. *Biomimetics*, *8*(1), 125. https://doi.org/10.3390/biomimetics8010125

Yang, P., Lim, B.T.H. and Oo, B.L., 2026. A conceptual framework for the adoption of a life cycle assessment-based emissions trading scheme in the Australian construction sector. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 30-43. DOI: https://doi.org/10.31705/WCS.2026.3. Available from: https://ciobwcs.com/papers/

# A CONCEPTUAL FRAMEWORK FOR THE ADOPTION OF A LIFE CYCLE ASSESSMENT-BASED EMISSIONS TRADING SCHEME IN THE AUSTRALIAN CONSTRUCTION SECTOR

**Pengqi Yang[1], Benson Teck Heng Lim[2] and Bee Lan Oo[3]**

## *ABSTRACT*

*As carbon governance in the construction sector shifts from a narrow focus on operational energy towards whole-of-life performance, understanding stakeholder intentions to adopt a Life Cycle Assessment (LCA)-based Emissions Trading Scheme (ETS) becomes increasingly relevant to exploring market-driven decarbonisation pathways for the industry. This study proposes a conceptual framework for understanding the factors influencing stakeholder adoption of an LCA-based ETS in the Australian construction sector. Drawing on a literature review, the proposed framework is underpinned by institutional theory, the technology acceptance model (TAM), and stakeholder theory, with systems thinking providing a broader analytical perspective. Three groups of factors form the basis of the framework. The first concerns the implementation barriers and potential benefits associated with LCA and ETS. The second involves the institutional conditions shaping the adoption context, including coercive, normative, and mimetic pressures, alongside stakeholder-related factors such as carbon mitigation perception and stakeholder pressure. The third relates to the behavioural constructs through which stakeholders form adoption intentions, namely perceived usefulness, perceived ease of use, and behavioural intention. The framework brings these factors together into a structured relationship linking external context, cognitive appraisal, and behavioural judgement. It suggests that the adoption of an LCA-based ETS should be understood as a progressive process situated within a broader socio-technical and institutional system.*

***Keywords:*** *Conceptual Framework; Construction Sector; Emissions Trading Scheme (ETS); Life Cycle Assessment (LCA); Stakeholder Adoption.*

## 1. INTRODUCTION

The construction sector is one of the major sources of global carbon emissions, accounting for around 37 to 39 per cent of energy- and industrial process-related carbon

[1] PhD Candidate, School of Built Environment, University of New South Wales, Australia, pengqi.yang@unsw.edu.au
[2] Associate Professor, School of Built Environment, University of New South Wales, Australia, b.lim@unsw.edu.au
[3] Associate Professor, School of Built Environment, University of New South Wales, Australia, bee.oo@unsw.edu.au

dioxide emissions worldwide (United Nations Environment Programme & Global Alliance for Buildings and Construction [UNEP & GlobalABC], 2024). In Australia, the sector also occupies an important position in national energy use and decarbonisation efforts, making it a critical area for climate change mitigation (Department of Climate Change, Energy, the Environment and Water [DCCEEW], 2026). As electricity systems continue to decarbonise, the relative share of operational emissions is gradually declining, while emissions associated with material production and construction are becoming more significant (Röck et al., 2020; UNEP & GlobalABC, 2024). This shift indicates that whole-of-life considerations are becoming increasingly important in carbon governance for the built environment. In this context, Life Cycle Assessment (LCA) and Emissions Trading Scheme (ETS) have been discussed as two potential mechanisms that may support this transition. LCA provides a systematic approach to assessing environmental impacts across the life cycle of buildings (Abd Rashid & Yusoff, 2015), while ETS introduces economic incentives for emission reduction through market-based carbon pricing (Aldy & Stavins, 2012). However, although both have been widely discussed within their respective fields, limited attention has been paid to the conditions under which they could be integrated in the construction sector (Ibn-Mohammed et al., 2013; Liu & Loo, 2026).

Central to this discussion is whether stakeholders in the construction sector would regard an LCA-based ETS as a feasible and worthwhile governance mechanism. Existing studies on carbon trading in the construction sector have mainly focused on jurisdictions where ETS or carbon pricing frameworks are already in place, such as China, South Korea, the European Union, and California, with more attention given to institutional design than to stakeholder adoption behaviour (Chen et al., 2015; Du et al., 2025; Liu & Loo, 2026). In Australia, the national carbon pricing mechanism was repealed in 2014, and there is still no ETS covering the construction sector (Commonwealth of Australia, 2014; International Carbon Action Partnership [ICAP], 2024). Research on stakeholder willingness to adopt such a mechanism therefore remains limited. Current research has not sufficiently explained how institutional pressures, perceived barriers, perceived benefits, and stakeholder expectations may interact to shape adoption intention towards an LCA-based ETS, especially where mature carbon market infrastructure is absent. In response to these gaps, this study proposes a conceptual framework for understanding the factors influencing stakeholder adoption of an LCA-based ETS in the Australian construction sector. Through a literature review, the paper integrates institutional theory, the technology acceptance model (TAM), and stakeholder theory, with systems thinking providing a broader analytical perspective. The contribution of the paper does not lie in reporting empirical findings, but in identifying the key factors influencing adoption of an LCA-based ETS and offering a theoretical foundation for subsequent empirical research.

## 2. METHOD

This study is a conceptual paper based on a targeted literature review. The review focused on four areas: the shift towards whole-of-life carbon management in construction, the roles and constraints of LCA and ETS as complementary mechanisms, institutional and stakeholder factors shaping adoption contexts, and technology acceptance as a lens for understanding behavioural intention. Publications were selected based on their relevance to whole-of-life carbon management, LCA and ETS mechanisms, construction sector decarbonisation, and stakeholder adoption behaviour. Studies outside the construction or

built environment context were included only where they provided transferable insights into ETS mechanisms or adoption theory. The selected literature was synthesised thematically to identify the technical, institutional, cognitive, and stakeholder-related factors informing the proposed conceptual framework.

The review was organised around three strands: problem context, implementation conditions, and adoption-related constructs. The first strand addresses the decarbonisation challenges associated with whole-of-life considerations in the construction sector. The second examines the respective roles and implementation constraints of LCA and ETS. The third considers the institutional, stakeholder, and behavioural factors that may shape adoption. These strands are then brought together to inform the development of a conceptual framework for understanding stakeholder adoption intention.

# 3. LITERATURE REVIEW FINDINGS

## 3.1 THE SHIFT TO WHOLE-OF-LIFE DECARBONISATION AND THE NEED FOR A SYSTEMS PERSPECTIVE

The preceding discussion indicates that decarbonisation in the construction sector increasingly requires attention to whole-of-life carbon performance, rather than operational energy use alone. In low-energy buildings, embodied carbon may account for close to half of whole-of-life emissions and, in some cases, may exceed operational emissions (Pomponi & Moncaster, 2018; Röck et al., 2020; UNEP & GlobalABC, 2024). As embodied carbon becomes more significant within total life cycle emissions, key decarbonisation opportunities are increasingly associated with material selection, supply chain management, and early design decisions (De Wolf et al., 2017; Pomponi & Moncaster, 2018). In this context, LCA has become an important tool for identifying emission hotspots and supporting whole-of-life decision-making (Abd Rashid & Yusoff, 2015; Buyle et al., 2013).

This shift also suggests that an LCA-based ETS may be better understood as more than a simple combination of two separate tools, but rather as a governance issue that spans multiple project stages and involves diverse stakeholder interests, as indicated by the construction carbon trading literature and stakeholder theory (Liu & Loo, 2026; Mitchell et al., 1997). LCA provides a relatively static basis for carbon quantification, while ETS operates as a dynamic market mechanism whose effects depend on policy design, market conditions, and behavioural response (Aldy & Stavins, 2012; Ellerman et al., 2010). The former supports the identification and comparison of emissions, while the latter introduces economic incentives for behavioural adjustment. From this perspective, their integration appears to depend not only on technical linkage, but also on how data, institutions, and behaviour are connected within a broader framework (Checkland, 1981; Jackson, 2003; Meadows, 2008). Therefore, a systems perspective is adopted in this study as an overall analytical boundary that frames the study, rather than as a standalone theoretical variable.

## 3.2 LCA AND ETS: COMPLEMENTARY FUNCTIONS AND IMPLEMENTATION CONSTRAINTS

The core value of LCA lies in its ability to provide a systematic assessment of environmental impacts across the life cycle of buildings (International Organization for Standardization [ISO], 2006a, 2006b). It makes carbon impacts across different stages

more visible and supports the comparison of design options and the identification of decarbonisation pathways (Dossche et al., 2017). However, the visibility of carbon information does not automatically translate into influence over decision-making (De Wolf et al., 2017; Pomponi & Moncaster, 2018). This is mainly due to the fragmented information chains in construction projects, which often lead to the loss of key metadata, such as system boundaries and data quality, as information moves across multiple parties (Marsh et al., 2023). Methodological inconsistency adds a further difficulty. Konradsen et al. (2024) noted that differences in product category rules and allocation methods can weaken the comparability of assessment results, a concern also raised by De Wolf et al. (2017) and Feng et al. (2022). More fundamentally, carbon reduction in most project settings still relies more on voluntary action than on direct market constraints, which limits the economic incentives for LCA implementation. This problem is likely to be more pronounced for small and medium-sized enterprises (SMEs), which often face ongoing costs in data collection and staff training (Gómez-Garza et al., 2024). These studies suggest that while LCA can improve carbon visibility, its influence on project decisions may remain constrained in practice.

The logic of ETS is different. Rather than improving carbon visibility, ETS seeks to influence organisational behaviour through market-based compliance obligations and carbon pricing. In the energy and heavy industry sectors, ETS has been associated with emissions reductions of around 5 to 21 per cent (Döbbeling-Hildebrandt et al., 2024), while also encouraging low carbon innovation in upstream industries (Calel & Dechezleprêtre, 2016). However, in the construction sector, the project-based nature of delivery, the dispersion of participants, and the ambiguity of responsibility boundaries can weaken the transmission of carbon price signals through the supply chain (Liu & Loo, 2026). In many cases, the party paying the carbon cost is not the same party making design or procurement decisions (Cludius et al., 2020). In Australia, this disconnection appears particularly strong because formal carbon pricing arrangements remain focused on large industrial facilities (Clean Energy Regulator, 2026), while a national framework for embodied carbon accounting in buildings has not yet been fully established (Infrastructure Australia [IA], 2024). This suggests that the application of ETS logic in construction may depend on more than carbon pricing alone.

To contextualise the discussion above, it is useful to outline the basic operation of ETS as a market-based mechanism. An ETS typically operates through a cap-and-trade structure, in which a regulatory authority sets an aggregate emissions cap and allocates or auctions tradable emission allowances to covered entities. Firms that reduce emissions below their allocation can sell surplus allowances, while those exceeding their cap must purchase additional permits, thereby establishing a carbon price signal that incentivises cost-effective abatement (Aldy & Stavins, 2012; Ellerman et al., 2010). This mechanism has been implemented in various jurisdictions, including the European Union Emissions Trading System, the Korean Emissions Trading Scheme, and California's Cap-and-Trade Program, each with different sectoral coverage, allocation methods, and compliance obligations (ICAP, 2024). However, these systems predominantly target large stationary emitters in energy and heavy industries, while embodied emissions in building construction remain largely outside mainstream ETS compliance coverage (Döbbeling-Hildebrandt et al., 2024; Liu & Loo, 2026). In Australia, the Safeguard Mechanism covers facilities exceeding 100,000 tonnes of $CO_2$-equivalent per year (Clean Energy Regulator,

2026), leaving the construction sector's embodied emissions largely outside formal carbon pricing frameworks.

While LCA and ETS address different aspects of the carbon management problem, LCA may provide a critical technical foundation for extending ETS logic into the construction sector. Conventional ETS frameworks primarily account for direct operational emissions at facility level, but in the construction sector, a substantial share of emissions is embodied in materials, transport, and construction processes that occur across fragmented supply chains (Ibn-Mohammed et al., 2013; Röck et al., 2020). LCA can expand the carbon accounting boundary by quantifying emissions across life cycle stages, including material extraction, manufacturing, transport, construction, and end-of-life (Abd Rashid & Yusoff, 2015; Buyle et al., 2013). In principle, this enables a more comprehensive basis for carbon pricing that captures embodied as well as operational emissions. However, this facilitation is conditional rather than automatic. For LCA outputs to serve as credible inputs to ETS-style compliance, they would need to meet minimum standards of data quality, system boundary consistency, transparent reporting, and verification readiness—requirements that current practice does not yet reliably satisfy (De Wolf et al., 2017; Konradsen et al., 2024; Marsh et al., 2023). The gap between LCA's technical potential and the verification demands of ETS compliance is therefore a key consideration for any future integration.

Taken together, LCA and ETS appear complementary in principle, but their integration in the construction sector is constrained by technical, organisational, and institutional conditions. The literature review reveals that the issue is not only whether the two mechanisms are theoretically compatible, but also whether these conditions support their practical use in the sector. This highlights the relevance of stakeholder judgement in the present study. Table 1 summarises the main barriers and potential benefits discussed above.

*Table 1: Key implementation barriers and potential benefits of LCA and ETS in the construction sector*

| | **LCA** | **ETS** |
|---|---|---|
| Main barriers | Metadata loss across project parties (Marsh et al., 2023)<br>Methodological inconsistency and weak comparability (De Wolf et al., 2017; Feng et al., 2022; Konradsen et al., 2024)<br>Cost and capacity constraints for implementation (Gómez-Garza et al., 2024)<br>Limited influence on project decision-making (De Wolf et al., 2017; Pomponi & Moncaster, 2018) | Weak carbon price signal transmission across the supply chain (Cludius et al., 2020; Liu & Loo, 2026)<br>Split incentives between cost bearers and decision-makers (Cludius et al., 2020)<br>Limited ETS compliance coverage for embodied emissions in building construction (Döbbeling-Hildebrandt et al., 2024; Liu & Loo, 2026)<br>National embodied carbon accounting framework not yet fully established (IA, 2024)<br>Limited SME compliance capacity (Gómez-Garza et al., 2024) |
| Potential benefits | Enhanced visibility of whole-of-life carbon emissions (Buyle et al., 2013) | Associated emissions reductions in energy and heavy industry contexts (Döbbeling-Hildebrandt et al., 2024) |

| | LCA | ETS |
|---|---|---|
| | Supports hotspot identification, option comparison, and carbon-informed decision-making (Abd Rashid & Yusoff, 2015; Dossche et al., 2017) | Encourages low-carbon innovation in upstream industries (Calel & Dechezleprêtre, 2016) |

## 3.3 INSTITUTIONAL AND STAKEHOLDER CONDITIONS INFLUENCING ADOPTION

Table 2 summarises institutional and stakeholder factors influencing the adoption of an LCA-based ETS. Beyond the barriers and benefits associated with the tools themselves, adoption is also shaped by the institutional environment in which organisations operate and by organisational relationships with multiple stakeholders. Institutional theory provides a useful starting point for this external dimension of analysis. Drawing on the logic of institutional isomorphism proposed by DiMaggio and Powell (1983), this study groups external pressures into three forms. Coercive pressure arises from policy and compliance requirements, as well as government incentive schemes that create obligations or economic signals for organisations (DiMaggio & Powell, 1983; Scott, 2014). For example, the Building Information Modelling (BIM) Level 2 mandate in the United Kingdom strengthened digital information management in public projects. This created more favourable conditions for data coordination relevant to LCA (HM Government, 2012). Similarly, recent Australian policy and procurement developments suggest that embodied carbon measurement and transparency are beginning to enter formal implementation discussions (IA, 2024). Normative pressure is reflected in industry standards, green certification, and ESG expectations, as well as competitive market dynamics that collectively shape carbon management practices (Green Building Council of Australia [GBCA], 2025; Kazemi et al., 2023). Mimetic pressure refers to the tendency of firms to adopt carbon mitigation strategies modelled on leading organisations in order to minimise uncertainties and reduce the risks associated with trial and error (DiMaggio & Powell, 1983). Teece et al. (1997) suggest that organisations often look to established leaders when responding to strategic uncertainty, and this logic is also reflected in emerging low-carbon initiatives in the construction sector (Singapore Green Building Council, 2023). These forms of pressure provide part of the external context in which organisations interpret implementation barriers, potential benefits, and the practical relevance of a new governance mechanism. In the Australian context, however, the institutional environment is related to both the existence and stability of external pressures. Where policy signals are inconsistent, institutional pressure may not strengthen adoption confidence and may instead weaken it (Scott, 2014).

*Table 2: Institutional and stakeholder factors influencing the adoption of an LCA-based ETS*

| Factor category | Specific factors | Representative references |
|---|---|---|
| Coercive pressure | • Policy and compliance requirements<br>• BIM-related data coordination<br>• Embodied carbon policy attention<br>• Government incentive schemes | DiMaggio & Powell, 1983; HM Government, 2012; IA, 2024; Scott, 2014 |
| Normative pressure | • Industry standards | GBCA, 2025; Kazemi et al., 2023 |

| Factor category | Specific factors | Representative references |
|---|---|---|
| | • Green certification<br>• ESG expectations<br>• Competitive market dynamics | |
| Mimetic pressure | • Imitation under uncertainty<br>• Adoption of carbon mitigation strategies modelled on leading organisations | DiMaggio & Powell, 1983; Singapore Green Building Council, 2023; Teece et al., 1997 |
| Stakeholder-related conditions | • Divergent stakeholder interests<br>• Cost and risk concerns<br>• SME resource and compliance constraints | Freeman, 1984; Gómez-Garza et al., 2024; IA, 2021; Mitchell et al., 1997 |
| Carbon mitigation perception | • Managerial carbon awareness<br>• Perceived relevance of proactive decarbonisation | Jiang et al., 2023; Sadri et al., 2022 |

Additionally, adoption of a new governance mechanism in the construction sector is not an isolated organisational decision. Projects usually involve developers, contractors, design consultants, clients, and supply chain actors whose interests and responsibilities are not always aligned (Freeman, 1984; Mitchell et al., 1997). Evidence from Australia suggests that stakeholder responses to decarbonisation are not uniform. Developers may support carbon reduction in principle, while remaining concerned about additional cost exposure, delivery risk, and the practical implications of implementation (IA, 2021). Contractors, on the other hand, may take a more cautious position when profit margins are tight and project risk increases (IA, 2021). SMEs may also face additional difficulties due to limited trained personnel, weak data foundations, and restricted organisational resources, which make carbon accounting and related compliance more difficult to absorb (Gómez-Garza et al., 2024). Stakeholders' carbon mitigation perception also appears relevant to adoption judgement. Jiang et al. (2023) reported that stronger managerial awareness of carbon issues was associated with a greater willingness to pursue proactive decarbonisation rather than minimum compliance, consistent with Sadri et al. (2022). From this perspective, stakeholder-related conditions may play a more immediate role in shaping adoption judgement than external pressures alone. They may also influence whether a new governance mechanism is seen as relevant to organisational responsibility, competitiveness, or project delivery.

While institutional pressures and stakeholder conditions may be important, this study argues that they do not automatically lead to adoption behaviour (Ajzen, 1991; Davis, 1989). Their influence is likely to depend on whether external pressures enter routine project logic and come to be understood as relevant to compliance, competitiveness, or risk management (Räihä et al., 2024; Venkatesh & Davis, 2000). This prepares the ground for the next part of the review, which focuses on how such stakeholder judgements are formed.

### 3.4 BEHAVIOURAL INTENTION AND THE APPLICABILITY OF TAM

Even if institutional pressure is present, adoption still depends on how stakeholders interpret the value, feasibility, and organisational implications of a given mechanism (Davis, 1989; Räihä et al., 2024). Existing studies on carbon pricing often assume that firms will respond rationally to price signals, and pay less attention to the subjective judgements and implementation concerns of actors in the construction sector (Räihä et al., 2024). For construction-related organisations, an LCA-based ETS may have implications for accounting procedures, procurement arrangements, and contractual responsibilities (Cludius et al., 2020; Liu & Loo, 2026). Adoption judgement may therefore involve an assessment of expected costs, perceived value, and practical difficulty, rather than a direct response to external pressure alone (Davis, 1989; Venkatesh & Davis, 2000). From this perspective, adoption is not only a matter of institutional context, but also of behavioural judgement (Ajzen, 1991; Davis, 1989).

The TAM provides a useful analytical logic for this part of the discussion (Davis, 1989). In the context of this study, perceived usefulness (PU) refers to whether stakeholders believe that an LCA-based ETS can improve carbon transparency, compliance readiness, or organisational competitiveness. Perceived ease of use (PEOU) is interpreted here in relation to implementation practicality in the construction sector, including the extent to which the mechanism is manageable in terms of accounting, coordination, and execution. Behavioural intention (BI) refers to the willingness to adopt, support, or engage with the mechanism. Given the absence of a mandatory ETS in the Australian construction sector, BI is treated in this study as a practical indicator of adoption readiness (Ajzen, 1991; Venkatesh & Davis, 2000). At the same time, TAM on its own is not sufficient to explain a sector shaped by multi-actor coordination and policy uncertainty. For this reason, TAM is used here together with institutional and stakeholder perspectives rather than as a standalone explanation. Together, these three groups of factors form the basis for the conceptual framework presented in the next section.

## 4. THE PROPOSED CONCEPTUAL FRAMEWORK

### 4.1 FRAMEWORK DIAGRAM AND OVERALL INTERPRETATION

Figure 1 presents the conceptual framework proposed in this study.

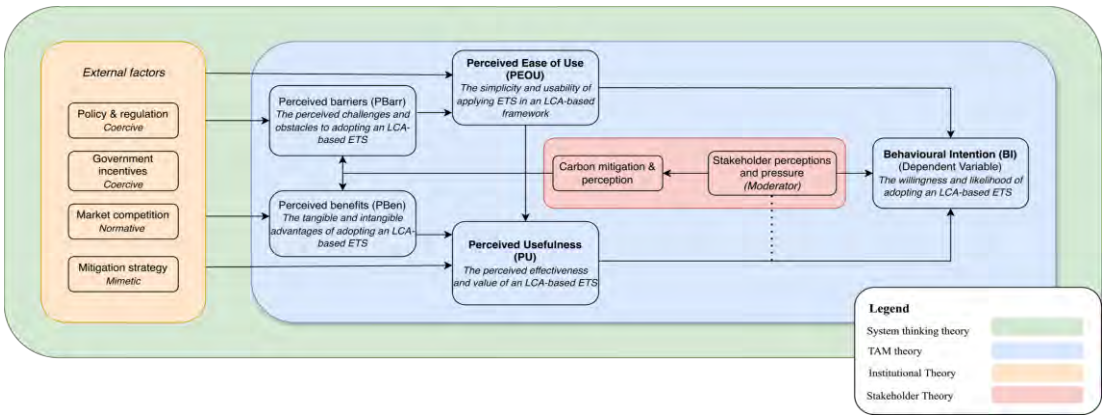



*Figure 1: The conceptual framework of stakeholder adoption intention towards an LCA-based ETS*

The framework integrates four theoretical perspectives, which inform different parts of the overall structure and their relationships. Systems thinking provides the overall analytical boundary. Institutional theory frames the external environment shaping the adoption context. The TAM represents the central cognitive-to-behavioural pathway. Stakeholder theory reflects the relational conditions that influence how adoption judgement develops. A colour legend is included in the figure to indicate the theoretical basis of each part of the framework.

The framework suggests that the adoption of an LCA-based ETS is not driven by technical performance or policy direction alone. Rather, it can be understood as a progressive process shaped by system conditions, structured by the institutional environment, mediated through cognitive appraisal, and influenced by stakeholder-related conditions. By visually linking each component to its underpinning theory, the framework clarifies how the four theoretical perspectives are integrated into a single conceptual structure rather than treated as separate explanatory elements. The framework will be further examined and refined through empirical research in the next stage of the study.

## 4.2 THEORETICAL FOUNDATION AND DIVISION OF ROLES

This study integrates four theoretical perspectives to support the proposed conceptual framework explaining stakeholder adoption intention towards an LCA-based ETS in the Australian construction sector. These theories are not presented as a parallel list. Instead, each is used to address a different dimension of the adoption problem. Systems thinking provides the overall analytical boundary. As discussed in sub-section 3.1, the adoption of an LCA-based ETS involves interactions across project stages, stakeholder groups, and levels of decision-making, and cannot be reduced to a technical assessment of a single tool. From this perspective, LCA and ETS are understood as interconnected parts of the same system rather than as separate objects of analysis (Checkland, 1981; Meadows, 2008). Systems thinking is therefore not introduced in the framework as a specific explanatory variable, but as the broader boundary within which the other three perspectives are applied.

Institutional theory is used to explain how the external institutional environment shapes the conditions under which adoption is considered. As reviewed in sub-section 3.3, coercive, normative, and mimetic pressures together form part of the external context in which organisations assess an LCA-based ETS. As argued in sub-section 3.3, these pressures do not determine adoption directly. Rather, they influence how organisations interpret the barriers, expectations, and possible value associated with the mechanism (DiMaggio & Powell, 1983; Scott, 2014).

TAM provides the main behavioural pathway in the framework. As noted in sub-section 0, adoption ultimately depends on how stakeholders interpret the value and practicality of the mechanism. In this study, TAM is used to explain how cognitive appraisal may be translated into adoption intention (Davis, 1989; Venkatesh & Davis, 2000).

Lastly, stakeholder theory adds a relational and contextual dimension to this process. Adoption of a mechanism in the construction sector is not simply an internal organisational judgement, but is shaped by ongoing interaction with clients, investors, governments, industry networks, and supply chain actors. Stakeholder theory is therefore used to explain how these external expectations and relationships may affect

organisational judgement and its translation into adoption intention (Freeman, 1984; Mitchell et al., 1997). Taken together, systems thinking defines the problem boundary, institutional theory explains the external context, TAM provides the cognitive-to-behavioural pathway, and stakeholder theory adds relational and contextual influence. This combination allows the framework to address the technical, institutional, and behavioural dimensions involved in the adoption of an LCA-based ETS.

It is important to note that these four perspectives are not simply combined as a parallel list of explanatory lenses. Their integration provides two specific analytical insights for interpreting LCA-based ETS adoption in the construction sector. First, institutional theory and TAM interact in a way that goes beyond a simple antecedent-outcome relationship. In contexts where institutional pressure is weak or absent, perceived usefulness may be understood primarily in terms of voluntary benefits such as improved sustainability performance or corporate reputation. However, under strong coercive pressure, the meaning of perceived usefulness itself may shift towards compliance readiness, risk reduction, and access to future carbon markets (DiMaggio & Powell, 1983; Venkatesh & Davis, 2000). In other words, institutional pressure does not merely increase the level of perceived usefulness; it may redefine what usefulness means in the adoption context. Second, stakeholder theory qualifies the assumptions of TAM in an important way. TAM assumes that adoption intention is primarily shaped by an individual or organisational actor's cognitive evaluation of usefulness and ease of use (Davis, 1989; Venkatesh & Davis, 2000). However, in the construction sector, adoption decisions are often distributed across multiple parties with unequal decision-making authority. Clients, principal contractors, and regulatory bodies may hold disproportionate power in determining whether an LCA-based ETS is adopted at the project level, while subcontractors and smaller firms may adopt primarily in response to contractual obligations rather than their own assessment of usefulness (Freeman, 1984; Mitchell et al., 1997). This suggests that TAM needs to be contextualised by stakeholder theory, because adoption intention in the construction sector may be shaped not only by cognitive evaluation, but also by power relations and project-based dependencies.

## 4.3 CORE CONSTRUCTS AND LOGICAL RELATIONSHIPS

Based on the three groups of factors identified in the preceding literature review, the proposed conceptual framework consists of several main constructs and their logical relationships. The framework begins with external inputs from the institutional environment. Coercive, normative, and mimetic pressures are treated as external factors that enter the framework from the left-hand side. These factors are not assumed to generate adoption intention directly. Instead, they influence how organisations interpret perceived barriers (PBarr) and perceived benefits (PBEn), and may also shape later judgements about perceived usefulness (PU) and perceived ease of use (PEOU). In this sense, the institutional environment affects how organisations understand an LCA-based ETS, rather than directly determining whether it will be adopted.

At the centre of the framework is the cognitive-to-behavioural pathway derived from TAM. As discussed in the previous sections, PBarr and PBEn provide a more immediate basis for pre-adoption judgement. PBarr refers to expected implementation difficulties, including issues such as fragmented data, methodological inconsistency, limited economic incentives, and capability constraints. PBEn refers to the expected strategic and operational value of the mechanism, including improved carbon transparency, stronger

compliance readiness, and possible gains in competitiveness. These two forms of evaluation are not treated as adoption intention in themselves. Rather, they are expected to shape how organisations judge the usefulness and practical manageability of the mechanism through PU and PEOU. At the same time, institutional pressures may also shape PU and PEOU more directly, particularly where regulatory expectations or industry norms influence how the practicality or strategic value of the mechanism is understood.

The framework also incorporates stakeholder-related constructs as contextual influences on this central pathway. Carbon mitigation perception (CMP) reflects the extent to which organisations recognise climate responsibility and the importance of carbon management. This may affect how barriers and benefits are interpreted and, in turn, how the value of the mechanism is judged. At the same time, stakeholder pressure (SP) represents the relational conditions surrounding adoption. In this framework, SP refers not only to the influence of external expectations and relationship networks, but is also expected to influence the extent to which positive judgements translate into adoption intention. Where low-carbon expectations from clients, investors, governments, or industry communities are more explicit, positive views of usefulness may be more likely to develop into adoption intention. Where such external pressure is weaker, organisations may still recognise potential value but delay action.

Behavioural intention (BI) represents the outcome variable in the framework. It is used here as the main outcome, representing an organisation's willingness to adopt, support, or engage with an LCA-based ETS. In the Australian context, where no mandatory ETS currently applies to the construction sector, BI is treated as a more suitable indicator of adoption readiness than actual behaviour. From this perspective, the adoption of an LCA-based ETS is not understood as an immediate response to a single policy or tool, but as a progressive process shaped by external inputs, cognitive appraisal, and stakeholder-related influences.

## 5. CONCLUSIONS

Through a targeted literature review, this paper proposes a conceptual framework for understanding the factors influencing stakeholder adoption of an LCA-based ETS in the Australian construction sector. The framework is underpinned by four theoretical perspectives, namely: systems thinking, institutional theory, TAM, and stakeholder theory. It brings the influencing factors together into a structure linking external context, cognitive appraisal, and stakeholder-related influences, suggesting that adoption is better understood as a progressive process rather than as an immediate response to a single tool or policy.

At the theoretical level, the contribution of this paper is not simply the use of multiple theories, but the way these theories are connected to explain how macro-level institutional pressures are translated into stakeholder-level adoption intention in a specific sectoral context. In particular, the framework reveals that institutional pressure may not only influence but redefine what stakeholders perceive as useful, and that stakeholder power asymmetries may limit the explanatory reach of TAM when applied to multi-actor project delivery settings. At the practical level, the framework suggests that promoting the application of an LCA-based ETS in the construction sector is unlikely to depend on carbon accounting accuracy or pricing design alone. It may also require attention to institutional stability, industry capability, and stakeholder coordination. This is

particularly relevant in the Australian context, where no mandatory ETS currently applies to the construction sector. In such a setting, questions of feasibility, institutional confidence, and implementation readiness become especially important to stakeholder adoption. However, the proposed framework remains conceptual and has not yet been empirically validated. Its contribution at this stage lies in providing a theoretically grounded structure for understanding the multi-level factors that may influence LCA-based ETS adoption. Future research should test and refine the proposed relationships through questionnaire-based empirical work within the Australian construction sector, with particular attention to whether the hypothesised interactions between institutional pressure, stakeholder power, and cognitive appraisal hold across different organisational types and project contexts.

# 6. REFERENCES

Abd Rashid, A. F., & Yusoff, S. (2015). A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews, 45*, 244–248. https://doi.org/10.1016/j.rser.2015.01.043

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Aldy, J. E., & Stavins, R. N. (2012). The promise and problems of pricing carbon. *The Journal of Environment & Development, 21*(2), 152–180. https://doi.org/10.1177/1070496512442508

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. *Renewable and Sustainable Energy Reviews, 26*, 379–388. https://doi.org/10.1016/j.rser.2013.05.001

Calel, R., & Dechezleprêtre, A. (2016). Environmental policy and directed technological change: Evidence from the European carbon market. *The Review of Economics and Statistics, 98*(1), 173–191. https://doi.org/10.1162/REST_a_00470

Checkland, P. (1981). *Systems thinking, systems practice*. John Wiley & Sons.

Chen, Y., Jiang, P., Dong, W., & Huang, B. (2015). Analysis on the carbon trading approach in promoting sustainable buildings in China. *Renewable Energy, 84*, 130–137. https://doi.org/10.1016/j.renene.2015.06.062

Clean Energy Regulator. (2026, April). *Safeguard Mechanism*. Clean Energy Regulator. https://cer.gov.au/schemes/safeguard-mechanism

Cludius, J., de Bruyn, S., Schumacher, K., & Vergeer, R. (2020). Ex-post investigation of cost pass-through in the EU ETS: An analysis for six industry sectors. *Energy Economics, 91*, 104883. https://doi.org/10.1016/j.eneco.2020.104883

Commonwealth of Australia. (2014). *Clean Energy Legislation (Carbon Tax Repeal) Act 2014* (Act No. 83 of 2014). Federal Register of Legislation. https://www.legislation.gov.au/C2014A00083/details

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly, 13*(3), 319–340. https://doi.org/10.2307/249008

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

Department of Climate Change, Energy, the Environment and Water. (2026). *Buildings*. Australian Government. https://www.dcceew.gov.au/energy/energy-efficiency/buildings

DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review, 48*(2), 147–160. https://doi.org/10.2307/2095101

Döbbeling-Hildebrandt, N., Miersch, K., Khanna, T. M., Bachelet, M., Bruns, S. B., Callaghan, M., Edenhofer, O., Flachsland, C., Forster, P. M., Kalkuhl, M., Koch, N., Lamb, W. F., Ohlendorf, N., Steckel, J. C., & Minx, J. C. (2024). Systematic review and meta-analysis of ex-post evaluations on the effectiveness of carbon pricing. *Nature Communications, 15*, 4147. https://doi.org/10.1038/s41467-024-48512-w

Dossche, C., Boel, V., & De Corte, W. (2017). Use of life cycle assessments in the construction sector: Critical review. *Procedia Engineering, 171*, 302–311. https://doi.org/10.1016/j.proeng.2017.01.338

Du, Q., Ma, M., Lu, C., Wang, X., & Bai, L. (2025). Assessing the impact of emission trading scheme and carbon tax in the building sector: An embodied carbon perspective. *Environmental Impact Assessment Review, 111*, 107732. https://doi.org/10.1016/j.eiar.2024.107732

Ellerman, A. D., Convery, F. J., & de Perthuis, C. (2010). *Pricing carbon: The European Union emissions trading scheme*. Cambridge University Press. https://doi.org/10.1017/CBO9781139162104

Feng, H., Zhao, J., Zhang, H., Zhu, S., Li, D., & Thurairajah, N. (2022). Uncertainties in whole-building life cycle assessment: A systematic review. *Journal of Building Engineering, 50*, 104191. https://doi.org/10.1016/j.jobe.2022.104191

Freeman, R. E. (1984). *Strategic management: A stakeholder approach*. Pitman. https://books.google.lk/books/about/Strategic_Management.html?hl=it&id=NpmA_qEiOpkC&redir_esc=y

Gómez-Garza, R., Güereca, L. P., Padilla-Rivera, A., & Aguilar Ibarra, A. (2026). Barriers and enablers of life cycle assessment in small and medium enterprises: A systematic review. *Environment, Development and Sustainability, 28*, 16925–16950. https://doi.org/10.1007/s10668-024-05622-1

Green Building Council of Australia. (2025). *Green Star Buildings v1.1*. Green Building Council of Australia. https://www.gbca.au/green-star-buildings-v1-1

HM Government. (2012). *Building information modelling*. GOV.UK. https://www.gov.uk/government/publications/building-information-modelling

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings: A review of current trends. *Energy and Buildings, 66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Infrastructure Australia. (2021). *A national study of infrastructure risk*. Australian Government. https://www.infrastructureaustralia.gov.au/sites/default/files/2021-10/A%20National%20Study%20of%20Infrastructure%20Risk%20211013a.pdf

Infrastructure Australia. (2024). *Embodied carbon projections for Australian infrastructure and buildings*. Australian Government. https://www.infrastructureaustralia.gov.au/reports/embodied-carbon-projections-australian-infrastructure-and-buildings

International Carbon Action Partnership. (2024). *Emissions trading worldwide: 2024 ICAP status report*. International Carbon Action Partnership. https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-2024-icap-status-report

International Organization for Standardization. (2006a). *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. International Organization for Standardization. https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006b). *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*. International Organization for Standardization. https://www.iso.org/standard/38498.html

Jackson, M. C. (2003). *Systems thinking: Creative holism for managers*. John Wiley & Sons. https://www.researchgate.net/publication/200026620_Systems_Thinking_Creative_Holism_for_Managers

Jiang, J., He, Z., & Ke, C. (2023). Construction contractors' carbon emissions reduction intention: A study based on structural equation model. *Sustainability, 15*(14), 10894. https://doi.org/10.3390/su151410894

Kazemi, M. Z., Elamer, A. A., Theodosopoulos, G., & Khatib, S. F. A. (2023). Reinvigorating research on sustainability reporting in the construction industry: A systematic review and future research agenda. *Journal of Business Research, 167*, 114145. https://doi.org/10.1016/j.jbusres.2023.114145

Konradsen, F., Hansen, K. S. H., Ghose, A., & Pizzol, M. (2024). Same product, different score: How methodological differences affect EPD results. *The International Journal of Life Cycle Assessment, 29*(2), 291–307. https://doi.org/10.1007/s11367-023-02246-x

Liu, Y., & Loo, B. P. Y. (2026). Carbon trading in the construction industry: A systematic review and a vigorous impact assessment framework to facilitate implementation. *Environmental Impact Assessment Review, 118*, 108271. https://doi.org/10.1016/j.eiar.2025.108271

Marsh, E., Allen, S., & Hattam, L. (2023). Tackling uncertainty in life cycle assessments for the built environment: A review. *Building and Environment, 231*, 109941. https://doi.org/10.1016/j.buildenv.2022.109941

Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing. https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/climate-communications/psychology-amp-behavior/Meadows-2008.-Thinking-in-Systems.pdf

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. *Academy of Management Review, 22*(4), 853–886. https://doi.org/10.2307/259247

Pomponi, F., & Moncaster, A. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews, 81*, 2431–2442. https://doi.org/10.1016/j.rser.2017.06.049

Räihä, J., Clarke, S., Sankelo, P., Ruokamo, E., & Kangas, H.-L. (2024). The importance of organization type: Construction sector perceptions of low-carbon policies and measures. *Environmental Science & Policy, 151*, 103602. https://doi.org/10.1016/j.envsci.2023.103602

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings: The hidden challenge for effective climate change mitigation. *Applied Energy, 258*, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Sadri, H., Pourbagheri, P., & Yitmen, I. (2022). Towards the implications of Boverket's climate declaration act for sustainability indices in the Swedish construction industry. *Building and Environment, 207*, 108446. https://doi.org/10.1016/j.buildenv.2021.108446

Scott, W. R. (2014). *Institutions and organizations: Ideas, interests, and identities* (4th ed.). SAGE. http://doi.org/10.22439/cjas.v32i2.4764

Singapore Green Building Council. (2023). *Singapore Building Carbon Calculator (SBCC)*. Singapore Green Building Council. https://www.sgbc.sg/sg-building-carbon-calculator/

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal, 18*(7), 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

United Nations Environment Programme & Global Alliance for Buildings and Construction. (2024). *Global status report for buildings and construction: Beyond foundations*. United Nations Environment Programme. https://globalabc.org/sites/default/files/2024 11/global_status_report_buildings_construction_2023.pdf

Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *Management Science, 46*(2), 186–204. https://doi.org/10.1287/mnsc.46.2.186.11926

Perera, B.K.C., Jayasena, H.S. and Siriwardena, M., 2026. A conceptual hybrid framework for CDE configuration: Balancing ISO 19650 rigidity with agile flexibility. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 44-57. DOI: https://doi.org/10.31705/WCS.2026.4. Available from: https://ciobwcs.com/papers/

# A CONCEPTUAL HYBRID FRAMEWORK FOR CDE CONFIGURATION: BALANCING ISO 19650 RIGIDITY WITH AGILE FLEXIBILITY

**B.K.C. Perera[1], H.S. Jayasena[2] and M. Siriwardena[3]**

## *ABSTRACT*

*While Building Information Modelling (BIM) workflows rely heavily on the Common Data Environment (CDE) for centralized information management, integrating rigid governance standards into turbulent construction phases creates significant operational friction. Specifically, the ISO 19650 standard mandates a highly structured BIM Execution Plan (BEP) and predefined data protocols. However, empirical realities within the Architecture, Engineering, and Construction (AEC) sector frequently expose ad-hoc, unmanaged workarounds as practitioners attempt to bypass static systems to maintain workflow speed. To resolve this paradox, this study proposes a novel Conceptual Hybrid Framework that balances rigid compliance with operational flexibility. Prioritizing theoretical contribution, this paper introduces two primary mechanisms to eliminate system friction: a "Two-Tier BEP" structure and the elevation of the Information Manager to an "ISO 19650 Gatekeeper." The Two-Tier BEP divides CDE configuration into a static "Core BEP" (The Rigid Backbone) for legal immutability and an iterative "Dynamic Appendix" (The Flexible Muscle) managed via Agile Project Management (APM) sprints. Derived via deductive document analysis and reinforced by technical desktop verification, this dual-layered approach ensures agile adaptability without compromising federated model integrity. Ultimately, this framework offers a structured pathway to substitute unmanaged chaos with Managed Agility. Future empirical studies will evaluate the practical validity of this framework through industry expert interviews.*

***Keywords:*** *Agile Project Management, Building Information Modelling, Common Data Environment, Hybrid Framework.*

## 1. INTRODUCTION

Building Information Modelling (BIM) serves as a digital catalyst for optimizing collaboration and asset data integration within the Architecture, Engineering, and Construction (AEC) sector (Biswas, Sim and Lau, 2024). In contemporary project delivery, BIM has transitioned from an optional technical enhancement to an

[1] Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, kavinya.p@sliit.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, Suranga@uom.lk
[3] Senior Lecturer, School of Civil Engineering and Built Environment, Liverpool John Moores University, United Kingdom, M.L.Siriwardena@ljmu.ac.uk

indispensable operational standard across construction workflows (Datta et al., 2023; Daoud et al., 2025). The realization of these sociotechnical benefits is highly contingent upon the deployment of a centralized Common Data Environment (CDE). As an integrated digital platform, the CDE dissolves traditional data silos by providing an immutable, synchronized node where multi-disciplinary project teams can access data concurrently, directly mitigating the fragmentation that historically penalizes industry productivity (Dolla, Venkatachalam and Kumar, 2024).

To institutionalize data governance and streamline BIM adoption across global supply chains, international regulatory frameworks have been established, most notably the ISO 19650 standard series (Gonzalez et al., 2024). The ISO 19650-1 and ISO 19650-2 guidelines advocate for a highly structured information management process, mandating that comprehensive information requirements, data protocols, and a definitive BIM Execution Plan (BEP) be front-loaded and frozen at the earliest stages of the project lifecycle.

However, empirical realities frequently diverge from these linear, perfectly fine-tuned expectations. The inherently turbulent, unpredictable nature of physical construction projects forces project participants to operate within highly fluid, localized information streams (Dolla et al., 2024). When confronted with the friction of rigid CDE access protocols, asymmetric team BIM maturities, and compressed design schedules, practitioners frequently bypass the authorized CDE to maintain operational speed, inadvertently creating unmanaged, ad-hoc information workarounds that dismantle the platform's status as the 'Single Source of Truth' (Malla et al., 2024; Radl and Kaiser, 2019).

While Agile Project Management (APM) principles have emerged as a viable alternative for navigating volatility through iterative adaptation, its direct application to CDE governance introduces a contractual paradox: unbridled flexibility threatens the legal accountability and standard compliance demanded by ISO 19650.

Current AEC literature extensively details the systemic friction of implementing ISO 19650 standards (Radl and Kaiser, 2019; Mesároš et al., 2022); however, a critical research gap remains: the lack of a concrete operational mechanism that balances contractual data rigidity with localized workflow agility. Existing frameworks treat the CDE as a monolithic repository with static architecture, failing to delineate which technical parameters must remain structurally immutable and which can be adapted dynamically without inducing system failure.

To address this gap, the primary aim of this study is to develop a conceptual Hybrid Framework for technical CDE configuration. This framework systematically splits platform variables into a fixed compliance layer governed by ISO 19650 guidelines and an iterative adaptive layer managed via Agile principles, thereby replacing unmanaged ad-hoc chaos with disciplined, managed flexibility.

## 2. LITERATURE REVIEW: INFORMATION MANAGEMENT FRICTION

This section presents the information friction in real-world practices when working in CDE. Thereby, it clearly demonstrates the triggering point where BIM team demands the most, as a result of construction workflow dynamics.

## 2.1 THE STATIC CDE ASSUMPTION

Much of the current literature and standard guidelines approach BIM implementation with the assumption of a smooth, linear transition of information. According to Jaskula et al. (2025) and Lestari, Purwanto and Saputra (2022) CDE is often treated as a static digital platform that is perfectly established and configured at the very beginning of the project. However, the fragile and turbulent project environment creates significant friction when applying these rigid, pre-defined workflows to real-world construction phases.

## 2.2 REAL-WORLD FRICTION POINTS

In practice, managing the CDE reveals an ad hoc nature that is highly controversial and contradicts the perfectly fine-tuned scenarios suggested by linear frameworks (Kaya and Özener, 2025). Several key friction points drive this chaos. First, construction schedules rarely follow perfect sequences, causing parallel executions where the CDE must manage multiple simultaneous workflow "mini-lifecycles." Second, standard workflows assume a smooth, one-way transition, yet real-world clash detections create rapid feedback and rejection loops; without system flexibility, practitioners bypass the CDE entirely (e.g., sending files via email), destroying the "Single Source of Truth" (Radl and Kaiser, 2019). Furthermore, real projects rely on progressive assurance rather than massive handovers, requiring continuous reconfiguration of suitability codes to indicate partial data maturity. Finally, projects frequently suffer a maturity reality gap, where rigid protocols break down across mixed-maturity teams, forcing manual interventions to uplift non-compliant data (Mesároš et al., 2022). These friction points highlight the necessity for adaptive gateways to execute workflows, rather than rigidly adhering to an initial plan.

## 2.3 THE AGILE ALTERNATIVE

Because of the above-mentioned friction points, there is a growing interest in the applicability of a flexible project management approach. APM represents a pragmatic shift from the traditional Waterfall approach. Originally introduced by the software industry due to its drawbacks in reacting to rapid technological evolutions, APM utilises structured agility and iterative development.

Instead of treating these practical friction points and iterative loops as project failures, APM recognises them as normal, expected changing requirements (Hohl et al., 2018; Owen and Koskela, 2006). Therefore, this paper will borrow APM principles to systematically manage the CDE, transforming chaotic ad-hoc practices into a structured, flexible workflow.

## 2.4 HYBRID PROJECT MANAGEMENT APPROACHES

To overcome the rigidity of traditional architectures while preventing the chaotic drift of unmanaged flexibility, modern organizational theory has shifted toward Hybrid Project Management (HPM) as a deliberate middle path (Reiff & Schlegel, 2022; Adaba, 2026; Krupa & Hájek, 2024). HPM represents a spectrum of design choices that systematically integrate plan-driven governance with adaptive execution mechanics (Silvius-Zuchi & Silvius, 2026).

### 2.4.1 Structural Archetypes and Customization Logic

While the project management literature identifies several distinct archetypal hybrid configurations such as Water-Scrum-Fall or the Hybrid V-Model (Reiff & Schlegel, 2022) this study aligns structurally with the Agile-Stage-Gate archetype. This model embeds short, time-boxed agile sprints inside structural stage-gate review milestones to achieve speed and tactical adaptivity within fixed administrative loops (Cooper & Sommer, 2018; Reiff & Schlegel, 2022). Operationally, applying this to a CDE requires a deliberate customization logic. Rather than segregating different methodologies into distinct, linear lifecycle stages ("Hybrid-by-Phases"), this framework necessitates a "Hybrid-by-Methods" approach (Mirzaei et al., 2025). This involves simultaneously blending contrasting agile and plan-driven practices within the exact same lifecycle phase to achieve continuous value optimization across complex socio-technical boundaries (Mirzaei et al., 2025).

### 2.4.2 Socio-Technical Hybridization Mechanisms

At the micro-operational layer, hybridization is an active process of socio-technical negotiation rather than a static design choice (Adaba, 2026). Grounded theory conceptualizations by Adaba (2026) establish that HPM stability is sustained through specific operational mechanisms including:

- Structural Anchoring: Utilizing formal governance frameworks to provide stability, auditability, and legal legitimacy inside compliance-heavy enterprise environments.
- Boundary Work and Role Hybridization: Deploying dedicated cross-functional translator roles who internalize dual accountability, seamlessly bridging the divide between control-oriented governance mandates and delivery-focused adaptive loops.

### 2.4.3 Enterprise Scaling vs. Project-Level Hybridity

While the broader software engineering discipline relies on comprehensive models like the Scaled Agile Framework (SAFe) for enterprise-level scaling and portfolio governance (Krupa & Hájek, 2024), direct application to CDE technical configuration presents a scope misalignment. The friction experienced in BIM implementation under ISO 19650 is rarely a failure of enterprise portfolio alignment; rather, it is a project-level, micro-operational conflict between static compliance gateways and dynamic task execution (Adaba, 2026). Therefore, the framework proposed in this study deliberately deviates from enterprise-scaled models, focusing instead on project-level socio-technical hybridity that governs the immediate interface between the Information Manager and the task teams.

## 3. METHODOLOGY

To systematically resolve the operational friction between standard compliance and site-level agility, this study adopts a qualitative deductive approach focused on conceptual theory-building, reinforced by an initial technical desktop verification. The research design is executed in three sequential stages: (1) exploratory identification of real-world CDE friction points via literature; (2) deductive document analysis of ISO 19650-1 and ISO 19650-2 to establish a Traceability Matrix; and (3) a desktop verification against active enterprise platforms to confirm baseline viability.

### 3.1 METHODOLOGICAL APPROACH: DEDUCTIVE DOCUMENT ANALYSIS

To address the chaos in developing CDEs and to conceptualise a flexible workflow, this study adopted a Deductive Document Analysis approach to derive the technical variables and construct the theoretical Hybrid Framework. This current paper focuses on establishing the necessary theoretical foundation for hybrid CDE configuration as a comprehensive, standalone conceptual theory-building study.

Initially, an exploratory literature search was conducted to identify and compile practical barriers and friction points that hinder the effective use of CDEs in real-world construction environments. The primary data source for this desk study was the ISO 19650 standard series (specifically Part 1 and Part 2), as it represents the globally recognised baseline for BIM implementation. Rather than arbitrarily selecting CDE features, the standard was analysed to extract mandatory information management mechanisms and cross-referenced with the friction points identified in the literature.

### 3.2 DERIVING THE VARIABLES (THE TRACEABILITY MATRIX)

To scientifically identify the functional requirements of the CDE product, a "Traceability Matrix" was developed. This matrix establishes a logical chain of evidence between a real-world project problem and the technical software setting required to manage it. The derivation process was executed through document-based manual coding, facilitated by Microsoft Word macros, to systematically map the identified friction points against specific normative clauses in ISO 19650. The derivation followed a three-step logic:

I. The Theoretical Need (The Problem): Identifying a functional information friction point from current AEC literature (e.g., teams using incorrect file versions).

II. The Operational Mechanism (The Standard): Identifying the specific clause or mechanism within ISO 19650 designed to govern that problem.

III. The Configuration Item (The Product Feature): Translating the ISO mechanism into a specific, configurable setting within the CDE platform (e.g., configuring automated status code validators).

By applying this traceability method, the study successfully translated broad BIM implementation challenges into a concrete "Provisional Product Backlog" of CDE settings. As illustrated in Table 1, this functional decomposition demonstrates how identified friction points were systematically mapped to ISO 19650 mechanisms and their corresponding CDE configuration items.

Ultimately, by extracting these concrete variables from the turbulent project environment, this derived list of configuration items serves as the essential foundation for categorising the CDE features into the proposed Hybrid Framework.

### 3.3 DEDUCTIVE CATEGORISATION (DEFINING THE HYBRID BOUNDARY)

Once the Provisional Product Backlog of CDE configuration items was derived, a deductive categorisation process was applied to allocate each item into the proposed Hybrid Framework layers. The boundary was defined by evaluating the "System Shock" risk of altering a variable mid-project. This deductive categorisation relied on the authors' expert judgement to evaluate the operational and contractual consequence of altering each variable.

*Table 1: Example of the traceability matrix for CDE variables*

| 1. Scientific Concept (Friction Point) | 2. Operational Mechanism (ISO 19650) | 3. Derived "Configuration Item" (CDE Feature) |
|---|---|---|
| Data Integrity and Trust: Continuous data updates create errors and force reliance on outdated models. (Radl and Kaiser, 2019) | Status Codes: Information containers must have a status code to indicate permitted use (ISO 19650-1). | Status Code Validation Rules: System settings that restrict file movement based on approved codes. |
| Interoperability: Fragmented disciplines struggle to align digital outputs. (Mesároš et al., 2022) | Unique Identification: Every container shall have a unique ID based on an agreed convention (ISO 19650-2). | Naming Convention Enforcers: Automated gateway rules that reject non-compliant file names. |
| Intellectual Property (IP): Firms are reluctant to share information due to liability risks. (Smith, 2014) | CDE States: Distinct separation between Work in Progress (WIP) and Shared states (ISO 19650-1). | Folder Permission Gates: Granular user access controls defining who can view or edit specific states. |

Variables whose alteration would compromise the legal integrity, federated model links, or ISO 19650-2 compliance were classified as the Rigid Backbone (Bucket A). Conversely, variables related to user experience (UX), workflow speed, and task-level access, which require adaptation to the turbulent project environment, were classified as the Flexible Muscle (Bucket B).

### 3.4 SCOPE AND INTENTIONAL BOUNDARIES OF TECHNICAL VERIFICATION

Conceding that the proposed framework is conceptual, a targeted technical desktop verification was conducted within this study to evaluate real-world alignment. This verification is explicitly non-comprehensive; it does not aim to verify all different software configurations or map every edge-case possibility across commercial platform APIs. Instead, its discrete objective is to perform a baseline reality check: observing whether the database-level limitations, schema mutations, and workflow controls of dominant commercial CDE architectures naturally segregate along the framework's hypothesized "Rigid Backbone" (Bucket A) and "Flexible Muscle" (Bucket B) boundaries.

The primary data source for the structural baseline was the ISO 19650 series. To cross-examine these findings against commercial realities, developer documentation, system incident logs, and technical user environments from five leading international CDE ecosystems were synthesized. To maintain source traceability, these documentation nodes are indexed within a compact URL Reference Matrix (Table 2).

## 4. PROPOSED CONCEPTUAL FRAMEWORK: THE HYBRID MODEL

Based on the literature survey to scrutinise the CDE configuration items and derive viable flexibility for each item, the following hybrid framework is explored.

### 4.1 OVERVIEW OF THE HYBRID FRAMEWORK AND AGILE PARADIGM SHIFT

To successfully apply APM to BIM implementation, a fundamental paradigm shift is required. This framework redefines the "Project" strictly as the technical configuration, development, and ongoing management of the CDE platform, treating it as an evolving digital service rather than a static repository established at project inception. Managing the CDE as an Agile product allows shifting requirements to be captured as new items in a "Product Backlog" for iterative refinement, rather than triggering system shocks under a rigid Waterfall approach.

*Table 2: Technical CDE verification URL reference matrix*

| Reference Tag | Source Platform / Ecosystem | Documented Technical Attribute / URL Link |
|---|---|---|
| URL1 | Autodesk Forums | ACC ISO 19650 Naming Standard Schema Migration |
| URL2 | IMAGINiT Technical Logs | ACC Naming Standards Field Enforcement Limits |
| URL3 | Bentley Communities | ProjectWise Database SQL Document Code Constraints |
| URL4 | Bentley Learn Server | ProjectWise Document Code Definition Wizard Workflows |
| URL5 | Procore Support Central | Editing Active In-Flight Workflow Templates |
| URL6 | Autodesk Technical Support | ACC Dynamic Candidate Modifications Mid-Review Engine |
| URL7 | ABC Training Documentation | Autodesk Docs Advanced Custom Attribute Management |
| URL8 | Autodesk University Systems | ACC API Metadata Extensions & Model Properties Indexing |

Consequently, standard Agile roles map directly to the ISO 19650-2 capability matrix (Hohl et al., 2018). The Appointing Party acts as the Product Owner, dictating workflow requirements based on the construction schedule. The Task Teams act as the Users, whose feedback drives iterative updates. Crucially, the Information Manager acts as the Developer and "ISO 19650 Gatekeeper." They filter all workflow requirements through a strict compliance check, rejecting operational updates that threaten the system's legal integrity to protect against ad-hoc chaos.

The findings from the functional decomposition suggest that the CDE cannot be treated as a single, homogenous entity. Instead, this Conceptual Hybrid Framework dictates that technical CDE configuration must be divided into two distinct management layers: a "Rigid Backbone" governed by strict Waterfall compliance (ISO 19650), and a "Flexible Muscle" managed via Agile iterations (Sprints).

To operationalise this visual model, the technical variables previously derived from the Traceability Matrix (Table 1) must be formally categorised. Table 3 presents the Hybrid CDE Configuration Matrix. This matrix serves as the functional blueprint for the Information Manager, explicitly delineating which CDE settings are locked within the legal contract (Bucket A) and which are managed iteratively as an evolving product (Bucket B) to prevent workflow friction.

To conceptualise the proposed solution, Figure 1 illustrates the Conceptual Hybrid Framework for CDE Development. This model visually articulates the paradigm shift from a monolithic, static CDE to a dynamic, dual-layered system. The framework begins by acknowledging the "Real-World Friction" generated within a turbulent project environment. Rather than allowing these friction points to trigger unrecorded workarounds, they are systematically captured as actionable requests within a "Product Backlog."

*Table 3: The hybrid CDE configuration matrix*

| Category | Configuration Item | Framework Allocation | Justification / Agile Function |
|---|---|---|---|
| Identity | Naming Convention (ISO 19650-2) | Bucket A (Rigid Backbone) | Changing field lengths or codes mid-project invalidates existing federated links. Causes severe "System Shock." |
| Governance and Security | State Gateways (WIP > Shared > Published) | Bucket A (Rigid Backbone) | These transitions define the fundamental rules for legal liability and contractual handovers. Cannot be bypassed. |
| Compliance | Immutable Audit Trail & Retention | Bucket A (Rigid Backbone) | System-level logs must be locked to ensure a permanent, legally binding "Single Source of Truth." |
| Workflow | Approval Routing & Timings | Bucket B (Flexible Muscle) | Automated review cycles (e.g., cutting a 14-day review to 3 days) must adapt iteratively to fast-tracked schedules. |
| Access | Granular Folder/File Permissions | Bucket B (Flexible Muscle) | Requires Agile sprints to rapidly grant access to newly onboarded specialist sub-consultants without core disruption. |
| User Experience (UX) | Container-Level Metadata & Tags | Bucket B (Flexible Muscle) | Iteratively adding project-specific attributes (e.g., "Fire Safety" tags) prevents user fatigue and improves searchability. |

Importantly, the model introduces a structural "Gatekeeper" mechanism. Before any CDE configuration is altered, the Information Manager subjects each backlog item to a rigorous "Bucket A Compliance Check." This decision node determines the trajectory of the requested change:

- Strategic Changes (High Risk): If a requirement threatens the legal integrity of the system (e.g., altering ISO 19650 naming conventions), it is routed to the central core, Bucket A: The Rigid Backbone. Here, changes are strictly governed by the Core BEP and require formal, Waterfall-style contract variations.
- Operational Updates (Safe): If the change is deemed legally safe (e.g., adjusting granular permissions or approval workflow timings), it is routed to the outer ring, Bucket B: The Flexible Muscle. Within this layer, the CDE is continuously refined through Agile Sprint Cycles, updating the Dynamic Appendix without disrupting the fixed core.

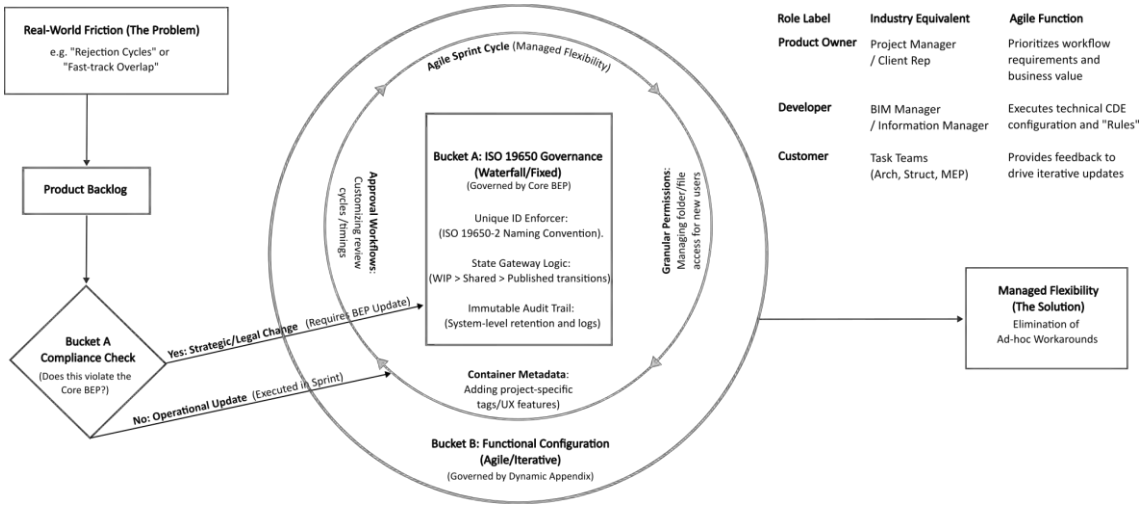



*Figure 1: The hybrid CDE framework showing the rigid backbone and agile muscle layers*

Ultimately, this structured workflow acts as a theoretical engine that processes chaotic project friction and outputs "Managed Flexibility. When mapped against established structural archetypes (Reiff and Schlegel, 2022), this framework functions as a direct project-level operationalization of the Agile-Stage-Gate model (Cooper & Sommer, 2018). It establishes an immutable macro-governance perimeter (Bucket A) to protect data integrity, while embedding short, time-boxed adaptive execution mechanics (Bucket B) to navigate localized workspace friction points. At the micro-operational layer, this dual-allocation represents a structural enactment of Mirzaei et al.'s (2025) "Hybrid-by-Methods" customization logic, simultaneously blending plan-driven standardization and sprint-driven flexibility within the exact same information management phase.

## 4.2 BUCKET A: THE RIGID BACKBONE (ISO 19650 COMPLIANCE)

Bucket A contains the configuration items that establish the project's legal and structural foundation. These are the settings that must be defined at the project's commencement. Altering these parameters mid-project causes a "System Shock" and introduces high risk to data integrity.

- Identity and Naming Conventions: ISO 19650-2 mandates a unique identifier for every information container. The CDE must be configured with file naming rules and mechanisms to rigorously enforce unique file naming. Changing these field lengths or codes mid-project invalidates existing links and federated files, making this a strictly rigid configuration.
- Security, Governance, and State Gateways: The transition of information across CDE states (Work in Progress > Shared > Published) acts as the fundamental rule for legal liability. Consequently, the system must rigidly track meta-data for the CDE state at the information level and utilise a strict version control system. These compliance metadata fields (e.g., S0, S1-S4) cannot be altered on a whim.
- Audit and Retention: To ensure a reliable and legally binding history of the project, system-level configurations for information archival and audit trail capture (recording both state transitions and WIP versions) must be locked. Preventing user modification of these logs ensures a permanent single source of truth.

## 4.3 BUCKET B: THE FLEXIBLE MUSCLE (AGILE / THE "PRODUCT")

Bucket B represents the adaptable components of the CDE product. These are the items that frequently drift into "ad-hoc" territory under traditional frameworks yet should be formally managed and updated via Agile Sprints to serve the evolving needs of the project team.

- Approval Workflows and Automation: While the ultimate legal states are rigid, the journey to get there is dynamic. The CDE's workflow engine, which handles the automation of repetitive workflows, as well as the specific approval and verification routing, must be iteratively adjusted. For instance, an initially configured "14-day review" window might prove too slow for a fast-tracked design phase and requires Agile adjustment.
- Granular Permissions and Access: High-level legal roles are fixed, yet customisable permission controls restricting read and write access at the job, folder, and file level require continuous Agile adaptation. This allows the BIM Manager to quickly grant remote accessibility or external access to a newly onboarded specialist sub-consultant without disrupting the broader system.
- Container-Level Meta-data and UX: As project priorities shift, the project team may request the addition of new meta-data at the information container level (e.g., adding a new "Fire Safety" attribute mid-project). Furthermore, user experience (UX) features such as notifications and alerts, advanced search functionality, and advanced reporting and analytics must be tweaked iteratively in Sprints to prevent user fatigue and improve workflow efficiency.

## 4.4 THE TWO-TIER BEP: RECONCILING AGILE WITH CONTRACTS

A common criticism when applying Agile approaches to BIM implementation is the assumption that continuous iterative changes violate the approved BEP. As discussed earlier, standard guidelines suggest a rigid BEP must be defined at the early stage of the project. However, because updating a formal BEP mid-project requires Appointing Party sign-offs and legal reviews, BIM team members often avoid formal updates. This reluctance forces the team to bypass the system, directly leading to the controversial ad-hoc nature of CDE management.

Hence, to successfully implement the Hybrid Framework without breaching legal boundaries, this study proposes a "Two-Tier BEP" structure. This paradigm shift divides the traditional monolithic document into two distinct components: the Core BEP and the Dynamic Appendix.

### 4.4.1 The Core BEP (The Legal Contract)

The Core BEP acts as the primary legal agreement established at project inception. This tier exclusively governs the "Rigid Backbone" (Bucket A) configurations. It defines the strict ISO 19650-2 naming conventions, high-level security protocols, and the legal parameters of the "Published" state. Altering these parameters causes system shocks to the federated models. Thus, the Core BEP remains strictly under a Waterfall approach and requires a formal contract variation to change.

### 4.4.2 The Dynamic Appendix (The Agile Playbook)

Conversely, the Dynamic Appendix functions as an evolving technical playbook. This tier manages the "Flexible Muscle" (Bucket B) configurations, including iterative folder

structures, granular permission matrices, and specific approval workflow timings. Rather than treating this as a static document, it is explicitly defined as a living appendix. Accordingly, the Information Manager (acting as the Developer) can systematically update the Dynamic Appendix at the end of every Agile Sprint to reflect the newly configured CDE settings. Thus, by categorising the BEP in this manner, the project team can substitute ad-hoc chaos with managed flexibility. Operational updates are executed rapidly within the Agile Sprint Cycle, ensuring the CDE adapts to the fragile and turbulent project environment while protecting the ISO 19650 legal baseline of the Core BEP.

## 4.5 TECHNICAL DESKTOP VERIFICATION: EMPIRICAL PLATFORM ALIGNMENT

To demonstrate the real-world operational validity of the proposed framework, its deductive boundaries were cross-examined against the documented technical architectures, database constraints, and runtime behaviours of market-leading Common Data Environments (CDEs). While commercial CDE platforms are built on traditional standard protocols, their administrative environments have evolved to satisfy site-level user demands, effectively institutionalizing a practical division between rigid data integrity and adaptive workspace flexibility. (Refer to Table 2 for URLs given below)

### 4.5.1 Bucket A (Rigid Backbone) Software Validation

Desktop evaluation confirms that modifications to core information schemas mid-project induce severe relational conflicts, schema mutations, or catastrophic data loss across active file systems.

- Schema Mutation Constraints: In Autodesk Construction Cloud (ACC), the file naming standard operates as a binary, mandatory schema validator. Altering an active root naming standard mid-project is structurally blocked if directories contain documents. It necessitates a complex, manual workaround where all existing models must be completely moved to an external workspace, the standard modified, and files migrated back, disrupting desktop sync continuity and model links (URL1, URL2).
- Database Transaction Blockers: In Bentley ProjectWise, document codes are locked via explicit SQL server integrity rules. Altering structural fields mid-lifecycle causes the integration server to audit existing records. If legacy rows contain blank values for a newly mandatory code field, the database aborts the commit and rejects the change with the explicit hard error: “Failed to update document code structure. New code definitions cannot be saved because some required fields are empty” (URL3, URL4).
- In-Flight Process Freezes: Regarding workflow states, Procore protects legal audit trails via rigid process encapsulation. Master workflow template changes cannot propagate dynamically to documents currently in transit. Forcing an update requires a destructive workflow template restart, which immediately erases all submitted reviewer responses, clears active review queues, and resets progress back to inception (URL5).

### 4.5.2 Bucket B (Flexible Muscle) Software Validation

In contrast to immutable core schemas, software vendors explicitly design localized operational parameters to absorb live project sprint dynamics via dynamic runtime engines and background processes.

Dynamic Review Infrastructure: To prevent process stagnation during design phases, ACC utilizes a runtime compiler pattern for its approval engine. Unlike rigid workflow architectures, ACC's "Current step candidates" user interface allows authorized administrators to add, remove, or substitute active reviewers on the fly without breaking the workflow thread or erasing active progress, keeping the legal audit trail perfectly intact (URL6).

Asynchronous Metadata Extensions: Appending custom descriptive fields (e.g., discipline codes or asset tags) to adapt to changing information requirements is natively handled as a non-disruptive layer across ACC and Aconex. When a new custom attribute is injected mid-lifecycle, the CDE database triggers an asynchronous background indexing routine (URL7, URL8). This schema extension propagates across thousands of documents silently with zero platform downtime, ensuring continuous coordination and searchability without altering the core ISO 19650 baseline.

# 5. CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

The development and management of Common Data Environment (CDE) pose a unique paradox in real-world practice. This research demonstrated the need and potential applicability of an iterative approach in using BIM projects rather than a rigid, waterfall-like approach in ISO 19650. Static and dictated by pre-planned project requirements creates system frictions, especially in project environments like in construction, which are characterised by many uncertainties. Owing to the inherited turbulent and dynamic nature, project team members are inevitably resorting to ad hoc workarounds.

To resolve this, this study utilised deductive document analysis and technical desktop verification to derive a Conceptual Hybrid Framework. The proposed conceptual hybrid model paves the way for a balance between a rigid backbone, namely the legal and structural foundation, and a flexible muscle that incorporates flexibility. Thereby, it addresses the system friction that exists in the standards.

The proposed hybrid model consists of both Bucket A-Rigid backbone and Bucket B-Flexible Muscle. By maintaining a Rigid Backbone for naming conventions, legal status codes, and security protocols (Bucket A) locked within a static "Core BEP," the project's contractual integrity remains intact. Simultaneously, by applying Agility to user-facing configurations such as folder structures, metadata tagging, and review workflows (Bucket B), the BIM Manager can act as a "Developer," responding to the "Product Owner's" shifting requirements to ensure a smooth workflow with minimal disruptions. This shift from "Unmanaged Flexibility" to "Managed Agility" ensures that the CDE remains a high-performance tool rather than a bureaucratic hurdle.

## 5.1 LIMITATIONS

While the proposed Conceptual Hybrid Framework provides a structured approach to CDE configuration, this study acknowledges explicit limitations. Primarily, the framework relies on a technical desktop verification of system schemas and developer documentation rather than primary empirical data gathered from human subjects. Furthermore, the technical desktop verification, while confirming baseline structural viability across major platforms, is limited to the API behaviours and database-level rules of dominant international environments and does not account for the extensive platform variability present in the wider AEC software market. Finally, the framework has not yet

been tested against project scale constraints; the operational friction and "System Shock" risks may vary significantly between small-scale localized builds and mega-infrastructure projects.

### 5.2 FUTURE WORK

To address these limitations, subsequent empirical research is recommended to test the practical utility of the framework via scenario-based semi-structured interviews with experts in the industry. While the current paper successfully validates the technical and structural feasibility of the dual-layered configuration through desktop simulation, future work will focus on evaluating human-centric factors, such as practitioner willingness to adopt the ISO 19650 Gatekeeper role and the contractual acceptability of the Two-Tier BEP across different procurement routes. This phase will be critical to evaluate platform-specific variabilities and scalability, validating the framework's practical efficacy in eliminating the "ad-hoc" drift in practice.

## 6. ACKNOWLEDGEMENT

The authors would like to acknowledge the use of Gemini AI for editing support, grammatical refinement, and improving the overall clarity and readability of this manuscript.

## 7. REFERENCES

Adaba, G. B. (2026). The pragmatics of hybridity: A grounded theory of method integration in software engineering projects. *Journal of Systems and Software, 235*, Article 112790. https://doi.org/10.1016/j.jss.2026.112790

Biswas, H.K., Sim, T. Y., & Lau., S. L. (2024) Impact of building information modelling and advanced technology in AEC sector: A contemporary review and future direction. *Journal of Building Engineering, 82*, Article 108165. https://doi.org/10.1016/j.jobe.2023.108165

Cooper, R. G., & Sommer, A. F. (2018). Agile-Stage-Gate for manufacturers: Changing the way new products are developed. *Research-Technology Management, 61*(2), 17–26. https://doi.org/10.1080/08956308.2018.1421380

Daoud, A. O., Oke, A. E., Singh, A. K., Famakin, I. O., Mahmoud Abdel Aziz, K., & Olayemi, T. M. (2025). Exploring the building information modelling benefits for sustainable construction using PLS-SEM. *Scientific Reports, 15*(1), 35781. https://doi.org/10.1038/s41598-025-14020-0

Datta, S. D., Tayeh, B. A., Hakeem, I. Y., & Abu Aisheh, Y. I. (2023). Benefits and barriers of implementing building information modelling techniques for sustainable practices in the construction industry—A comprehensive review. *Sustainability, 15*(16), 12466. https://doi.org/10.3390/su151612466

Dolla, T., Venkatachalam, S., & Kumar, V. S. (2024). Institutional shaping of CDE implementation in BIM-enabled AEC projects. *Journal of Information Technology in Construction (ITcon), 29*, 826–849. https://doi.org/10.36680/j.itcon.2024.036

Gonzalez, C. F. L., Rodriguez, A. M. R., & Manzanares, F. V. (2024). Disruptive method for managing BIM design and construction using Kanban. *Organization, Technology and Management in Construction: An International Journal, 16*(1), 1–12. https://doi.org/10.2478/otmcj-2024-0001

Hohl, P., Klünder, J., Van-Bennekum, A., Lockard, R., Gifford, J., Münch, J., Stupperich, M., & Schneider, K. (2018). Back to the future: Origins and directions of the "Agile Manifesto" – views of the originators. *Journal of Software Engineering Research and Development, 6*(1), 15. https://doi.org/10.1186/s40411-018-0059-z

Jaskula, K., Kifokeris, D., Papadonikolaki, E., & Rovas, D. (2025). Common data environments in construction: State-of-the-art and challenges for practical implementation. *Construction Innovation, 25*(5), 1522–1541. https://doi.org/10.1108/CI-04-2023-0088

Kaya, U., & Özener, O. Ö. (2025). A strategic evaluation of BIM-driven information management in the context of ISO 19650-2 standard. *Engineering, Construction and Architectural Management, 32*(11), 7857–7886. https://doi.org/10.1108/ECAM-03-2024-0387

Krupa, M., & Hájek, J. (2024). Hybrid project management models: A systematic literature review. *International Journal of Project Organisation and Management, 16*(2), 233–261. https://doi.org/10.1504/IJPOM.2024.139253

Krupa, M., Hájek, J., Šimůnek, D., Schlegel, D., & Dvouletý, O. (2026). Deliberate or emergent? How organizations adopt hybrid project management. *Project Management Journal*. Advance online publication. https://doi.org/10.1177/87569728261438120

Lestari, S., Purwanto, H., & Saputra, J. (2022). Application of Common Data Environment (CDE) as a method of design review in construction project. *Jurnal Rancang Bangun dan Teknologi, 22*, 103–109. https://doi.org/10.31940/logic.v22i2.103-109

Malla, V., Tummalapudi, M., & Delhi, V. S. K. (2024). Perceptions of built-environment professionals on using ISO 19650 standards for information management. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *16*(1), 04523045. https://doi.org/10.1061/JLADAH.LADR-1076

Mesároš, P., Mandičák, T., & Behúnová, A. (2022). Use of BIM technology and impact on productivity in construction project management. *Wireless Networks, 28*(2), 855–862. https://doi.org/10.1007/s11276-020-02302-6

Mirzaei, M., Mabin, V. J., & Zwikael, O. (2025). Customising hybrid project management methodologies. *Production Planning & Control*, *36*(9), 1188–1205. https://doi.org/10.1080/09537287.2024.2349231

Owen, R., & Koskela, L. (2006). Agile construction project management. In *Proceedings of the 6th International Postgraduate Research Conference in the Built and Human Environment* (pp. 22–33). University of Salford.

Radl, J., & Kaiser, J. (2019). Benefits of implementation of Common Data Environment (CDE) into construction projects. *IOP Conference Series: Materials Science and Engineering, 471*(2), Article 022021. https://doi.org/10.1088/1757-899X/471/2/022021

Reiff, J., & Schlegel, D. (2022). Hybrid project management – a systematic literature review. International *Journal of Information Systems and Project Management*, *10*(2), 45–63. https://doi.org/10.12821/ijispm100203

Silvius-Zuchi, D., & Silvius, G. (2026). Designing a fitting hybrid project management approach: A contingency perspective. *International Journal of Information Systems and Project Management*, *14*(1), Article e140103. https://doi.org/10.12821/ijispm140103

Smith, P. (2014). BIM implementation – Global strategies. *Procedia Engineering*, 85, 482–492. https://doi.org/10.1016/j.proeng.2014.10.575

Amaradiwakara, A.W.G.S.B. and Devaproya, K.A.K., 2026. A conceptual management framework for resource and financial optimisation of construction SMEs in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 58-70. DOI: https://doi.org/10.31705/WCS.2026.5. Available from: https://ciobwcs.com/papers/

# A CONCEPTUAL MANAGEMENT FRAMEWORK FOR RESOURCE AND FINANCIAL OPTIMISATION OF CONSTRUCTION SMES IN SRI LANKA

**A.W.G.S.B. Amaradiwakara[1] and K.A.K. Devapriya[2]**

## *ABSTRACT*

*Construction small and medium-sized enterprises (SMEs) in Sri Lanka play a significant role in project delivery. However, many continue to manage procurement, site records, inventory movements, supplier payments, and financial information through fragmented and partially manual systems. This fragmentation contributes to delayed reconciliation, duplicated data entry, weak audit trails, limited visibility of committed costs, and inadequate monitoring of project cash-flow exposure. This study developed a conceptual management framework for strategic resource and financial optimisation in Sri Lankan construction SMEs. A sequential explanatory mixed-method research design was adopted. The quantitative phase comprised a questionnaire survey of 30 construction practitioners, and the responses were analysed using Relative Importance Index (RII). The qualitative phase comprised eight semi-structured interviews with SME-related stakeholders, and the data were analysed thematically to refine and validate the proposed framework. The findings revealed that budget overruns, wastage, stock mismatches, cash-flow uncertainty, and poor cost visibility were the most critical management challenges. The highest-ranked framework requirements were exception-based alerts, real-time cash-flow visibility, supplier payment tracking, delivery-status monitoring, and budget-versus-actual dashboards. The proposed framework consists of four interrelated layers, namely mobile site-data capture, validation and three-way matching, accounting-system interface, and analytical dashboards. The study contributes to construction SME management by proposing an affordable, modular, and practically implementable conceptual management framework that links site-level resource evidence with financial control. Future research should develop and test a functional prototype to evaluate its impact on reconciliation time, payment delays, stock accuracy, and cost visibility.*

***Keywords:*** *Construction SMEs; Financial management; Resource management; Sri Lanka.*

## 1. INTRODUCTION

The construction industry depends on the continuous coordination of materials, site production records, procurement approvals, and financial transactions. When these

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, amaradiwakaraawgsb.21@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, kakdevapriya@uom.lk

information flows are delayed or fragmented, they can contribute to cost overruns, schedule inefficiencies, weak audit trails, and poor project-level decision-making (World Economic Forum, 2016). This issue is particularly significant for SMEs, where limited digital capacity, restricted administrative resources, and informal management practices often reduce the visibility of project operations and financial commitments (Gessa et al., 2023).

Sri Lankan construction SMEs operate in a dynamic environment due to cost pressure, fluctuating payment cycles, and limited working-capital resilience, which further underscores the importance of timely operational and financial control (Central Bank of Sri Lanka, 2023). However, many SMEs continue to rely on Excel sheets, manual records, and disconnected software applications. These practices limit real-time visibility of inventory movements, committed costs, invoice status, supplier payments, and project cash-flow exposure (Ranadewa et al., 2018). Existing accounting tools may support ledger management, but they often remain disconnected from procurement, material tracking, goods received notes (GRNs), and project-level cost commitments. Conversely, full enterprise resource planning (ERP) systems may provide broader integration, but their cost, complexity, and implementation requirements can exceed the capacity of many construction SMEs.

Accordingly, the aim of this study is to develop a conceptual management framework for strategic resource and financial optimisation in Sri Lankan construction SMEs, rather than to develop or test a functional software prototype. Questionnaire and interview evidence was used to examine prevailing practices, diagnose control-related weaknesses, and establish implementation considerations relevant to SME operations. The objectives are to identify the major problems in resource and financial management, examine the effectiveness and limitations of existing management practices, and propose an SME-oriented approach for improving decision support in construction SME operations.

The scope of the study is limited to resource management, procurement coordination, supplier-payment visibility, budgetary control, and cash-flow monitoring within Sri Lankan construction SMEs.

## 2. LITERATURE REVIEW

The literature emphasises that effective coordination of procurement, inventory, site operations, and accounting information is critical to construction project performance (World Economic Forum, 2016). This requirement is particularly important for SMEs, as they commonly operate with limited managerial capacity, informal administrative processes, restricted digital capability, and reliance on tacit knowledge (Gessa et al., 2023). Although such practices may be manageable in small-scale projects, they become less effective when project complexity, transaction volume, and external market uncertainty increase.

### 2.1 OVERVIEW OF CONSTRUCTION SMES IN SRI LANKA

In the construction industry, especially in the economies of the developing world, construction SMEs contribute significantly to employment creation, economic development, and project delivery (Bandaranaike et al., 2024). Despite their significance, these companies generally have less financial capacity, operational flexibility, and managerial resources than large construction organisations (Nuwandhara et al., 2024).

Construction SMEs in the Sri Lankan context are typically affected by limited access to finance, poor cash-flow management, labour shortages, supply-chain disruptions, and low levels of technology adoption, which reduce productivity and business resilience (Weerakoon et al., 2023). These conditions increase their exposure to project delays, cost escalation, and weak coordination between site-level activities and financial-control processes (Madhavika et al., 2025).

## 2.2 MAJOR ISSUES IN SMES

SMEs face a wide range of challenges related to finance, resource management, operations, legal matters, and risk management. These issues affect the day-to-day functioning and long-term sustainability of SMEs in different business settings.

*Table 1: Major issues in SMEs*

| Category | Main Issues | References |
|---|---|---|
| **Financial** | Cash-flow problems, limited finance access, rising costs, and weak financial control | (1), (2), (3), (4), (5), (6),(7) |
| **Resource Management** | Skilled labour shortages, poor training, supply delays, and weak resource coordination | (1), (3), (4), (5), (8),(9),(10),(11) |
| **Operational** | Project delays, budget overruns, low productivity, poor quality, and safety control issues | (1), (3), (4), (5), (12) |
| **Contractual/Legal** | Contract issues, approval delays, compliance burden, dispute risk | (1), (3), (4), (5), (14), (15), (16) |
| **Risk Management** | Late payments, theft/losses, economic downturns, and weak contingency planning | (1), (5), (13), (17), (19), (18) |

(1)-(Bandaranaike et al., 2024), (2)-(Hailu & Tshehla, 2025), (3)-(Ranadewa et al., 2018), (4)-(Nuwandhara et al., 2024),(5)- (Dodanwala & Santoso, 2024),(6)-(Uwonda & Okello, 2015),(7)-(Odio et al., 2021),(8)-(Whyman et al., 2015),(9)-(Casalino et al., 2015),(10)-(Madzimure et al., 2020),(11)-(Fanelli, 2021),(12)-(Madhavika et al., 2025),(13)-(Weerakoon et al., 2023),(14)-(Ratnayake et al., 2025),(15)-(Akinboye et al., 2025),(16)-(Escrivão et al., 2017),(17)-(Perera & Dewagoda, 2021),(18)-(Wickramansinghe & Sharma, 2005),(19)-(Mafimisebi et al., 2025)

As shown in Table 1, SMEs face interconnected challenges across financial, resource-management, operational, contractual/legal, and risk-management areas. However, financial and resource-management issues are more frequently emphasised in the reviewed literature because they directly affect cash-flow stability, labour availability, material coordination, and project continuity. Financial constraints reduce the ability of SMEs to maintain stable business activities, while resource-related limitations such as labour shortages, poor training, supply delays, and weak coordination further affect performance and growth. Therefore, greater attention should be given to improving financial capacity and strengthening resource management in SMEs (Ranadewa et al., 2018; Bandaranaike et al., 2024).

## 2.3 RESOURCE MANAGEMENT CHALLENGES IN CONSTRUCTION SMES

The visibility of material requests, receipts, issues, and returns is vital to construction performance because these records link physical production with cost control (World Economic Forum, 2016). This is particularly important when stores and procurement

records are maintained through manual logs or independent spreadsheets, as reconciliation becomes time-consuming, irregular, and dependent on manual effort (Olanipekun & Sutrisna, 2021).

Delays in GRNs, delivery notes, and stock updates limit managers' ability to track consumption, manage wastage, and validate supplier claims (Perera & Dewagoda, 2021). This weakens replenishment planning and increases the likelihood of stock mismatches, unplanned purchasing, and avoidable project delays (Ratnayake et al., 2025).

## 2.4 FINANCIAL MANAGEMENT, CASH-FLOW AND PAYMENT DELAYS

Cash flow in construction is structurally imbalanced because contractors incur continuous expenditure on labour, materials, and subcontractors, while revenue depends on valuation, certification, and payment-release cycles (Perera & Dewagoda, 2021). Compared with larger companies, SMEs are more exposed to delayed payments and short working-capital cycles. Therefore, real-time visibility of cost commitments and payables is strategically important (Gessa et al., 2023).

Stand-alone accounting packages may support statutory reporting, ledger maintenance, and invoice processing. However, they do not always preserve the operational context associated with purchase orders, partial deliveries, site transfers, and committed costs (Monk & Wagner, 2008). As a result, budgetary pressure may become visible to managers only after supplier invoices have been entered into the accounts or after cash-flow constraints have already affected site operations (Chathuranga et al., 2000).

## 2.5 INTEGRATED MANAGEMENT FRAMEWORK REQUIREMENT

Construction SMEs require a real-time platform because many current practices depend on spreadsheets, manual updates, and disconnected systems that restrict timely decision-making and operational efficiency (Gessa et al., 2023). Poor integration among material records, procurement activities, and financial-control processes contributes to supplier-payment delays, cash-flow uncertainty, stock variances, and limited cost visibility in the Sri Lankan construction context (Bandaranaike et al., 2024). A conceptual management framework can improve visibility, coordination, and control by identifying the required connections between materials, payments, budgets, and site activities (Ranadewa et al., 2018). For SMEs, such a framework should define platform requirements that are affordable, practical, and easy to implement in daily project operations (Gessa et al., 2023).

## 2.6 EXISTING DIGITAL TOOLS AND DIGITAL-MATURITY INDICATORS

Existing digital tools used by construction SMEs commonly include spreadsheets, manual records, stand-alone accounting packages, project management applications, procurement systems, inventory systems, and ERP systems. Spreadsheets and manual records are widely used because they are low-cost, flexible, and familiar to users, but they often create duplicated data entry, delayed reconciliation, weak audit trails, and limited real-time visibility (Ranadewa et al., 2018). Stand-alone accounting packages can support ledger recording, invoice processing, payment tracking, and statutory reporting, but they may not fully capture site-level operational transactions such as purchase orders, GRNs, material issues, delivery records, and site transfers (Monk & Wagner, 2008). ERP systems provide broader integration between operational and financial functions, but their cost,

complexity, training needs, and implementation requirements can limit adoption among SMEs (Gessa et al., 2023). Therefore, construction SMEs require an intermediate platform that is more integrated than spreadsheet-based control but more affordable and practical than full enterprise system implementation. Based on this literature, ERP integration, site-finance linkage, duplicate data entry, and Excel-based material tracking were selected as digital-maturity indicators because they reflect the extent to which SMEs can capture, connect, and use operational and financial information for decision-making. These indicators informed the questionnaire design and helped assess the level of information integration required for the proposed conceptual management framework. This comparison shows that existing tools either support isolated functions or require substantial implementation capacity. Accordingly, the proposed framework addresses the gap between fragmented low-cost tools and complex enterprise systems by identifying practical platform requirements for integrated resource and financial control in construction SMEs.

## 3. RESEARCH METHODOLOGY

This study adopted a sequential explanatory mixed-method research design to develop a conceptual management framework for Sri Lankan construction SMEs (Creswell, 2014). A structured questionnaire survey was first conducted among construction practitioners engaged in procurement, stores management, quantity surveying, site management, project management, and finance. The final dataset consisted of 30 usable responses, which were used to identify current practices, site-finance integration issues, resource and financial control problems, real-time information requirements, desired platform characteristics, adoption barriers, and enabling conditions.

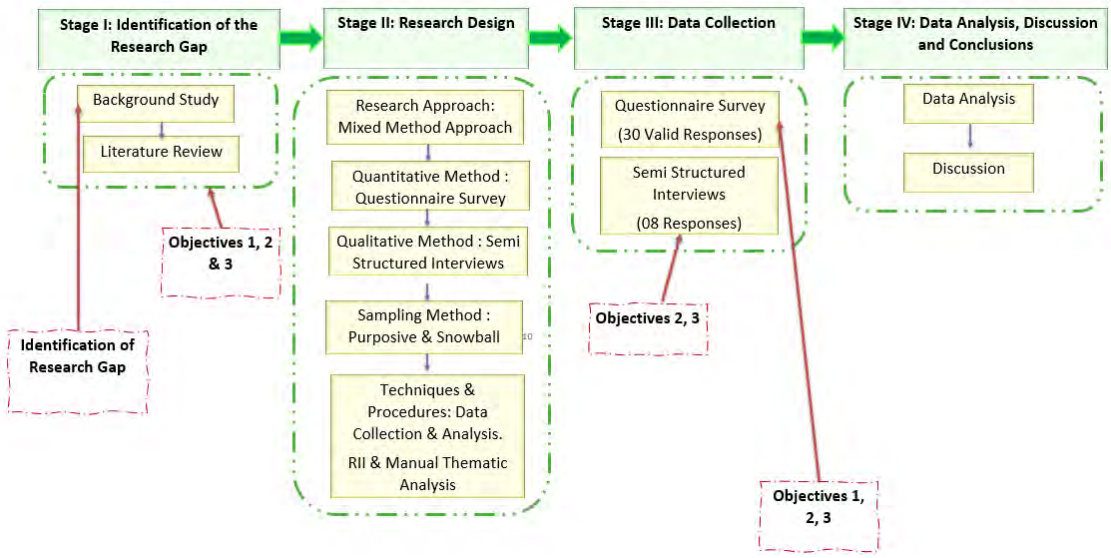



*Figure 1: Research process framework*

The sample size was considered appropriate for the exploratory nature of the study because the objective was to rank key issues and develop a conceptual management framework rather than to make population-level statistical generalisations. The 30 questionnaire responses provided the basis for RII-based prioritisation, while the eight semi-structured interviews strengthened the interpretation of the findings by explaining practical requirements and implementation conditions. The interview data were analysed

thematically. This approach was appropriate because the study aimed to prioritise key issues and translate them into an SME-relevant framework.

### 3.1 QUANTITATIVE ANALYSIS

The quantitative questionnaire data were analysed using the RII. RII was applied to determine the relative significance of the identified resource-management challenges, financial-control issues, platform requirements, adoption barriers, and enabling conditions. This method was appropriate because the study aimed to rank the factors according to their perceived importance among respondents.

The RII was calculated using the following formula:

$$RII = \frac{\sum W}{A \times N} \qquad (01)$$

W = Weight assigned by respondents

A = Highest weight on the scale

N = Total number of respondents

### 3.2 QUALITATIVE ANALYSIS

The interview data were analysed using thematic analysis to identify key suggestions and practical recommendations. The interview responses were reviewed, coded, categorised, and synthesised into themes related to improving financial and material management in construction SMEs.

The questionnaire findings guided the qualitative analysis. Since the survey had already identified the main resource and financial management issues, the interviews focused on exploring practical solutions and implementation requirements. Accordingly, the qualitative data were organised into solution-oriented themes to support the formulation of the proposed conceptual management framework.

## 4. RESULTS AND DISCUSSION

### 4.1 RESPONDENT PROFILE AND CURRENT DIGITAL MATURITY

The questionnaire dataset consisted of 30 usable responses. Quantity Surveyors represented the largest respondent group at 66.7%, followed by site engineers at 20.0%, material controllers at 6.7%, and project management and other roles at 3.3% each as shown in Figure 2. This respondent profile indicates that the analysis was informed mainly by practitioners who are directly involved in cost control, procurement coordination, material management, and site reporting.

The findings indicate a high level of digital fragmentation among the surveyed organisations. Among the 30 valid responses relating to ERP adoption, 82.8% indicated that their organisations did not have a fully integrated ERP system, while 17.2% reported the use of a fully integrated system. Only 16.7% reported that site records were fully connected with financial records, while 83.3% indicated that such records were either partially connected or not connected. Regarding duplicate data entry, 70.0% of respondents answered “yes,” while a further 26.7% answered “sometimes”. Excel-based material tracking was reported by 76.7% of respondents, indicating that spreadsheet-based or semi-manual control remains common among construction SMEs

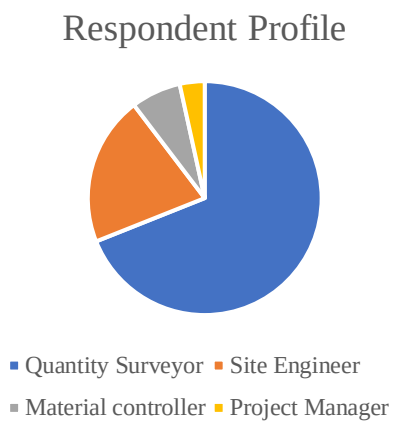



*Figure 2: Respondent profile*

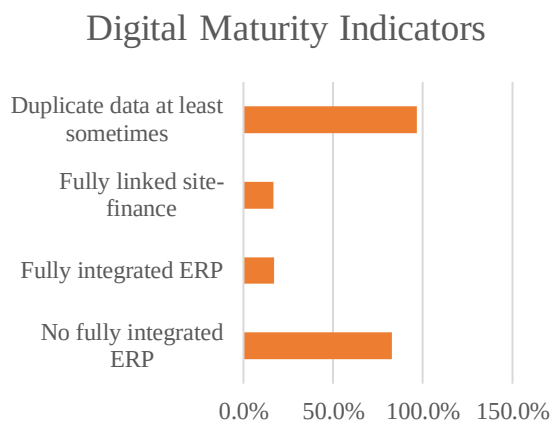



*Figure 3: Digital maturity indicators*

## 4.2 PRIORITY PROBLEMS

The RII analysis was used to rank all identified resource-management and financial-control problems. Figure 4 presents the highest-ranked problem themes only to maintain visual clarity and avoid overcrowding the figure. The highest-ranked problem theme was budget overruns (RII = 0.887), followed by wastage (RII = 0.873), stock mismatch between site and store records (RII = 0.853), cash-flow uncertainty (RII = 0.853), and poor cost visibility (RII = 0.847). These findings indicate that the most critical problems are concentrated around budgetary control, material wastage, stock reconciliation, cash-flow uncertainty, and cost visibility.

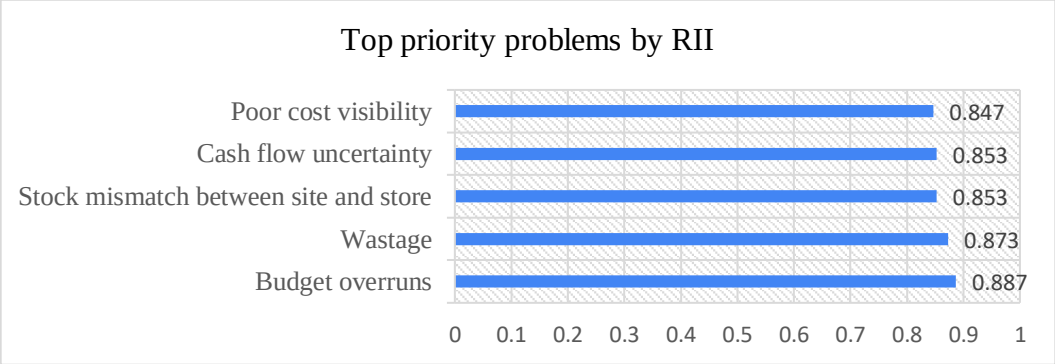



*Figure 4: Top priority problems by RII*

Other problem items were also included in the RII analysis but obtained comparatively lower values than the main themes shown in Figure 4. These included over-ordering, inaccurate stock records, invoice-matching issues, delayed supplier payments, duplicated data entry, project delays, theft or loss, difficulty tracking committed cost through purchase orders, payment delays affecting work progress, late GRNs or delivery notes, missing invoices, late deliveries, price variations not captured early, payment-approval delays, and disputes with suppliers or subcontractors. These issues remain relevant to the proposed framework.

## 4.3 PLATFORM REQUIREMENTS

The RII analysis was also used to rank all identified platform requirements. Figure 5 presents the highest-ranked platform requirement themes only to improve visual clarity.

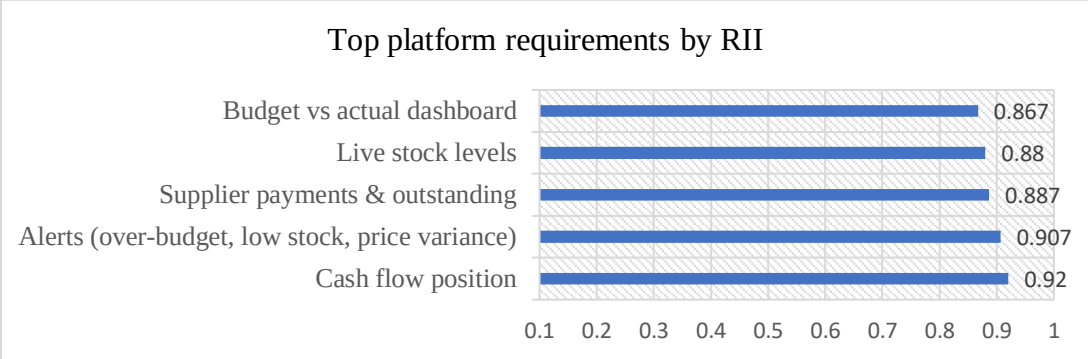



*Figure 5: Top requirements by RII*

The highest-ranked requirement was real-time cash-flow position (RII = 0.920), followed by exception alerts for over-budget conditions, low stock, and price variance (RII = 0.907), supplier-payment and outstanding-balance visibility (RII = 0.887), livestock levels (RII = 0.880), and budget-versus-actual dashboards (RII = 0.867). These findings show that respondents prioritised practical decision-support functions related to cash-flow monitoring, exception alerts, supplier-payment tracking, stock visibility, and budget control.

Other platform requirements were also included in the analysis but obtained comparatively lower RII values. These included inventory and stores control, delivery-status tracking, supplier outstanding information, committed cost visibility through purchase orders not yet invoiced, approvals and audit trail, cost-code and budget-control functions, cost-code spending visibility, and mobile site-data capture. These lower-ranked requirements were not excluded from the analysis; rather, they were treated as supporting requirements that may be incorporated in subsequent stages of the proposed real-time management framework.

## 4.4 ADOPTION BARRIERS AND ENABLERS

The RII analysis was further used to assess the barriers influencing the adoption of the proposed conceptual management framework. Cost was the highest-ranked adoption barrier (RII = 0.907), followed by training time (RII = 0.833), staff resistance or attitude (RII = 0.807), fear of monitoring (RII = 0.773), data privacy concerns (RII = 0.707), and internet or device limitations (RII = 0.500). These findings indicate that affordability, training requirements, and user acceptance are the main issues that should be considered during implementation.

The adoption-enabler results further support this interpretation. Training support was the highest-ranked enabler (RII = 0.900), followed by low subscription cost (RII = 0.893), simple user interface (RII = 0.867), SME-specific templates (RII = 0.800), role-based access (RII = 0.793), offline mode with synchronisation (RII = 0.647), and local language support (RII = 0.620). These findings suggest that the platform framework should be cost-sensitive, simple to use, supported by training, and suitable for the operational capacity of SMEs.

Overall, the quantitative findings indicate that the proposed conceptual management framework should initially prioritise core resource and financial-control functions before progressing towards advanced enterprise-level integration. The most important areas are budget control, material wastage reduction, stock reconciliation, cash-flow visibility, supplier-payment monitoring, exception alerts, and live material information. The findings also show that implementation success depends on affordability, training support, user acceptance, and simplicity of use.

## 4.5 THEMATIC ANALYSIS

The interview data were analysed using thematic analysis to identify recurring suggestions and practical recommendations. The responses were coded, categorised, and grouped into themes that informed the development of the proposed conceptual management framework.

### 4.5.1 Theme 1: Requirement for Real-Time Financial Visibility and Control

The interviewees emphasised the need to access financial data in real time. They explained that problems such as delayed supplier payments, cash-flow uncertainty, and budget overruns could be reduced if managers had access to real-time information on cash position, payment schedules, supplier-payment status, and budget performance. This indicates that financial monitoring should be one of the core functions of the proposed management framework. This theme supports the questionnaire findings, where cash-flow visibility and supplier-payment tracking were identified as important platform requirements.

### 4.5.2 Theme 2: Requirement for Improved Material Follow-up and Operational Organization

The participants highlighted the need to improve material control across procurement, delivery, utilisation, and stock recording. They observed that delayed updates and separate record-keeping practices can create stock mismatches, inaccurate records, and weak coordination between site and office teams. Therefore, the interviewees suggested features such as live inventory updates, delivery-status tracking, and electronic GRN recording. This theme supports the survey finding that inventory control and delivery visibility are priority requirements for the proposed management framework.

### 4.5.3 Theme 3: Requirement to Integrate and Eliminate Redundant Data Entry

The recurring theme was the need for an integrated system that reduces duplicate data entry and fragmented information flows. The participants noted that spreadsheets, paper-based records, and disconnected tools create inconsistencies and delays in decision-making. They suggested a centralised platform framework that connects material management, cost tracking, supplier payments, and reporting. This finding is consistent with the questionnaire results, where duplicate records and weak site-finance integration were identified as significant operational issues.

### 4.5.4 Theme 4: Requirement for a Simple, Low-priced, and Usable System by SMEs

This theme concerned the implementation requirements of SMEs. Respondents emphasised that the platform framework should be affordable, easy to use, and suitable for daily project operations. Software cost, lack of training, and resistance to change were

identified as barriers to adoption. Consequently, the interviewees suggested a simple interface, low-cost implementation, and practical training support. This theme is consistent with the questionnaire findings on cost, training, and ease of adoption.

### 4.6 INTEGRATING QUANTITATIVE AND QUALITATIVE FINDINGS

The questionnaire and interview findings provide an empirical basis for the proposed management framework. The questionnaire phase identified and ranked the main resource and financial management issues, while the interview phase explained how these requirements could be translated into practical platform features for construction SMEs.

The findings indicate that the proposed framework should not function only as a financial reporting tool or a material-tracking application. Instead, it should integrate cost control, supplier payments, inventory status, delivery progress, and alert mechanisms. It should also reflect SME conditions, including limited resources, cost sensitivity, and the need for user-friendly tools.

This integration strengthens the practical relevance of the framework because it combines quantitatively ranked priorities with qualitatively identified implementation requirements.

## 5. CONCEPTUAL MANAGEMENT FRAMEWORK IMPLICATIONS

The survey findings indicate that the proposed conceptual management framework should prioritise transaction points where poor visibility creates the greatest operational and financial risk. These transaction points include requisitions, purchase orders, goods received notes, invoice processing, and payment authorisation. The proposed framework does not require SMEs to replace all existing systems. Instead, it links key operational functions through mobile site-data capture, procurement-to-payment validation, budget and cash-flow dashboards, and synchronised posting to the accounting ledger.

Three-way matching forms a central control mechanism within the framework because it compares the approved purchase order, GRN, and supplier invoice before payment is released. This can reduce the risk of mismatches, duplicate payments, and unrecorded liabilities (Doxey, 2021). Audit trails and exception alerts are also important because the survey findings indicate problems related to late goods received notes, stock mismatches, and payment-approval delays.

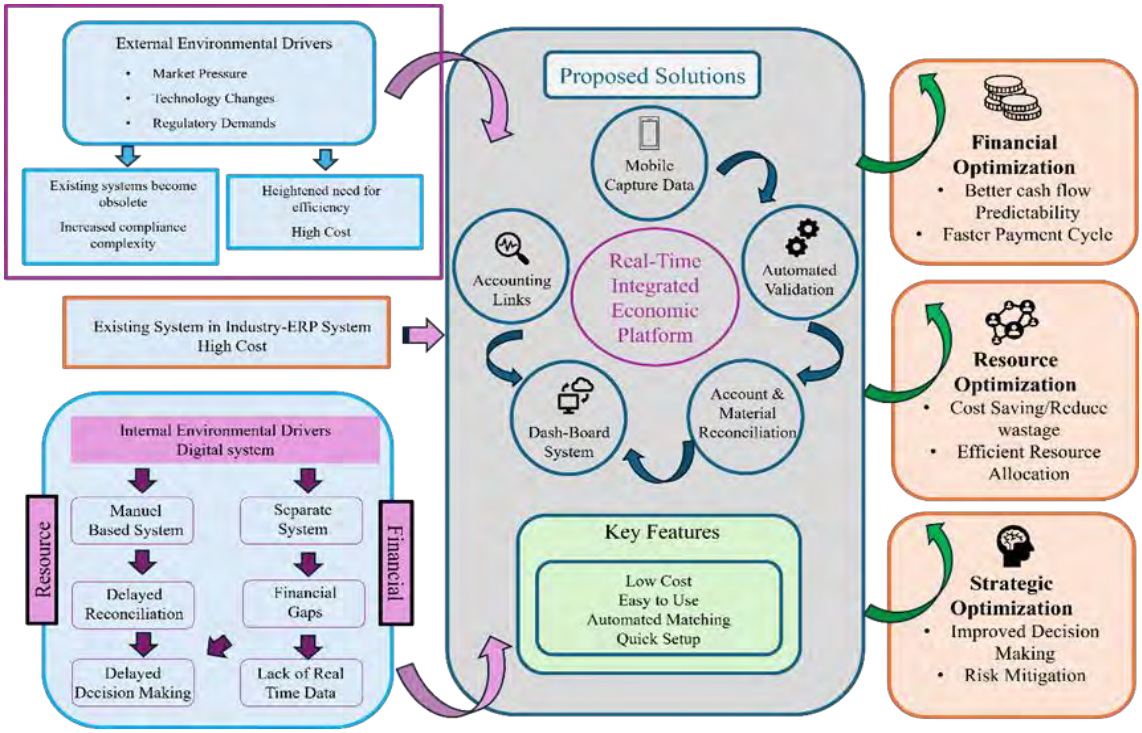



*Figure 6: Conceptual management framework*

The framework should be mobile-first, affordable, and modular to suit SME conditions. Mobile or tablet-based capture is required because primary operational evidence is generated at site level, while phased implementation can reduce cost and resistance to change (Radman et al., 2025).

## 6. CONCLUSIONS

This study developed a conceptual management framework for strategic resource and financial optimisation in Sri Lankan construction SMEs using 30 questionnaire responses and eight semi-structured interviews. The findings indicate that SMEs are affected by fragmented records, duplicated data entry, weak site-finance integration, and limited digital visibility. The RII analysis identified budget overruns, wastage, stock mismatches, cash-flow uncertainty, and poor cost visibility as the most critical issues.

Theoretically, the study contributes by linking digital transformation in construction SMEs with an integrated management framework that connects site-level resource evidence with financial-control requirements. Practically, the framework supports SMEs in identifying key information flows, validation controls, and decision-support functions for improving stock accuracy, supplier-payment monitoring, budget control, cost visibility, and cash-flow decision-making.

The study is limited to conceptual framework development and preliminary empirical investigation. It does not develop or test a fully operational software prototype. Future research should develop and evaluate a working prototype in live construction SME project settings.

# 7. REFERENCES

Akinboye, A. K., Morrish, S. C., & Collins, J. D. (2025). Policy pathways and barriers: Examining the effects on SME growth in Australasia. *Humanities and Social Sciences Communications*, 12, Article 1379. https://doi.org/10.1057/s41599-025-05422-6

Bandaranaike, B. B., Gallage, S. D., & Sivanraj, S. (2024). Risk management in Sri Lankan SME construction sector: Identifying barriers and enablers. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, & H. Chandanie (Eds.), *Proceedings of the 12th World Construction Symposium*, 9–10 August 2024, Sri Lanka (pp. 891–903). https://doi.org/10.31705/WCS.2024.71

Casalino, N., Cavallari, M., De Marco, M., Ferrara, M., Gatti, M., & Rossignoli, C. (2015). Performance management and innovative human resource training through flexible production systems aimed at enhancing the competitiveness of SMEs. *The IUP Journal of Knowledge Management*, 13(4), 29–42. http://hdl.handle.net/10807/71170

Central Bank of Sri Lanka. (2023). *Annual economic review 2023*. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-economic-review/annual-economic-review-2023.

Chathuranga, I. H. N., Siriwardana, C. S. A., & Ariyaratne, I. E. (2024). Assessing the readiness for digital technologies adoption for enhancing productivity in the Sri Lankan construction industry. *International Conference On Sustainable Built Environment 2023*, 15-17 December 2023, Sri Lanka (pp. 1137 – 1148).

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). SAGE Publications. https://doi.org/10.5539/ELT.V12N5P40

Dodanwala, T. C, & Santoso, D. S. (2024). Critical factors influencing the bid/no-bid decisions of small and medium-sized contractors in Sri Lanka. *International Journal of Construction Education.* https://doi.org/10.1080/15578771.2024.2332237

Doxey, C. H. (2021). *Invoice processing. In The new accounts payable toolkit.* Wiley. https://doi.org/10.1002/9781119700548.ch12

Escrivão Filho, E., Alexandre, F. A., Marcelo, S. N., Luiz, A. P., & Oliveira, J. D. (2017). Identifying SME mortality factors in the life cycle stages: An empirical approach of relevant factors for small business owner-managers. *Journal of Global Entrepreneurship Research, 7*, Article 5. https://doi.org/10.1186/s40497-017-0064-4

Fanelli, R. M. (2021). Barriers to adopting new technologies within rural small and medium enterprises (SMEs). *Social Sciences, 10(11),* Article 430. https://doi.org/10.3390/socsci10110430

Gessa, A., Jiménez, A., & Sancha, P. (2023). Exploring ERP systems adoption in challenging times. Insights of SMEs stories. *Technological Forecasting and Social Change*, *195*, 122795. https://doi.org/10.1016/J.TECHFORE.2023.122795

Hailu, H., & Tshehla, M. (2025). Mapping the landscape: Challenges and growth prospects for construction SMEs in Gauteng province, South Africa. *International Journal of Research in Business and Social Science (2147- 4478)*, *14*(2), 365–374. https://doi.org/10.20525/ijrbs.v14i2.3900

Madhavika, N., Bandara, M., Manchanayake, M., Perera, C., Bandara, W., Jayasinghe, P., & Ehalapitiya, S. (2025). Navigating economic crisis: Factors shaping resilience in Sri Lankan construction SME supply chains. *International Journal of Construction Management*, *25*(11), 1324–1336. https://doi.org/10.1080/15623599.2024.2415158

Madzimure, J., Mafini, C., & Dhurup, M. (2020). E-procurement, supplier integration and supply chain performance in small and medium enterprises in South Africa. *South African Journal of Business Management*, *51*(1). https://doi.org/10.4102/SAJBM.V51I1.1838

Mafimisebi, O. P., Obembe, D., & Ogunsade, A. I. (2025). Planned, improvised or resilience: Small business owner-managers' perception and response to crises in crisis-prone environments. *Journal of General Management*, *51*(1), 45–66. https://doi.org/10.1177/03063070231159568

Monk, E., & Wagner, B. J. (2008). *Concepts in Enterprise Resource Planning*. https://www.researchgate.net/publication/235720403

Nuwandhara, R., Perera, A., & De Silva, G. (2024). Survival challenges faced by the small-scale building contractors in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, &

H. Chandanie (Eds.), *12th World Construction Symposium* (pp. 961–973). https://doi.org/10.31705/wcs.2024.76

Odio, P. E., Kokogho, E., Olorunfemi, T. A., Nwaozomudoh, M. O., Adeniji, I. E., & Sobowale, A. (2021). Innovative financial solutions: A conceptual framework for expanding SME portfolios in Nigeria's banking sector. *International Journal of Multidisciplinary Research and Growth Evaluation*, *2*(1), 495–507. https://doi.org/10.54660/.ijmrge.2021.2.1.495-507

Olanipekun, A. O., & Sutrisna, M. (2021). Facilitating digital transformation in construction: A systematic review of the current state of the art. In *Frontiers in Built Environment* (Vol. 7). Frontiers Media S.A. https://doi.org/10.3389/fbuil.2021.660758

Perera, K. S., & Dewagoda, K. (2021). Streamlining the management of payment delays: The case of Sri Lankan Government building construction projects. *Journal of Financial Management of Property and Construction*, 26(2), 236–256. https://doi.org/10.1108/JFMPC-05-2020-0041

Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2025). Real-Time tracking and analysis in construction projects: A RealCONs framework. *Advanced Engineering Informatics*, *67*, 103511. https://doi.org/10.1016/J.AEI.2025.103511

Ranadewa, K. A. T. O., Sandanayake, Y. G., & Siriwardena, M. (2018). A SWOT analysis for Sri Lankan Construction SMES. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, & S. Gunatilake (Eds.), *7th World Construction Symposium* (pp. 961–973). https://ciobwcs.com/downloads/WCS2018-Proceedings.pdf

Ratnayake, M. R. I. U. K., Wijerathna, M. R. D. P., Ranadewa, K. A. T. O., & Perera, B. A. K. S. (2025). A Scoping review of construction SMEs: global vs local. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *13th World Construction Symposium - 2025* (pp. 69–82). https://doi.org/10.31705/WCS.2025.6

Uwonda, G., & Okello, N. (2015). Cash flow management and sustainability of small medium Enterprises (SMEs) in northern Uganda. *International Journal of Social Science and Economics Invention*, *1*(03). https://doi.org/10.23958/ijssei/vol01-i03/02

Weerakoon, T. G., Wimalasena, S., & Fedotova, K. (2023). Economic crisis adaptation in Sri Lankan construction industry: Pathway to prosperity. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1), 240–256. https://doi.org/10.2478/bjreecm-2023-0015

Whyman, P. B., & Petrescu, A. I. (2015). Workplace flexibility practices in SMEs: Relationship with performance via redundancies, absenteeism, and financial turnover. *Journal of Small Business Management*, 53(4), 1097–1126. https://doi.org/10.1111/jsbm.12092

Wickramansinghe, N., & Sharma, S. K. (2005). Key factors that hinder SMEs in succeeding in today's knowledge-based economy. *International Journal of Management and Enterprise Development*, 2(2), 141–158. https://doi.org/10.1504/IJMED.2005.006308

World Economic Forum. (2016). *World Economic Forum. Annual Report. Shaping the Future of Construction: A Breakthrough in Mindset and Technology.* https://www.weforum.org/publications/shaping-the-future-of-construction-a-breakthrough-in-mindset-and-technology/

Kumar, M. and Loganathan, S. 2026. A framework for parametric BIM implementation and design automation in transportation infrastructure projects in India. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 71-84. DOI: https://doi.org/10.31705/WCS.2026.6. Available from: https://ciobwcs.com/papers/

# A FRAMEWORK FOR PARAMETRIC BIM IMPLEMENTATION AND DESIGN AUTOMATION IN TRANSPORTATION INFRASTRUCTURE PROJECTS IN INDIA

**M. Kumar[1] and S. Loganathan[2]**

## *ABSTRACT*

*Transportation infrastructure projects in India are characterised by repetitive components, complex geometries, and multiple design parameters. However, design practices in such projects still rely heavily on two-dimensional drawings and manual three-dimensional modelling, which often lead to increased modelling effort, limited flexibility, and inconsistencies across similar structural elements. The integration of design automation with parametric Building Information Modelling (BIM) provides an approach to improve modelling efficiency, standardisation, and scalability in the design of transportation infrastructure projects. This study presents the implementation of Parametric BIM and design automation in a transportation infrastructure project in India through a case study of a typical bridge structure. A parametric BIM was developed in Autodesk Revit using structural design drawings, where key geometric dimensions was defined to enable flexible modification. Design automation was incorporated using the Dynamo visual programming platform, allowing automated control of parameters and rapid generation of multiple bridge configurations. The results indicate that the automated BIM approach significantly reduces modelling time, improves design adaptability, and enhances data consistency compared to conventional modelling methods. The developed framework also demonstrates scalability, making it suitable for linear infrastructure projects involving repetitive structures.*

***Keywords:*** *Building Information Modelling; Design Automation; Dynamo Visual Programming; Parametric Modelling; Transportation Infrastructure.*

## 1. INTRODUCTION

Transportation infrastructure is a key driver of economic development, regional connectivity, and urban expansion in emerging economies such as India. The country has witnessed significant growth in infrastructure investments through projects such as highways, railway corridors, metro systems, and bridge construction. These projects are inherently complex due to their linear nature, geographical dispersion, repetitive structural elements, and the need for coordinated execution across multiple work fronts.

[1] Post Graduate Student, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India; Senior Engineer, L&T Construction, Chennai, Tamil Nadu, India, dmanoj2905@gmail.com, orcid.org/0009-0005-4604-648X
[2] Assistant Professor, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India, lsanthosh@nitt.edu, orcid.org/0000-0003-2997-0599

Despite the increasing scale and complexity of infrastructure projects, design practices in India still predominantly rely on conventional two-dimensional (2D) drawings and manual three-dimensional (3D) modelling approaches (Rinchen et al., 2024). While 2D drawings serve as an essential communication medium, they often lack the capability to effectively represent spatial relationships and design intent, leading to challenges in visualisation and coordination. Manual 3D modelling enhances visualisation yet can be time-consuming and susceptible to inconsistencies, particularly in projects involving repetitive structural components such as culverts, minor bridges, and retaining structures. These limitations may result in increased modelling effort, reduced flexibility in accommodating design changes, and difficulties in maintaining standardisation across similar infrastructure projects.

BIM has emerged as a transformative digital approach that enables the creation of intelligent and information-rich models integrating geometric and non-geometric data within a collaborative environment (Doan et al., 2025). BIM enhances visualisation, coordination, and design understanding, allowing project stakeholders to identify potential conflicts and improve decision-making during the early design stages of the project (Waqar et al., 2026). Although BIM adoption has gained momentum in vertical construction, its application in transportation infrastructure projects, particularly in combination with design automation, remains relatively limited in the Indian context (Pirdavani et al., 2023).

Design automation, supported by parametric modelling and visual programming tools, provides a promising solution to address the challenges such as repetitive manual modelling tasks, design inconsistencies, coordination errors and time-consuming revisions, across complex infrastructure projects. Parametric modelling allows designers to define relationships between geometric parameters, ensuring that changes in input values automatically update the entire model. Visual programming environments further enable automated workflows and rule-based generation of design alternatives without extensive coding expertise.

However, practical case studies demonstrating the combined implementation of parametric BIM and design automation in Indian infrastructure projects are limited. This research addresses the gap by developing a structured framework for automated BIM, demonstrated through a bridge case study using Autodesk Revit and Dynamo scripts. The framework applies parametric modelling and rule-based automation to enhance modelling efficiency, flexibility, and scalability in transportation infrastructure design.

Therefore, this study aims to develop and demonstrate a structured automated BIM framework integrating parametric modelling and design automation for transportation infrastructure projects in India through a bridge case study using Autodesk Revit and Dynamo. The study further evaluates the effectiveness of the proposed framework in improving visualisation, modelling efficiency, design flexibility, and coordination compared to conventional design practices.

## 2. LITERATURE REVIEW

The literature review section reviews existing literature on conventional infrastructure design practices, Parametric BIM implementation, parametric modelling, and design automation. It critically examines previous research to identify technological advancements, implementation challenges, and research gaps related to automated BIM

workflows in transportation infrastructure projects, particularly within developing country contexts.

## 2.1 CONVENTIONAL DESIGN PRACTICES IN INFRASTRUCTURE PROJECTS

Design practices in infrastructure projects have traditionally relied on 2D drawings, spreadsheet-based calculations, and experience-driven decision-making. In transportation infrastructure projects such as bridges, culverts, and rail corridors, design information is typically communicated through multiple drawings, including general arrangement drawings, cross-sections, and reinforcement details. Studies indicate that these tools often operate independently, resulting in fragmented information flow and limited coordination between design disciplines (Hartmann et al., 2012). Such fragmented practices can lead to inconsistencies, increased effort in managing revisions, and coordination challenges in repetitive infrastructure components (Lu et al., 2019; Kaur et al., 2025).

## 2.2 ROLE OF BIM IN INFRASTRUCTURE DESIGN AND VISUALISATION

BIM has emerged as a digital approach that integrates geometric and non-geometric data within a single model, enhancing design visualisation and coordination. Research highlights that BIM improves spatial understanding of complex infrastructure elements and supports multidisciplinary collaboration compared to traditional drawings (Khan et al., 2024). Furthermore, BIM enables early clash detection, improved constructability analysis, and enhanced communication among project stakeholders, thereby reducing design conflicts. Despite these benefits, studies indicate that BIM adoption in transportation infrastructure remains less mature than in vertical construction due to implementation challenges and lack of tailored workflows (Castañeda et al., 2024).

## 2.3 PARAMETRIC MODELLING IN BIM

Parametric modelling is a key feature of BIM that enables the definition of relationships and constraints among geometric parameters. Researchers have demonstrated that parametric modelling improves design flexibility and consistency while reducing modelling errors (Ding et al., 2014). In infrastructure contexts, this capability is particularly useful for repetitive structural elements, as it supports standardised yet customisable design solutions (Wang et al., 2023). Additionally, parametric BIM provide structured data environments that facilitate downstream integration with scheduling and cost estimation processes (Sacks et al., 2022).

## 2.4 DESIGN AUTOMATION USING VISUAL PROGRAMMING

Design automation builds upon parametric modelling by enabling rule-based generation of BIM through visual programming tools such as Dynamo and Grasshopper. These tools allow designers to automate repetitive tasks, control geometric parameters, and rapidly generate multiple design alternatives. Studies suggest that automation improves modelling efficiency, minimises human errors, and enhances consistency across similar components (Ding et al., 2014). In linear infrastructure projects, visual programming has been shown to be particularly effective for generating repetitive structural elements along alignments, thereby improving scalability and productivity (Wang et al., 2023). Furthermore, automation facilitates advanced workflows such as generative design and optimisation, expanding the potential applications of BIM in infrastructure projects (Alizadehsalehi et al., 2021).

Although the literature highlights the individual benefits of BIM, parametric modelling, and design automation, their combined implementation in transportation infrastructure remains limited. Existing studies are largely concentrated on vertical construction, with fewer real-world case studies demonstrating automated BIM workflows for infrastructure assets, particularly in developing countries (Khattra et al., 2024). Barriers such as resistance to technological change, lack of skilled professionals, and uncertainty regarding return on investment have further slowed BIM adoption in infrastructure projects (Das et al., 2023). Moreover, there is a lack of structured frameworks illustrating how visual programming can be integrated with parametric BIM to address repetitive infrastructure design challenges.

This research addresses the identified gaps by proposing and implementing a structured framework for automated BIM, demonstrated through a practical bridge case study in India. The framework integrates parametric modelling and design automation to establish a systematic workflow, thereby providing empirical insights into scalable and efficient BIM automation for transportation infrastructure projects.

## 3. RESEARCH METHODOLOGY

This study adopts an implementation-oriented case study methodology to investigate the integration of automated BIM and design automation in transportation infrastructure projects in India through a Road Under Bridge (RUB) case study. Initially, a comprehensive literature review was conducted to identify research gaps related to BIM implementation, parametric modelling, and automation workflows in infrastructure projects. Based on the identified gaps, the research objectives and framework were formulated. Subsequently, project data were collected and analysed to understand the structural configuration and repetitive components of the selected bridge. Critical geometric and structural parameters were identified and structured into primary and secondary parameters with predefined logical relationships and constraints. Parametric BIM families were then developed in Autodesk Revit for structural components such as box sections and retaining walls by incorporating reference planes, dimensional constraints, and parametric formulas. Following this, Autodesk Dynamo visual programming was integrated with Revit to automate repetitive modelling operations. The developed automation scripts facilitated automatic propagation of parameter changes across interconnected components, thereby reducing manual modelling effort and improving design consistency. Multiple design alternatives were generated by varying predefined input parameters to evaluate modelling flexibility, scalability, and constructability feasibility. Finally, the effectiveness and practical relevance of the proposed automated BIM framework were validated through expert feedback collected from transportation infrastructure professionals using questionnaires and discussions.

## 4. PROPOSED FRAMEWORK FOR AUTOMATED BIM IMPLEMENTATION

To address the identified gap in structured integration of parametric modelling and design automation within transportation infrastructure projects, this study proposes a systematic automated BIM implementation framework as illustrated in Figure 1.

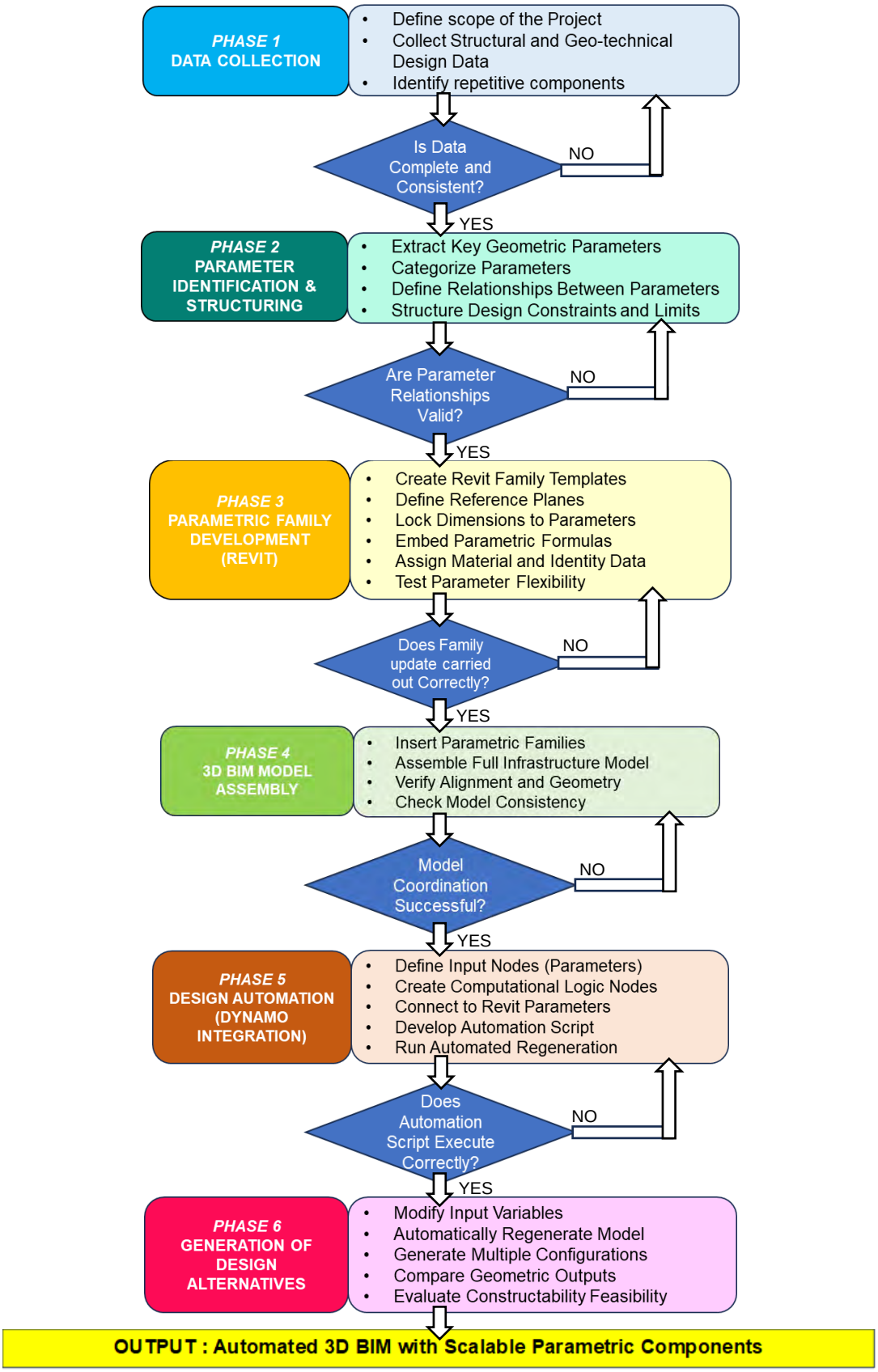



*Figure 1: Framework for automated BIM implementation*

# 5. DEVELOPMENT OF BIM PROJECT

After establishing the proposed framework for automated BIM implementation, the following section presents its application within a selected transportation infrastructure case study in India. The framework is utilised to develop an automated BIM project of a RUB minor bridge, demonstrating how structured phases of data preparation, parametric modelling, and automation enable efficient model generation and design flexibility.

## 5.1 PHASE 1: DATA COLLECTION

The data collection phase establishes the technical foundation for implementing the automated BIM framework. In accordance with the case study methodology adopted in this research, comprehensive design documentation was compiled, including general arrangement drawings, cross-sectional details, structural design calculations, and geo-technical investigation reports. These documents were systematically reviewed to understand the structural configuration, dimensional standards, and alignment characteristics of the selected bridge.

Emphasis was placed on identifying repetitive structural components such as box sections and retaining walls, which are typical in minor bridges in transportation infrastructure projects. Governing dimensions, thickness specifications, material properties, and geometric constraints were extracted and organised for digital translation. Additionally, alignment references and elevation data were examined to ensure spatial accuracy during model development.

This structured and analytical review ensured that the subsequent parametric modelling and automation processes were grounded in validated engineering inputs, thereby, minimising inconsistencies and supporting reliable rule-based model generation.

## 5.2 PHASE 2: PARAMETER IDENTIFICATION AND STRUCTURING

Following the systematic compilation of design data, the second phase focused on transforming conventional drawing information into structured, controllable modelling parameters. Based on the reviewed structural and general arrangement drawings, critical geometric variables such as span length, box width, deck slab thickness, wall thickness, foundation depth, and vertical clearances were identified. These variables were categorised into primary driving parameters (independent variables controlling overall geometry) and secondary dependent parameters (dimensions governed by predefined relationships).

Hierarchical control logic was established to ensure that modifications to primary parameters would consistently update related geometric elements. Constraint rules and parametric formulas were defined to preserve structural proportions and maintain dimensional integrity. Boundary conditions and permissible design ranges were incorporated to prevent invalid configurations and ensure engineering feasibility.

This structured parameter mapping created a robust computational framework that enabled seamless integration with Revit families and Dynamo automation, forming the core logic for reliable and scalable automated BIM generation.

## 5.3 PHASE 3: PARAMETRIC FAMILY DEVELOPMENT (REVIT)

In this phase, parametric families were developed in Autodesk Revit to convert extracted parameters into BIM components. Family templates were created for structural elements such as box sections as shown in Figure 2 and retaining walls as shown in Figure 3, incorporating reference planes to control geometric behaviour.

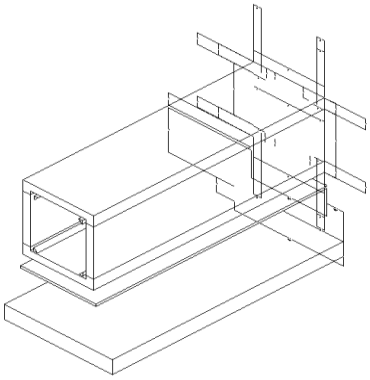


*Figure 2: Family – Box section*

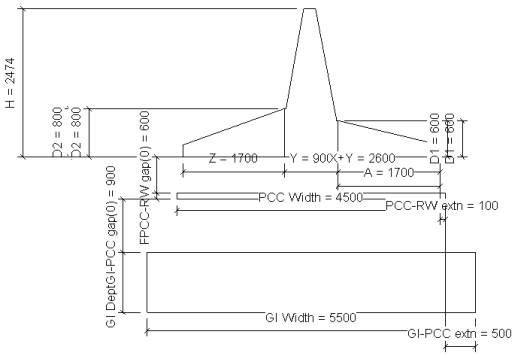



*Figure 3: Family – Retaining wall*

Critical dimensions were constrained and locked to predefined parameters to enable controlled adaptability. Parametric formulas were embedded to maintain relationships between thickness, height, and span variables, ensuring geometric integrity during modifications. Material properties and identity data were assigned to enrich information content. Flexibility testing was done by varying input parameters to validate model responsiveness, consistency, and compliance with structural design intent.

## 5.4 PHASE 4: BIM PROJECT CREATION

Following parametric family development, the validated families were instantiated and assembled to generate the complete BIM project of the bridge infrastructure.

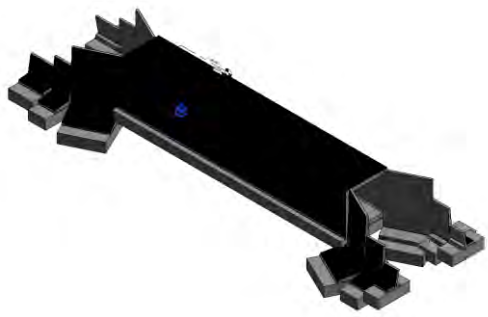


*Figure 4: Bridge – 3D view (a)*

*Figure 5: Bridge – 3D view (b)*

Parametric components such as box families and retaining wall families were positioned according to alignment references and structural layout requirements derived from the design drawings. Geometric alignment, connectivity, and dimensional consistency between components were systematically verified. Model coordination checks were conducted to ensure integration accuracy and eliminate spatial conflicts. This phase

resulted in a coherent, information-rich BIM project as shown in Figure 4 and 5 ready for automation integration and iterative design modification.

# 6. DESIGN AUTOMATION

## 6.1 PHASE 5: DESIGN AUTOMATION (DYNAMO INTEGRATION)

In this phase, design automation was implemented by integrating Autodesk Revit with the Dynamo visual programming environment to enable rule-based control of the parametric BIM. Dynamo scripts were developed to access and manipulate Revit family parameters identified in earlier phases. Input nodes were used to define variable geometric parameters, while computational and logical nodes processed relationships governing component dimensions and spatial configurations. The scripts established a bidirectional data exchange between Dynamo and Revit, ensuring real-time synchronisation between input values and model geometry. Automation logic was designed for the box portion as shown in Figure 6 and the retaining wall portion as shown in Figure 7 to regulate repetitive modelling operations, including dimensional updates and component regeneration, thereby eliminating manual intervention. Any modification to input parameters automatically propagated throughout the interconnected model, preserving consistency across repetitive infrastructure elements.

*Figure 6: Box section automation code*

*Figure 7: Retaining wall section automation code*

The Dynamo scripts were developed and replicated across multiple components to efficiently generate the complete BIM project as shown in Figure 8.

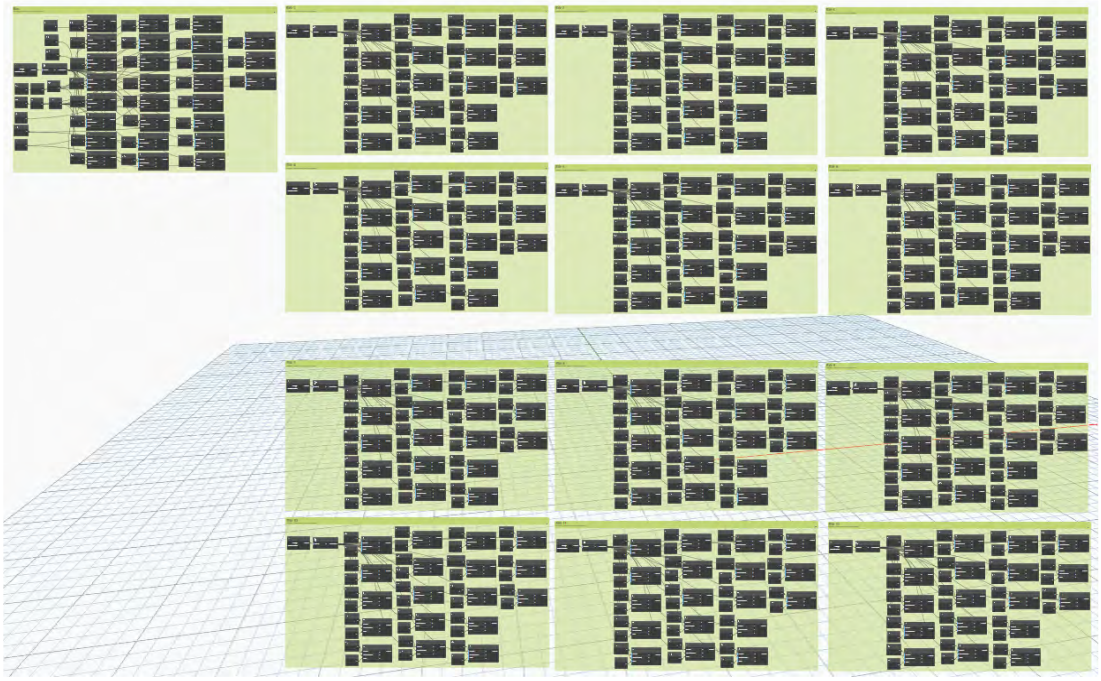


*Figure 8: Integrated Dynamo scripts to develop a project*

The automation process enabled rapid modification of design parameters and automatic regeneration of the BIM project without manual intervention. The automation workflow involved establishing a connection between Dynamo scripts and Revit parameters. Input nodes were used to define variable parameters, while computational nodes processed these inputs to update geometric relationships within the BIM project. The scripted logic ensured that any change in input parameters automatically propagated throughout the model, maintaining consistency across interconnected components. The workflow demonstrated effective data exchange between Revit and Dynamo, enabling a synchronised and automated modelling environment.

## 6.2 GENERATION OF DESIGN ALTERNATIVES

In this phase, the developed automation framework was leveraged to systematically generate and evaluate multiple bridge design configurations. By modifying predefined input parameters within the Dynamo interface; such as box section width, box slab thickness, retaining wall height, span length, and alignment offsets - the BIM project was automatically regenerated without manual remodelling. The embedded parametric constraints ensured that all dependent components updated consistently, preserving geometric relationships and structural integrity. This capability enabled rapid iteration of design scenarios to address varying site conditions, clearance requirements, and functional constraints typical of transportation infrastructure projects. Instead of creating separate models for each variation, a single parametric model dynamically responded to input adjustments. The generated alternatives were subsequently assessed for dimensional accuracy, constructability, and scalability across repetitive infrastructure segments. This phase demonstrated the efficiency, flexibility, and decision-support

capability of the automated BIM framework in supporting optimised infrastructure design development.

# 7. RESULTS AND DISCUSSION

The effectiveness of the proposed automated BIM framework was further evaluated through expert feedback obtained from 48 industry professionals involved in transportation infrastructure projects. The proposed framework, along with the developed BIM project, was presented to the professionals, and their opinions were collected to compare conventional project management practices such as the usage of 2D model drawings and disintegrated (or) partially integrated scope-schedule-cost Management with BIM-enabled project workflows. The questionnaire included questions covering key project management aspects such as integration, scope, schedule, cost, quality, resource, risk, procurement, communication, and stakeholder management. Respondents were asked to evaluate the performance of conventional methods and BIM-integrated approaches across these dimensions. The expert opinion survey was conducted to understand the practical relevance, perceived benefits, and implementation challenges of integrating parametric BIM and design automation in transportation infrastructure projects. The insights obtained from the survey support the interpretation of the case study results and provide industry-oriented validation of the proposed workflow.

## 7.1 IMPROVEMENT IN VISUALISATION AND DESIGN UNDERSTANDING

The results obtained from the expert survey and follow-up interviews indicate that the adoption of automated BIM significantly improves visualisation and design understanding compared to conventional 2D drawing-based practices. Most respondents reported that automated BIM provide clearer spatial representation of infrastructure components, enabling better interpretation of complex structural layouts. The survey results indicated an improvement of approximately 52% in visual reporting and presentation of project information when compared to conventional methods. Experts also highlighted during interviews that automated BIM enhances communication of design intent and facilitates better coordination among multidisciplinary teams, thereby supporting improved decision-making and early identification of potential design conflicts.

## 7.2 REDUCTION IN MANUAL EFFORT THROUGH DESIGN AUTOMATION

The findings obtained from the expert survey and follow-up interviews indicate that integrating design automation with BIM significantly reduces manual effort associated with repetitive modelling tasks in infrastructure projects. Survey responses showed an improvement of approximately 39% in reducing manual effort in design preparation and planning activities compared to conventional workflows. Experts highlighted during interviews that automation tools such as Dynamo enable rapid generation and modification of repetitive infrastructure components, thereby minimising manual modelling time. In addition to improving efficiency and productivity, respondents noted that automated BIM workflows support sustainability by reducing design rework, optimising resource utilisation, and enabling more efficient planning of infrastructure components.

## 7.3 IMPROVED DESIGN FLEXIBILITY AND CHANGE MANAGEMENT

Expert survey responses and follow-up interviews indicate that the integration of BIM and design automation enhances design flexibility and supports more effective change management in infrastructure projects. The survey responses showed an improvement of approximately 16% in parameters related to scope clarity and variation management when compared to conventional design approaches. During the interviews, industry professionals emphasised that the parametric nature of BIM enables rapid modification of geometric parameters, allowing changes to automatically propagate across interconnected model components. This capability reduces the need for extensive manual remodelling and facilitates quicker implementation of design revisions, which is particularly beneficial in transportation infrastructure projects where alignment changes and design modifications occur frequently.

## 7.4 REDUCTION IN ERRORS AND IMPROVED DESIGN CONSISTENCY

Quality-related survey responses indicated reductions in design errors and rework by 24% when using automated BIM. Traditional design workflows often involve manual data transfer between drawings and models, increasing the risk of inconsistencies. In contrast, automated parametric models ensure standardised generation of infrastructure components, improving consistency and reliability of design outputs. This reduction in errors not only enhances design quality yet contributes to improved constructability and reduced downstream rework.

## 7.5 COMMUNICATION AND COLLABORATION BENEFITS

Another significant outcome of BIM adoption was improved communication and collaboration among project stakeholders. Survey findings showed improvements of approximately 48% in transparency of project information and communication efficiency. The use of automated BIM enables stakeholders to visualise design elements collectively, facilitating multidisciplinary coordination and informed decision-making. This enhanced communication capability is particularly beneficial in infrastructure projects where teams are geographically distributed and require a shared understanding of design information.

## 7.6 CHALLENGES IN IMPLEMENTING PARAMETRIC BIM AND DESIGN AUTOMATION

Despite the demonstrated benefits, expert opinions identified several challenges associated with implementing parametric BIM and design automation. Limited awareness and uneven technical expertise among stakeholders were highlighted as primary barriers to adoption. Additionally, the development of parametric families and automation scripts requires an initial investment of time and technical skill, which may discourage early implementation. Practical constraints such as limited availability of BIM-enabled hardware and software at site level and resistance to adopting new workflows were also reported as challenges. These findings suggest that successful adoption of BIM automation requires organisational support, training initiatives, and appropriate technological infrastructure.

### 7.7 DISCUSSION

The findings of the present study demonstrate that integrating parametric BIM with design automation provides measurable improvements over traditional design practices in transportation infrastructure projects. Enhanced visualisation improves design understanding and coordination, while automation significantly reduces manual modelling effort and increases productivity. The parametric nature of automated BIM supports efficient design modifications and ensures consistency across repetitive infrastructure components. However, the gap between awareness and implementation highlights the need for targeted training, standardisation of workflows, and improved technological readiness to support BIM automation adoption.

Overall, the results confirm that parametric BIM and design automation serve as a robust digital foundation for improving infrastructure design processes. By enhancing visualisation, efficiency, and collaboration, automated BIM workflows contribute to more reliable and scalable design practices and provide a pathway for future integration with advanced BIM dimensions and digital project delivery frameworks. Furthermore, the adoption of automated BIM processes can support broader sustainability goals in infrastructure development by enabling optimised resource utilisation, reducing design rework, improving material estimation accuracy, and supporting environmentally responsible planning and decision-making throughout the project lifecycle. These outcomes align with the objectives of Sustainable Development Goal (SDG) 9: Industry, Innovation and Infrastructure, SDG 11: Sustainable Cities and Communities, and SDG 12: Responsible Consumption and Production, which emphasise resilient infrastructure development, sustainable urban planning, and efficient use of resources in construction practices.

## 8. CONCLUSIONS

This study investigated the implementation of parametric BIM integrated with design automation for transportation infrastructure projects in India through a RUB minor bridge case study. The findings indicate that the combined use of parametric modelling and visual programming significantly enhances design efficiency, visualisation, and consistency compared to traditional design practices. Khan et al. (2024) highlighted that BIM improves collaborative design processes and enhances communication among project stakeholders, which aligns with the improved visualisation and coordination observed in this study.

The integration of automation reduced manual modelling effort and enabled rapid generation of repetitive infrastructure components. This finding and the ability of the automated 3D model is consistent with Ding et al. (2014), who demonstrated that parametric BIM enhances modelling efficiency, and with Wang et al. (2023), who reported that automation improves scalability and consistency in linear infrastructure projects.

Despite these advantages, the study has certain limitations. The research focused on a single infrastructure case study, which may limit the generalisability of the results across other infrastructure asset types. Additionally, the automation framework primarily addressed geometric modelling pertaining to the design and planning phase of the project. These limitations reflect the challenges identified by Khattra et al. (2024) and Das et al. (2023), who reported that BIM adoption in infrastructure projects is constrained by skill

gaps, technological barriers, and organisational readiness across different phases of the project.

Future research should extend automated BIM workflows toward integration with scheduling, cost management, and real-time monitoring systems. Integrating automation with advanced technologies such as generative design and digital twins can further improve infrastructure lifecycle performance. These developments can also support sustainable infrastructure planning by optimising resource utilisation, minimising design rework, and contributing to SDG 9, SDG 11, and SDG 12, which promote resilient infrastructure and responsible resource use.

# 9. REFERENCES

Abanda, F.H., Vidalakis, C., Oti, A.H., & Tah, J.H.M. (2015). A critical analysis of building information modelling systems used in construction projects. *Advances in Engineering Software*, 90, 183–201. https://doi.org/10.1016/j.advengsoft.2015.08.009

Alizadehsalehi, S., Hadavi, A., & Huang, J.C. (2021). Assessment of AEC students' performance using BIM-into-VR. *Applied Sciences*, 11(7), 3225. https://doi.org/10.3390/app11073225

Alshehri, A.M., Al Hajji, F., Waqar, A., Bageis, A.S., Houda, M., & Benjeddou, O. (2024). Building information modeling (BIM) driven performance-based construction for the optimization of sustainable and smart structures development. *Environmental Challenges*, 16, 100980. https://doi.org/10.1016/j.envc.2024.100980

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., & O'Reilly, K. (2011). BIM adoption and implementation for architectural practices. *Structural Survey*, 29(1), 7–25. https://doi.org/10.1108/02630801111118377

Auti, A., & Skitmore, M. (2008). Construction project management in India. *International Journal of Construction Management*, 8(2), 1–15. https://doi.org/10.1080/15623599.2008.10773116

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, 11(3), 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Barlish, K., & Sullivan, K. (2012). How to measure the benefits of BIM—A case study approach. *Automation in Construction*, 24, 149–159. https://doi.org/10.1016/j.autcon.2012.02.008

Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management*, 138(3), 431–442. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000433

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). *Building information modelling: Technology foundations and industry practice*. Springer. https://doi.org/10.1007/978-3-319-92862-3

Bryde, D., Broquetas, M., & Volm, J.M. (2013). The project benefits of BIM. *International Journal of Project Management*, 31(7), 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001

Castañeda, K., Sánchez, O., Herrera, R.F., Gómez-Cabrera, A., & Mejía, G. (2024). Building information modeling uses and complementary technologies in road projects: A systematic review. *Buildings*, 14(3), 563. https://doi.org/10.3390/buildings14030563

Cheng, J.C.P., & Ma, L.Y.H. (2013). BIM-based system for demolition and renovation waste estimation. *Waste Management*, 33(6), 1539–1551. https://doi.org/10.1016/j.wasman.2013.01.001

Das, P., Hijazi, A.A., Maxwell, D.W., & Moehler, R.C. (2023). Can Business Models Facilitate Strategic Transformation in Construction Firms? A systematic review and research agenda. *Sustainability*, 15(17), 13022. https://doi.org/10.3390/su151713022

Ding, L., Zhou, Y., & Akinci, B. (2014). BIM application framework: Expanding from 3D to computable nD. *Automation in Construction*, 46, 82–93. https://doi.org/10.1016/j.autcon.2014.04.009

Doan, D. T., Atencio, E., Rivera, F. M. L., & Alnajjar, O. (2025). A systematic literature review of building information modelling (BIM) and offsite construction (OSC) integration: Emerging technologies and future trends. *Applied Sciences, 15*(18), 8981. https://doi.org/10.3390/app15189981

Gao, X., Wu, Y., & Li, Y. (2019). Information integration of construction project management based on BIM. *IOP Conference Series: Earth and Environmental Science*, 267(3), 032069. https://doi.org/10.1088/1755-1315/267/3/032069

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption. *Automation in Construction*, 19(8), 988–999. https://doi.org/10.1016/j.autcon.2010.09.002

Hartmann, T., van Meerveld, H., Vossebeld, N., & Adriaanse, A. (2012). Aligning BIM tools and construction management methods. *Automation in Construction*, 22, 605–613. https://doi.org/10.1016/j.autcon.2011.12.011

Jagadeesh, G.M., & Jagadisan, S. (2019). Investigation of BIM adoption in India. *IJERT*, 8(11), 1–5. https://www.ijert.org/research/investigation-of-bim-adoption-in-india-IJERTV8IS110124.pdf

Kassem, M., & Succar, B. (2017). Macro BIM adoption: Comparative market analysis. *Automation in Construction*, 81, 286–299. https://doi.org/10.1016/j.autcon.2017.04.005

Kaur, A., Garia, S., Singh, K., Singh, R., & Kumar, R. (2025). A comprehensive review on building information modelling (BIM), its implementations and applications. *Discover Civil Engineering*, *2*(177). https://doi.org/10.1007/s44290-025-00342-5

Khan, A.A., Bello, A.O., Arqam, M., & Ullah, F. (2024). Integrating Building Information Modelling and Artificial Intelligence in Construction Projects: A review of challenges and mitigation strategies. *Technologies*, 12(10), 185. https://doi.org/10.3390/technologies12100185

Khattra, S.K., & Jain, R. (2024). BIM overview of concepts and applications. *Advances in Research*, 25(5), 140–149. https://doi.org/10.9734/air/2024/v25i51145

Linderoth, H.C.J. (2010). Understanding adoption and use of BIM as the creation of actor networks. *Automation in Construction*, 19(1), 66–72. https://doi.org/10.1016/j.autcon.2009.09.003

Love, P.E.D., Matthews, J., Simpson, I., Hill, A., & Olatunji, O. (2014). A benefits realization management building information modeling framework for asset owners. *Automation in Construction*, 37, 1–10. https://doi.org/10.1016/j.autcon.2013.09.007

Lu, W., Xu, J., & Söderlund, J. (2019). Exploring the Effects of Building Information Modeling on Projects: Longitudinal Social Network Analysis. *Journal of Construction Engineering and Management*, 145(10), 04019082. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001823

Pirdavani, A., Muzyka, S., Vandervoort, V., & Van Hoye, S. (2023). Application of building information modeling (BIM) for transportation infrastructure: A scoping review. *Transportation Research Procedia*, *73*, 110–117. https://doi.org/10.1016/j.trpro.2023.11.898

Rinchen, S., Banihashemi, S., & Alkilani, S. (2024). Driving digital transformation in construction: Strategic insights into building information modelling adoption in developing countries. *Project Leadership and Society*, *5*, 100138. https://doi.org/10.1016/j.plas.2024.100138

Sacks, R., Wang, Z., Ouyang, B., Utkucu, D., & Chen, S. (2022). Toward Artificially Intelligent Cloud-based Building Information Modelling for Collaborative Multidisciplinary Design. *Advanced Engineering Informatics*, 53, 101711. https://doi.org/10.1016/j.aei.2022.101711

Succar, B. (2009). Building Information Modelling Framework: A research and delivery foundation for industry stakeholders. *Automation in Construction*, 18(3), 357–375. https://doi.org/10.1016/j.autcon.2008.10.003

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modelling (BIM) for Existing Buildings - Literature review and future needs. *Automation in Construction*, 38, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Wang, T., & Chen, H.M. (2023). Integration of building information modelling and project management in construction project life cycle. *Automation in Construction*, 150, 104832. https://doi.org/10.1016/j.autcon.2023.104832

Waqar, A., Alrasheed, K. A., & Almujibah, H. R. (2026). A BIM-infused Perspective on Enhanced Visualization and Design Analysis for the Residential Construction. *KSCE Journal of Civil Engineering*, *30*(3), Article 100412. https://doi.org/10.1016/j.kscej.2025.100412

Zhang, J., & Hu, Z. (2011). BIM- and 4D-based Integrated Solution of Analysis and Management for Conflicts and Structural Safety Problems During Construction: 1. Principles and methodologies. *Automation in Construction*, 20(2), 155–166. https://doi.org/10.1016/j.autcon.2010.09.013

Arsecularatne, B.P., Rodrigo, N., and Chang, R., 2026. A methodology for selecting a digital twin platform for application development in construction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 85-98. DOI: https://doi.org/10.31705/WCS.2026.7. Available from: https://ciobwcs.com/papers/

# A METHODOLOGY FOR SELECTING A DIGITAL TWIN PLATFORM FOR APPLICATION DEVELOPMENT IN CONSTRUCTION

**B.P. Arsecularatne[1], N. Rodrigo[2] and R. Chang[3]**

## *ABSTRACT*

*Digital Twin Platforms (DTPs) are being utilised more frequently to facilitate predictive analysis, energy management, carbon emissions reduction, and building operations. Nevertheless, selecting a suitable DTP remains difficult due to the significant variation in platform capabilities, costs, interoperability, usability, and technical complexity. The study provides a systematic methodology for selecting appropriate DTPs to develop Digital Twin (DT) applications. Academic literature, industry reports, software documentation, and vendor websites were reviewed to identify the key functionalities, characteristics, and requirements of DTPs in the construction sector. 12 currently available DTPs were analysed, and the underlying technology and purpose of each were identified. A set of evaluation criteria was then established. The methodology allows users to assign weightings to an established criterion in accordance with operational priorities and project-specific requirements. The most suitable DTP for the intended application is subsequently determined by calculating weighted scores. The methodology was tested using a building-focused DT case study aimed at improving energy efficiency and reducing carbon emissions. The DTP proposed by this developed methodology for the case study was a simulation-based platform, given the study's emphasis on energy modelling, affordability, ease of use, and educational accessibility. The findings demonstrate that the methodology provides a practical, structured approach to selecting DTPs while balancing technical capability, usability, and cost.*

***Keywords:*** *Carbon Emission; Digital Twin Platform; Energy Efficiency; Methodology; Sustainability.*

## 1. INTRODUCTION

The construction industry (CI) represents a significant portion of worldwide energy consumption, including approximately 32% of total energy demand and 34% of CO2 emissions, with operational emissions peaking at 9.8 gigatonnes and embodied carbon estimated at 2.9 gigatonnes (United Nations Environment Programme, 2025). The sector

[1] PhD Candidate, School of Civil Engineering and Construction Management, Adelaide University, Australia, buddhika.arsecularatne@adelaide.edu.au
[2] Senior Lecturer, School of Civil Engineering and Construction Management, Adelaide University, Australia, navodana.rodrigo@adelaide.edu.au
[3] Associate Professor, School of Civil Engineering and Construction Management, Adelaide University, Australia, ruidong.chang@adelaide.edu.au

is not on track to meet net-zero carbon and climate resilience targets by 2050, as progress is slow and scattered (United Nations Environment Programme, 2025). Integrating sustainability considerations with developing technologies, like DT, allows for real-time decision-making and performance optimisation throughout a building's life cycle (Kaewunruen et al., 2020). DTs were initially used in aeronautics but are now widely used in other industries (Ferr et al., 2022). The CI has experienced a substantial increase in the use of DT applications, with this trend more pronounced since 2023 (Arsecularatne et al., 2025), but DT applications were not widely adopted in the CI until 2018 (Opoku et al., 2021). DTs are currently being applied across a wide range of purposes in CI, including real-time structural health monitoring, cost estimation, greenhouse gas emissions tracking, on-site safety monitoring, and off-site construction management (Han et al., 2025; Liu et al., 2023; Moghimi et al., 2026; Wang et al., 2026). Apart from that, by facilitating the simulation of design possibilities, evaluating their impact on time constraints and costs, and fostering collaboration among stakeholders, the utilisation of DT improves project planning and management (Arsecularatne et al., 2024). DT also plays a significant role throughout the building lifecycle, mainly in the operational phase by improving energy efficiency, reducing carbon emissions, enhancing occupant comfort, optimising building performance, and supporting predictive maintenance strategies (Geng et al., 2026; B. Arsecularatne et al., 2024; Sayed et al., 2025; Bibri & Huang, 2025; de las Morenas et al., 2025). When using DT technology, it's important to consider how to design a fit-for-purpose solution (Dodero et al., 2025).

Off-the-shelf DT solutions for the construction sector are becoming more widely available from software suppliers, building information modelling (BIM) providers, and equipment manufacturers. Examples are Autodesk Tandem (Autodesk, 2026), Bentley Digital Twins (Bentley, 2026) and ProtoTwin (Prototwin, 2026). However, some level of work is usually required when deploying a DTP. Despite the growing availability of DTP in the CI, there is still a lack of a structured methodology to guide researchers and practitioners, particularly those without extensive technical expertise, in selecting the most appropriate platform for their specific project requirements. In light of this, this study aims to develop a methodology for choosing an appropriate DTP for construction applications by accomplishing the following objectives: (1) review the existing literature on DTPs and platform features; and (2) identify and assess the primary factors influencing the choice of DTPs. By accomplishing these objectives, the study hopes to provide researchers and professionals in the construction sector with a systematic understanding of DTPs, their mandatory selection criteria, and their suitability for various construction-related requirements. This will facilitate better decision-making when choosing appropriate DTPs for infrastructure and building applications.

## 2. LITERATURE REVIEW

This section provides a complete summary of the findings from the content analysis conducted for this study. The section describes the range of existing DTPs available for construction-related use cases

The DT is regarded as the next generation of modelling, simulation, and optimisation approaches since it can accurately represent the dynamic mapping between physical objects and their digital equivalents (Rosen et al., 2015). DTs consist of three primary components: the physical asset, its virtual representation, and the communication link that enables data exchange between the two (Wagg *et al.*, 2020; Abdelrahman *et al.*, 2025).

In addition to them, it encompasses (4) real-time capabilities, (5) real-time synchronisation of the digital system with the physical system, and (6) decision support capabilities (Deren et al., 2021; Boschert & Rosen, 2016). The virtual component of the DT is developed and managed within a dedicated DTP, which provides the tools and environment required for modelling, simulation, visualisation, and data integration (Ibrahim et al., 2023). DTPs needed to have features such as configurability, scalability, modifiability, and extendibility for DT models, data, algorithms, IoT connectivity, interaction, simulation, and visualisation, and should be comprehensive, universal, and developmental to meet the different needs of users (Tao et al., 2024). The DTP selection was based on an evaluation of its capabilities, including synchronisation, real-time behaviour, interoperability, physical twin convergence, connectivity, data security, modifiability, reusability, and domain expert involvement (Lehner et al., 2022). DTPs heavily relied on data from multiple sources to build accurate and comprehensive DT models (Kandemir et al., 2024).

Major software companies and leaders in the manufacturing industry have increasingly introduced DTPs to support the development and operation of DTs. These platforms are available in both commercial and open-source forms, offering varying levels of functionality, flexibility, and accessibility to meet different user requirements (Khalifa & Marzouk, 2025). DTPs vary considerably in their intended use, ranging from engineering and manufacturing applications to building management and infrastructure monitoring. Table 1 summarise a few of the DTPs available for CI.

*Table 1: Digital twin platforms*

| Platform | Usage | Free trial | Subscription details | Focused Technology | Source |
|---|---|---|---|---|---|
| **Ansys Twin Builder (P1)** | Simulation-driven digital twins for engineering, product design, and operational optimisation | Trial duration varies | Subscription-based pricing, with various plans depending on simulation complexity and support services | Simulation | (Ansys, 2024) |
| **Autodesk Forge (P2)** | BIM, digital twin visualisation, and integration with other Autodesk tools | Trial for 90 days | Subscription-based on API usage; various plans available | BIM | (Autodesk, 2024) |
| **Azure Digital Twins (P3)** | IoT integration, building management, real-time monitoring, and predictive maintenance | Trial period details vary | Pay-as-you-go model; pricing based on usage of instances, messages, and queries | Internet of Things (IoT) | (Microsoft, 2024) |
| **Bentley iTwin (P4)** | Infrastructure digital twins, asset performance, and | Trial duration varies | Usage-based pricing model, with different tiers depending on data | BIM + IoT + Simulations | (Bentley Systems, 2024) |

| Platform | Usage | Free trial | Subscription details | Focused Technology | Source |
|---|---|---|---|---|---|
| | engineering data integration | | volume and services | | |
| **Cityzenith SmartWorldPro2 (P5)** | Urban planning, smart cities, and building management | Free trial for 30 days | Subscription-based, tiered pricing model based on project scale and features | BIM | (Cityzenith, 2021) |
| **Dassault Systèmes 3DEXPERIENCE (P6)** | Product lifecycle management, digital twins for manufacturing, engineering, and construction | Trial duration varies | Subscription-based pricing, with different tiers based on the number of users, features, and support levels | Simulation | (Dassault Systèmes, 2024) |
| **GE Predix (P7)** | Industrial IoT, asset performance management, and operational efficiency | Trial duration varies | Custom pricing based on usage, number of assets, and data volume | IoT | (General Electric, 2024) |
| **IBM Digital Twin Exchange (P8)** | Asset management, predictive maintenance, and operational optimisation | Trial duration varies | Subscription-based pricing, with options for different levels of service and support | IoT | (IBM, 2024) |
| **OpenTwin (P9)** | An open-source digital twin software platform primarily for product development, lifecycle management, simulation integration, and collaborative workflows. | Free | Free | Simulation | (OpenTwin, 2025) |
| **Proto Twin (P10)** | A browser-based and application-based industrial simulation platform for robotics systems and dynamic systems | Free trial available | Subscription-based, The educational version is free | Simulation | (Prototwin, 2025) |
| **Siemens MindSphere (P11)** | Industrial IoT, manufacturing, building automation, and | Free trial for 30 days | A tiered subscription model, based on the number of | IoT | (Siemens, 2024) |

| Platform | Usage | Free trial | Subscription details | Focused Technology | Source |
|---|---|---|---|---|---|
| | energy management | | connected assets and data volume | | |
| **Willow Twin (P12)** | Real estate, smart buildings, and infrastructure management | Free trial upon request | Subscription-based pricing, depending on the number of assets and the scope of services | BIM | (Willow, 2021) |

The comparison shows that most DTPs are commercial tools with subscription-based pricing models, limited free trials, and varied levels of support for BIM integration, simulation, IoT connectivity, and predictive analytics. Building management, infrastructure monitoring, energy analysis, and asset performance are all supported by platforms such as Bentley iTwin, Autodesk Forge, Azure Digital Twins, and Willow Twin, which are specifically pertinent to the built environment.

## 3. RESEARCH METHODOLOGY

This study employs a qualitative and comparative research approach to develop a structured methodology for selecting appropriate DTPs for construction applications. The study largely relies on a structured literature-based comparative evaluation approach to identify, analyse, and assess DTPs. The literature review aims to highlight the essential characteristics, functionalities, and prerequisites of DTPs. Academic papers, industry reports, software documentation, and vendor websites were examined to comprehend the current application of DTPs in the construction sector and to identify the most critical criteria for platform selection. The inclusion criteria focused on studies related to DT implementation in the construction and built environment sectors and platforms, particularly those associated with building operations, energy management, carbon reduction, IoT integration, simulation capabilities, and real-time data synchronisation. In addition, the availability of free trial access, educational versions, or research access was considered to ensure that the platforms could be practically explored and evaluated in an academic research context. To enhance the reliability of the comparative assessment, platform capabilities were cross-checked using multiple information sources, including official platform documentation, published academic studies, technical specifications, implementation case studies, and customer feedback. This helped to minimise potential bias associated with relying solely on vendor-provided information.

Following the literature review, the DTP selection methodology was identified. The proposed DTP selection methodology as shown in Figure 1 follows a structured decision-making process tailored to the operational requirements of the intended DT application. The process begins with identifying the functional and operational needs of the DT. Based on the identified requirements, weights are assigned to the DTP assessment criteria according to their relative importance within the selected application context. The weighted evaluation is then conducted using the Simple Multi-Attribute Rating Technique (SMART) to comparatively assess and rank the DTPs identified. This process enables the identification of the highest-ranked and most suitable platform options for the intended application. Following the ranking process, the operational requirements and practical suitability of the highest-rated platforms are further reviewed. If the highest-ranked platform is considered suitable for the identified DT requirements, the DT

development process proceeds using the selected platform. If limitations or incompatibilities are identified during the suitability assessment stage, the next highest-ranked platform is evaluated and considered for implementation.

Based on literature DTPs were classified based on their principal functioning and construction significance. Platforms can be categorised as BIM-oriented, IoT-driven, simulation-focused, or fully integrated digital twin environments, based on underlying technology (Refer to Table 1). These platforms were selected based on their relevance to building operational management, accessibility for research and educational purposes, availability of free trial or educational versions, interoperability capabilities, IoT integration support, simulation functionality, scalability, visualisation features, and applicability to energy and carbon management scenarios. This DTP classification helps to identify the advantages and drawbacks of various platforms based on their intended use. As a first step, a set of criteria for platform selection was formulated. Criteria were formulated because the platform evaluation was conducted using a multi-criteria decision-making method, namely the SMART. There are several studies, such as Nanayakkara et al. (2021), and Dodero et al. (2025) that have used SMART when evaluating and selecting the most suitable platform for an application. The criteria were chosen for their relevance to the construction industry, ensuring alignment with essential requirements across all stages of the building life cycle and within the project budget. The criteria contain BIM compatibility, IoT integration, real-time data synchronisation, interoperability, scalability, visualisation capability, simulation support, energy and carbon modelling capability, artificial intelligence integration, user-friendliness, licensing costs, and educational accessibility. These criteria aim to establish a systematic methodology for evaluating DTPs pertinent to both scholars and practitioners. The DTP selection methodology is shown in Figure 1.

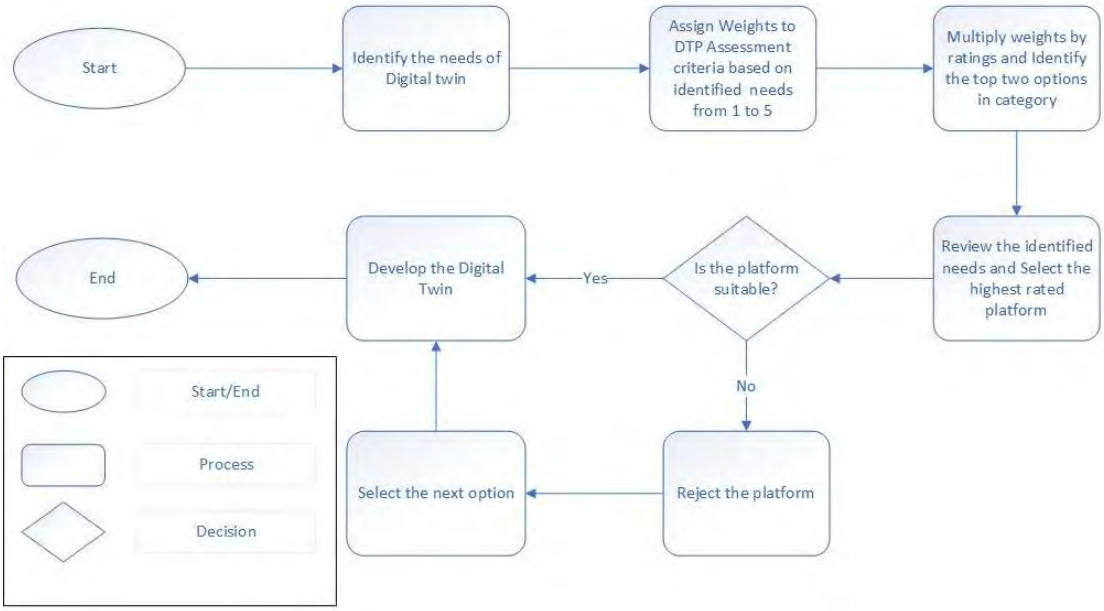



*Figure 1: DTP selection methodology*

Following the identification of the assessment criteria (DTPs assessment criteria), ratings were assigned to each criterion based on DTPs, software documentation, and user

feedback. To test and demonstrate the proposed methodology, a university classroom was selected as the case study environment, with particular emphasis on improving operational energy efficiency and reducing carbon emissions. The university classroom was considered an appropriate case study due to its variable occupancy patterns and intensive daily use. Based on the characteristics and operational requirements of the selected classroom environment, the key functional requirements of the DT were identified. Based on that, weights were given to the criterion in the assessment criteria (Refer to Table 3). Subsequently, weighted scores were given to each platform (Refer to Table 4), followed by relevant calculations (See Table 5 and Table 6) to select the most suitable DTP for developing the DT model.

This Methodology aims to assist future academics and practitioners in making informed choices when selecting digital twin platforms that align with their specific project objectives, technical specifications, and resource constraints.

## 4. FINDINGS, RESULTS AND DISCUSSION

This section presents the study's findings and results. Firstly, the study developed a comprehensive set of assessment criteria, organised into distinct categories, to assist stakeholders in selecting an acceptable DTP. The criteria were established by studying the research conducted by Dodero et al., (2025). This guaranteed a relationship between user needs and platform functionalities.

Table 2 presents the key evaluation criteria for assessing DTPs. These criteria give a formal basis for assessing different platforms in terms of their technical functionality, usability, and applicability for research and industrial applications.

*Table 2: DTPs assessment criteria*

| Criteria | Key Items to Assess |
|---|---|
| BIM compatibility (A) | IFC support; Revit integration; CAD/BIM model import; asset metadata handling; clash detection capability |
| IoT integration (B) | Sensor connectivity; MQTT/API support; device compatibility; cloud platform integration; real-time sensor dashboards |
| Real-time data synchronisation (C) | Live data streaming; refresh frequency; bidirectional updates; latency performance; historical data logging |
| Interoperability (D) | Open standards support; API availability; third-party software integration; database compatibility; cross-platform connectivity |
| Scalability (E) | Ability to manage multiple buildings; support for large sensor networks; cloud scalability; multi-user access; performance under high data loads |
| Visualisation capability (F) | 2D/3D visualisation; dashboard customisation; immersive/AR/VR support; real-time graphical updates |
| Simulation support (G) | Energy simulation; occupancy simulation; scenario testing; predictive modelling |
| Energy and carbon modelling capability (H) | Energy consumption analysis; operational carbon tracking; embodied carbon assessment; net-zero scenario testing; sustainability reporting |

| Criteria | Key Items to Assess |
|---|---|
| DTP category (I) | Main platform purpose; dominant technical capabilities; typical application areas; level of visualisation and analytics support; degree of integration and operational functionality |
| Artificial intelligence integration (J) | Machine learning support; predictive analytics; anomaly detection; optimisation algorithms; automated decision-making |
| User-friendliness (K) | Ease of navigation, dashboard usability |
| Licensing costs (L) | Free trial availability; subscription cost; enterprise licensing; educational discounts |
| Educational accessibility (M) | Student version availability; academic licensing; tutorials and documentation; community support |

In the subsequent stage, users are required to have a comprehensive understanding of the assessment criteria delineating the DTP as specified in Table 2. This entails meticulously analysing the specified criteria, after which users must assign weights to these factors using a weight matrix on a scale of 1 to 5, where 1 denotes minimal relevance and 5 denotes maximal importance. Weightages will vary across users based on individual requirements. After evaluating assessment criteria in detail, weightages were assigned as per the requirements of the case study. The assigned weightages are illustrated in Table 3.

*Table 3: Weightages assigned based on the case study*

| Criteria | Weights |
|---|---|
| BIM compatibility (A) | 4 |
| IoT integration (B) | 4 |
| Real-time data synchronisation (C) | 4 |
| Interoperability (D) | 3 |
| Scalability (E) | 3 |
| Visualisation capability (F) | 4 |
| Simulation support (G) | 4 |
| Energy and carbon modelling capability (H) | 4 |
| DTP category (I) | 5 |
| Artificial intelligence integration (J) | 3 |
| User-friendliness (K) | 5 |
| Licensing costs (L) | 5 |
| Educational accessibility (M) | 5 |

After setting weightages, users should evaluate each DTP's ratings using the assessment criteria. By entering these ratings into the weight matrix and multiplying the allotted weights by the ratings, users can calculate the total score for each DTP as demonstrated in Table 4.

*Table 4: Ratings - DTPs assessing criteria*

| Platform | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P1 | 2 | 3 | 4 | 4 | 4 | 3 | 5 | 4 | 5 | 4 | 3 | 2 | 3 |

| Platform | A | B | C | D | E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P2 | 5 | 3 | 4 | 5 | 4 | 5 | 2 | 3 | 2 | 3 | 4 | 2 | 4 |
| P3 | 2 | 5 | 5 | 5 | 5 | 3 | 3 | 3 | 3 | 5 | 3 | 3 | 3 |
| P4 | 5 | 4 | 4 | 5 | 4 | 5 | 3 | 4 | 3 | 3 | 4 | 2 | 3 |
| P5 | 4 | 4 | 4 | 4 | 4 | 5 | 2 | 4 | 2 | 3 | 4 | 2 | 3 |
| P6 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 4 | 5 | 4 | 3 | 2 | 3 |
| P7 | 2 | 5 | 5 | 4 | 5 | 3 | 4 | 3 | 4 | 4 | 3 | 2 | 2 |
| P8 | 2 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 |
| P9 | 4 | 3 | 3 | 4 | 3 | 4 | 4 | 3 | 5 | 3 | 3 | 5 | 5 |
| P10 | 2 | 3 | 4 | 3 | 3 | 5 | 4 | 2 | 5 | 3 | 5 | 5 | 5 |
| P11 | 2 | 5 | 5 | 5 | 5 | 3 | 4 | 4 | 4 | 4 | 3 | 2 | 2 |
| P12 | 4 | 5 | 5 | 4 | 5 | 4 | 3 | 4 | 3 | 4 | 4 | 2 | 3 |

The assigned scores were not intended to represent absolute performance measurements, but rather the relative suitability of each platform for building energy and carbon management applications within the context of the study. The evaluation was conducted by reviewing official platform documentation, technical specifications, vendor resources, publicly available implementation examples, and practical platform accessibility, including free trial and educational versions where available. ProtoTwin was selected as an example platform to explain how the weightages and comparative scores were assigned to each evaluation criterion.

ProtoTwin was comparatively evaluated against the selected DTP assessment criteria based on its suitability for building energy and carbon management applications within the selected university classroom case study. The platform received comparatively higher scores for visualisation capability, simulation support, user-friendliness, licensing cost, educational accessibility, and DTP category due to its strong simulation-oriented environment, interactive real-time visualisation capabilities, and accessibility for academic experimentation and pilot-scale implementation. ProtoTwin also demonstrated suitable support for real-time data synchronisation and IoT connectivity through API-based integration approaches, making it appropriate for operational monitoring and DT development in educational and research contexts. Furthermore, the availability of educational licensing and comparatively lower implementation barriers contributed to its higher evaluation in accessibility-related criteria (Prototwin, 2026; Software Advice, 2026). However, ProtoTwin received comparatively lower scores for BIM compatibility, interoperability, and energy and carbon modelling capability when compared with BIM-oriented and enterprise-scale platforms such as Autodesk Forge, Bentley iTwin, and Ansys Twin Builder. Although ProtoTwin supports 3D model integration and simulation-based DT environments, it does not provide advanced native BIM interoperability, integrated building energy simulation, or dedicated carbon analysis functionalities comparable to specialised engineering and building performance platforms (Ansys, 2024; Autodesk, 2026; Bentley, 2026). Therefore, the assigned scores were intended to represent the relative suitability of the platform within the operational requirements, technical constraints, and educational context of the selected case study rather than absolute performance measurements across all application domains.

After weightages were assigned, they were multiplied by the platform ratings. Then the calculated values were added to find the total value for the relevant DTP. In order to show the calculations, Table 5 illustrate calculated values of P1 - Ansys Twin Builder.

*Table 5: Weighted score calculation for P1*

| Criteria | Weightage | Weightage for P1 | Calculated value for P1 |
|---|---|---|---|
| BIM compatibility (A) | 4 | 2 | 8 |
| IoT integration (B) | 4 | 3 | 12 |
| Real-time data synchronisation (C) | 4 | 4 | 16 |
| Interoperability (D) | 3 | 4 | 12 |
| Scalability (E) | 3 | 4 | 12 |
| Visualisation capability (F) | 4 | 3 | 12 |
| Simulation support (G) | 4 | 5 | 20 |
| Energy and carbon modelling capability (H) | 4 | 4 | 16 |
| DTP category (I) | 5 | 5 | 25 |
| Artificial intelligence integration (J) | 3 | 4 | 12 |
| User-friendliness (K) | 5 | 3 | 15 |
| Licensing costs (L) | 5 | 2 | 10 |
| Educational accessibility (M) | 5 | 3 | 15 |
| Total for P1 - Ansys Twin Builder | | | 185 |

Subsequently, this was followed for all DTPs identified in this study. The results are as illustrated in Table 6.

*Table 6: Weight matrix (platform evaluation)*

| Criteria | Weight (w) | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 4 | 2 | 5 | 2 | 5 | 4 | 3 | 2 | 2 | 4 | 2 | 2 | 4 |
| | | 8 | 20 | 8 | 20 | 16 | 12 | 8 | 8 | 16 | 8 | 8 | 16 |
| B | 4 | 3 | 3 | 5 | 4 | 4 | 3 | 5 | 4 | 3 | 3 | 5 | 5 |
| | | 12 | 12 | 20 | 16 | 16 | 12 | 20 | 16 | 12 | 12 | 20 | 20 |
| C | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 5 | 4 | 3 | 4 | 5 | 5 |
| | | 16 | 16 | 20 | 16 | 16 | 16 | 20 | 16 | 12 | 16 | 20 | 20 |
| D | 3 | 4 | 5 | 5 | 5 | 4 | 5 | 4 | 4 | 4 | 3 | 5 | 4 |
| | | 12 | 15 | 15 | 15 | 12 | 15 | 12 | 12 | 12 | 9 | 15 | 12 |
| E | 3 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 4 | 3 | 3 | 5 | 5 |
| | | 12 | 12 | 15 | 12 | 12 | 15 | 15 | 12 | 9 | 9 | 15 | 15 |
| F | 4 | 3 | 5 | 3 | 5 | 5 | 5 | 3 | 3 | 4 | 5 | 3 | 4 |
| | | 12 | 20 | 12 | 20 | 20 | 20 | 12 | 12 | 16 | 20 | 12 | 16 |
| G | 4 | 5 | 2 | 3 | 3 | 2 | 5 | 4 | 3 | 4 | 4 | 4 | 3 |
| | | 20 | 8 | 12 | 12 | 8 | 20 | 16 | 12 | 16 | 16 | 16 | 12 |

| Criteria | Weight (w) | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 | P12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | 4 | 4 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 4 | 4 |
| | | 16 | 12 | 12 | 16 | 16 | 16 | 12 | 12 | 12 | 8 | 16 | 16 |
| I | 5 | 5 | 2 | 3 | 3 | 2 | 5 | 4 | 3 | 5 | 5 | 4 | 3 |
| | | 25 | 10 | 15 | 15 | 10 | 25 | 20 | 15 | 25 | 25 | 20 | 15 |
| J | 3 | 4 | 3 | 5 | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 4 | 4 |
| | | 12 | 9 | 15 | 9 | 9 | 12 | 12 | 12 | 9 | 9 | 12 | 12 |
| K | 5 | 3 | 4 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 5 | 3 | 4 |
| | | 15 | 20 | 15 | 20 | 20 | 15 | 15 | 15 | 15 | 25 | 15 | 20 |
| L | 5 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 5 | 5 | 2 | 2 |
| | | 10 | 10 | 15 | 10 | 10 | 10 | 10 | 15 | 25 | 25 | 10 | 10 |
| M | 5 | 3 | 4 | 3 | 3 | 3 | 3 | 2 | 3 | 5 | 5 | 2 | 3 |
| | | 15 | 20 | 15 | 15 | 15 | 15 | 10 | 15 | 25 | 25 | 10 | 15 |
| **Weighted score** | | **185** | **184** | **189** | **196** | **180** | **203** | **182** | **172** | **204** | **207** | **189** | **199** |
| **Rank** | | **8** | **9** | **6** | **5** | **11** | **3** | **10** | **12** | **2** | **1** | **6** | **4** |

To demonstrate the proposed methodology, a university classroom was selected as the case study environment, with the DT intended primarily for research-oriented operational energy monitoring, predictive analysis, and carbon emission reduction within an educational building context. The case study required real-time IoT-based environmental monitoring, including operational building data integration, visualisation, simulation capability, and interoperability with BIM. The carbon management focus of the study was limited to operational carbon emissions associated with energy consumption rather than embodied carbon assessment. Furthermore, the proposed DT framework was intended for pilot-scale academic implementation under limited financial resources and varying technical expertise levels among users. Following the weighted evaluation process, the DTPs were comparatively ranked to determine the most suitable platform for developing the proposed DT framework considering a case study related to building energy and carbon management applications. The results indicate that ProtoTwin (P10) achieved the highest overall weighted score, demonstrating strong performance across key criteria such as real-time simulation capability, interoperability, visualisation, user accessibility, and integration potential for operational building management. The findings indicate that selecting a suitable DTP for the built environment goes beyond technical functionality and should also consider implementation practicality, educational accessibility, licensing availability, and resource constraints.

The findings of this study also highlight the importance of developing application-oriented platform selection methodologies tailored to the operational requirements of the built environment. Existing studies related to DTP selection, such as Dodero et al. (2025), primarily focus on manufacturing-oriented Digital Twin applications. While these studies provide valuable guidance for structured platform evaluation processes, direct comparison with the findings of the present study remains limited due to the significant differences between manufacturing systems and building operational environments. Unlike manufacturing applications, building energy and carbon management require greater emphasis on factors such as occupancy-driven operations, energy monitoring,

environmental performance, interoperability with BMS, and long-term operational sustainability.

## 5. CONCLUSIONS

This paper proposes a methodology to select a suitable DTP for construction applications. In the literature, existing platforms were identified based on their underlying technology and usage (Refer to Table 1): BIM-oriented platforms, IoT-driven platforms, simulation-focused platforms, and integrated digital twin environments. While the core technologies of BIM, IoT, and simulation are well established in the CI, the proposed methodology conceptualises BIM-oriented, IoT-driven, simulation-focused, and fully integrated platforms as functional architectural pillars that influence the operational capabilities and suitability of DTPs within the CI. Furthermore, the literature review helped to identify potential assessment criteria. Then, a weighted scoring mechanism was applied, enabling users to rank platforms according to their suitability for each project. The methodology was demonstrated through a case study aimed at improving building energy efficiency and reducing carbon emissions. Based on the weighting and scoring model established in this study, platforms focused on simulation emerged as the most suitable category. ProtoTwin and OpenTwin received the highest ratings among the evaluated platforms, with ProtoTwin selected as the final choice for its intuitive user interface, visualisation capabilities, support for real-time simulation, educational accessibility, and free licence options.

The main contribution of this paper is a repeatable method for selecting a suitable DTP. At the time of writing, very few studies were found that provided guidelines for selecting a DTP, and none were directly associated with buildings. Thus, this study fills a gap in knowledge and theory by providing a novel categorisation schema for DTPs and demonstrating a weighted scoring mechanism, SMART, to select the most suitable platform. Although only 12 DTPs were reviewed in this study, this methodology can be applied using refined assessment criteria to analyse all available DTPs. From a practical perspective, this research offers clear decision-making steps for researchers and practitioners seeking to identify which DTPs align with their technical requirements, sustainability objectives, and resource constraints.

Limitations include that platform ratings and associated weightings were determined by available information on platforms, reviews and comments published online by users, and the priorities outlined in the case study. Thus, the suitable DTP may differ for other projects based on project needs and objectives, budgets, technical requirements, or operational priorities.

## 6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by Adelaide University, Australia through Adelaide University Research Scholarships.

This research is supported by ARC Training Centre for Whole Life Design of Carbon Neutral Infrastructure (IC230100015)

The authors acknowledge the use of AI-assisted language tools, including ChatGPT and Google Gemini, during the preparation of this manuscript for brainstorming and grammatical refinement.

# 7. REFERENCES


Abdelrahman, M., Macatulad, E., Lei, B., Quintana, M., Miller, C., & Biljecki, F. (2025). What is a Digital Twin anyway? Deriving the definition for the built environment from over 15,000 scientific publications. *Building and Environment*, *274*, 1–19. https://doi.org/10.1016/j.buildenv.2025.112748

Ansys. (2024). *Ansys Twin Builder*. https://www.ansys.com/products/digital-twin/ansys-twin-builder

Arsecularatne, B., Rodrigo, N., & Chang, R. (2024). Digital Twins for Reducing Energy Consumption in Buildings : A Review. *Sustainability*, *16*(October), 1–17. https://doi.org/https://doi.org/ 10.3390/su16219275

Arsecularatne, B., Rodrigo, N., & Chang, R. (2025). Reduce Energy Consumption through Digital Twin : A Literature Review Reduce Energy Consumption through Digital Twin : A Literature Review. *The Proceedings of the 23rd CIB World Building Congress*, 1–12. https://doi.org/https://doi.org/10.7771/3067-4883.1245

Autodesk. (2024). *Autodesk Platform Services*. https://aps.autodesk.com/

Autodesk. (2026). *Autodesk tandem*. https://intandem.autodesk.com/about-digital-twins/

Bentley. (2026). *Digital twins*. https://www.bentley.com/software/digital-twins/

Bentley Systems. (2024). *Itwin platform*. https://developer.bentley.com/

Bibri, S. E., & Huang, J. (2025). AI and AI-powered digital twins for smart, green, and zero-energy buildings: A systematic review of leading-edge solutions for advancing environmental sustainability goals. *Environmental Science and Ecotechnology*, *28*, 1–41. https://doi.org/10.1016/j.ese.2025.100628

Boschert, S., & Rosen, R. (2016). Digital Twin—The Simulation Aspect. In *Boschert, S., Rosen, R.* (pp. 59–74). https://doi.org/10.1007/978-1-84996-080-9_15

Cityzenith. (2021). *SmartWorldPro2*. http://cityzenith.com/smartworldpro-2/smartworldpro/

Dassault Systèmes. (2024). *3DEXPERIENCE*. https://www.3ds.com/3dexperience

de las Morenas, J., Belmonte, L. M., & Morales, R. (2025). Designing an AI-driven digital twin architecture for building energy prediction. *Journal of Building Engineering*, *113*(August), 1–23. https://doi.org/10.1016/j.jobe.2025.113966

Deren, L., Wenbo, Y., & Zhenfeng, S. (2021). Smart city based on digital twins. *Computational Urban Science*, *1*(4), 1–11. https://doi.org/10.1007/s43762-021-00005-y

Dodero, C., Mccormick, M. R., Malik, A. A., & Harik, R. (2025). Systematic selection framework for digital twin development environments in smart manufacturing. *Digital Twin*, *2*(4), 1–29. https://doi.org/10.1080/27525783.2025.2565246

Ferr, J., Casals, M., & Gangolells, M. (2022). The adoption of urban digital twins. *Cities*, *131*(August), 1–12. https://doi.org/10.1016/j.cities.2022.103905

General Electric. (2024). *Digital Twin*. https://www.ge.com/digital/applications/digital-twin

Geng, L., Li, S., Farsangi, E. N., Xu, X., & Tam, V. W. Y. (2026). How do digital technologies reduce carbon emissions in the construction industry? a systematic review. *Energy and Buildings*, *350*(September 2025), 1–13. https://doi.org/10.1016/j.enbuild.2025.116605

Han, Y., Chen, M., Li, N., Ji, M., & Wang, X. (2025). Digital twin in construction safety management: Recent advances, challenges, and future directions from 4M1E perspective. *Safety Science*, *192*(July), 1–20. https://doi.org/10.1016/j.ssci.2025.107006

IBM. (2024). *What is Digital Twin*. https://www.ibm.com/topics/what-is-a-digital-twin

Ibrahim, M., Rjabtšikov, V., & Gilbert, R. (2023). Overview of Digital Twin Platforms for EV Applications. *Sensors*, *23*(January), 1–15. https://doi.org/https:// doi.org/10.3390/s23031414

Kaewunruen, S., Peng, S., & Phil-Ebosie, O. (2020). Digital twin aided sustainability and vulnerability audit for subway stations. *Sustainability (Switzerland)*, *12*(19), 1–17. https://doi.org/10.3390/SU12197873

Kandemir, E., Hasan, A., Kvamsdal, T., Abdel, S., & Alaliyat, A. (2024). Predictive digital twin for wind energy systems : a literature review. *Energy Informatics*, *7*(68), 1–36. https://doi.org/10.1186/s42162-024-00373-9

Khalifa, F., & Marzouk, M. (2025). Integrated blockchain and Digital Twin framework for sustainable building energy management. *Journal of Industrial Information Integration*, *43*(December 2024), 1–19. https://doi.org/10.1016/j.jii.2024.100747

Lehner, D., Pfeiffer, J., Tinsel, E.-F., Strljic;, M. M., Vierhauser, M., Sint;, S., & Wimmer, M. (2022). Digital Twin Platforms : Requirements , Capabilities , and Future Prospects. *IEEE Software*, *39*(2), 53–61.

Liu, C., Zhang, P., & Xu, X. (2023). Literature review of digital twin technologies for civil infrastructure. *Journal of Infrastructure Intelligence and Resilience*, *2*(3), 1–10. https://doi.org/10.1016/j.iintel.2023.100050

Microsoft. (2024). *What is Azure Digital Twins?* https://learn.microsoft.com/en-us/azure/digital-twins/overview

Moghimi, N., Arshang, O., & Hamzeh, F. (2026). Digital twins in offsite construction: Current implementations, challenges, and future pathways. *Automation in Construction*, *183*(August 2025), 1–17. https://doi.org/10.1016/j.autcon.2026.106820

OpenTwin. (2025). *OpenTwin*. https://opentwin.net/

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*(May), 1–15. https://doi.org/10.1016/j.jobe.2021.102726

Prototwin. (2025), "Industrial Simulation Software | ProtoTwin", *Prototwin*, available at: https://prototwin.com/.\

Prototwin. (2026), "Industrial Simulation Software | ProtoTwin", Prototwin, available at: https://prototwin.com/.

Rosen, R., Von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine*, *28*(3), 567–572. https://doi.org/10.1016/j.ifacol.2015.06.141

Sayed, A. N., Bensaali, F., Himeur, Y., Dimitrakopoulos, G., & Varlamis, I. (2025). Enhancing building sustainability: A Digital Twin approach to energy efficiency and occupancy monitoring. *Energy and Buildings*, *328*(November 2024), 1–14. https://doi.org/10.1016/j.enbuild.2024.115151

Siemens. (2024). *Digital Twin*. https://www.sw.siemens.com/en-US/technology/digital-twin/

Software Advice. (2026). *ProtoTwin*. Simulation Software. https://www.softwareadvice.com.au/software/523572/ProtoTwin?utm_source

Tao, F., Sun, X., Cheng, J., Zhu, Y., Liu, W., Sun, Z., Xu, J., Bao, J., Xiang, F., & Jin, X. (2024). makeTwin : A reference architecture for digital twin software platform. *Chinese Journal of Aeronautics*, *37*(1), 1–18. https://doi.org/10.1016/j.cja.2023.05.002

United Nations Environment Programme. (2025). *Global Status Report for Buildings and Construction 2024/2025*. https://www.unep.org/resources/report/global-status-report-buildings-and- construction-20242025

Wagg, D. J., Gardner, P., Barthorpe, R. J., & Worden, K. (2020). On key technologies for realising digital twins for structural dynamics applications. In *Model Validation and Uncertainty Quantification* (Vol. 3, pp. 267–272). https://doi.org/10.1007/978-3-030-12075-7_30

Wang, Y., Rezaei, A., & Hicks, S. (2026). Digital twins in the construction industry: A systematic review of current practices and future directions. *Journal of Information Technology in Construction*, *31*(February), 149–179. https://doi.org/10.36680/j.itcon.2026.007

Willow. (2021). *Willow Digital Twin*. https://developers.willowinc.com/docs/resource-guide-willow-digital-twin/

Rahman, M.A., 2026. A review of Building Information Modelling (BIM) research in New Zealand academia from 2010-2025. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 99-109. DOI: https://doi.org/10.31705/WCS.2026.8. Available from: https://ciobwcs.com/papers/

# A REVIEW OF BUILDING INFORMATION MODELLING (BIM) RESEARCH IN NEW ZEALAND ACADEMIA FROM 2010-2025

**Mohammad Afjalur Rahman[1]**

## *ABSTRACT*

*Over the past decade, Building Information Modelling (BIM) has become a focal point for both academia and the global construction industry. A vast body of international literature exists, exploring the benefits and challenges of BIM while supporting its adoption within local contexts. Similarly, BIM has gained significant traction within the New Zealand construction industry over the last 15 years; however, academic research specifically tailored to the New Zealand context remains an emerging field. This paper aims to identify and synthesize existing research on BIM within New Zealand academia to evaluate the nature of these publications and the contributions of various institutions. To achieve this, a systematic review was conducted using online databases (such as Scopus and ScienceDirect), complemented by a manual review of New Zealand-based BIM researcher profiles. After the analysis, this study identified 97 articles published during the period of 2010-2025 and divided the articles in six key themes. This study also provides deep insights into the current state of BIM research in New Zealand and serves as a baseline for academia and government to develop effective strategies for future research initiatives.*

***Keywords:*** *BIM; New Zealand; Research; Review.*

## 1. INTRODUCTION

Building Information Modelling (BIM) has been identified as a transformative technology in the global Architecture, Engineering, Construction, and Operation (AECO) industry (Zhao, 2017). BIM is a technological advancement that facilitates the creation of precise virtual models of construction structures embedded with intelligent object data (Azhar, 2011). This intelligent, precise geometric data supports processes throughout construction project's lifecycle from the design stage to the demolition stage. For example, in the design stage, BIM software helps to quickly generate design alternatives with various sustainability analyses (such as energy and water use), coordinates models across different disciplines, provides realistic virtual visualizations and automated documentation, and identifies clashes between a model's components. In the construction stage, BIM's intelligent, object-based geometric data helps cost estimators attain accurate quantities; assists planners in simulating schedules to identify workspace conflicts and select appropriate construction methods; and improves construction safety through realistic visualization of installation processes, construction sequences, and virtual

[1] Lecturer, Building Construction School, Unitec Institute of Technology, New Zealand, arahman@unitec.ac.nz

walkthroughs. For manufacturers, BIM can be utilized to fabricate building components (such as columns, beams, and slabs) directly from the model. Finally, in the post-construction stage, BIM as-built data can be used by owners or facility managers to create maintenance schedules and assist with asset tracking and management.

In the context of construction stakeholders, BIM provides a wide range of benefits across the various stages of a project. In their study, Ghaffarianhoseini et al. (2017) categorized the core benefits of BIM into nine areas: i) technical (higher analytical ability compared to CAD); ii) knowledge management (intelligent data management); iii) standardization (data shareability between different vendor software); iv) diversity management (support for existing building maintenance and management); v) integration (a collaborative platform for clients, designers, and contractors); vi) economics (minimized documentation errors, reduced rework, and fewer unforeseen contractual costs); vii) planning/scheduling (schedule simulation and workspace conflict identification); viii) building life-cycle assessment (LCA) benefits (providing geometric data for use from the design to the post-construction stage); and ix) decision support (through data-sharing models).

The well-documented benefits of BIM have accelerated its adoption by industry practitioners worldwide, including those in New Zealand. In New Zealand, BIM adoption has seen a rise across different industries due to government and construction company initiatives, such as developing common industry guidelines, training, and seminars. Based on a survey in 2021, it was found that 70% of respondents reported using BIM on some or all their projects. The survey also found that the design sector (92% of architects and engineers) remains the primary user of BIM; however, there is increasing adoption in the construction (72%) and facilities management (25%) industries as well. This progress aligns with NZ BIM research and government objectives of creating a standardized framework to improve productivity, reduce waste, and enhance asset management across the industry (BIM Acceleration Committee, 2023; EBOSS, 2021).

This industry trend is mirrored in the academic world, where the subject of BIM has evolved over time and received continuous attention from researchers who advocate for its use in supporting the AECO industry (Zhao, 2017). While BIM adoption is a practical industry phenomenon, the rationale for focusing specifically on academic and research publications is critical for two reasons. First, academic literature serves as a lead indicator for industry research, development, and innovation. Second, academic institutions act as the primary organizations for the research and development of evidence-based frameworks that government and industry bodies (such as the BIM Acceleration Committee) rely upon to develop national standards. By analysing academic publications, this research can help identify BIM research dimensions and trends, and guide future research initiatives.

## 2. LITERATURE REVIEW

Wen et al. (2021) found that BIM has been analysed by researchers across diverse areas covering both technical and non-technical aspects. Through a cluster analysis of the literature co-citation network, they identified nine core research directions. These include a technical cluster containing Augmented Reality (AR), Geographic Information Systems (GIS), Computer-Aided Design (CAD), engineering design, and model analysis. Additionally, Zhao (2017) identified ten significant co-citation clusters using the log-

likelihood ratio algorithm; these include technical clusters such as mobile computing (cloud BIM), laser scanning, interoperability, and artificial intelligence (construction simulation). The technical aspect of BIM research primarily focuses on the integration of BIM with other technologies. For example, Mahdjoubi et al. (2013) researched the integration of BIM with laser scanning, while Wang et al. (2013) integrated BIM with Augmented Reality. Irizarry et al. (2013) combined BIM with Geographic Information System (GIS) to improve supply-chain systems by visualizing the real-time status of materials throughout the supply chain.

On the other hand, non-technical clusters identified by Wen et al. (2021) include construction safety, education, virtual learning, life-cycle assessment, and prefabricated housing production. Zhao (2017) also identified non-technical clusters such as innovation (BIM critical success factors), return on investment, engineering education, safety, and ontology. Beyond these clusters, other notable areas include Green BIM (sustainability and sustainable development), Lean-BIM, knowledge management, project management, implementation, and impacts on cost and scheduling. As an example of non-technical BIM research, Uddin et al. (2021) integrated BIM and local green building materials into a design software (Revit) database to identify the most sustainable designs. Malagnino et al. (2021) conducted a review to understand current progress on the integration of BIM and the Internet of Things (IoT) to enhance sustainability. Tak et al. (2021) developed a framework to integrate BIM with mobile crane operations to improve the safety of heavy-lifting tasks, while Li et al. (2019) developed a framework to support decision-making systems for prefabricated housing production via BIM.

To present the current state of BIM research and further analyse its various branches, many researchers have conducted reviews of existing literature. Among them, Zhao (2017) performed a scientometric review of global BIM literature between 2005 and 2016, analysing 614 journal articles to identify research trends. Similarly, Saka and Chan (2019) reviewed the development of BIM research between 2006 and 2017, analysing 914 journals. Wen et al. (2021) conducted a bibliometric-based visualization analysis of 1,369 journal articles from 2010 to 2019 to understand progress in the field. They found that the period of 2010–2012 was the early stage (less than 100 publications worldwide), after which publications gradually increased to over 100 articles yearly. In the year 2019, the total number of articles exceeded 1,000. On the other hand, Wen et al. (2021) also analysed the geographical distribution of BIM research and found that 50 countries, including New Zealand, have engaged in BIM research in the past 10 years. Among these countries, China takes the lead with 298 publications (until 2019). Chihib et al. (2019) created bibliometric maps of BIM articles (2003–2018), analysing 4,307 articles by 10,636 distinct authors from 314 institutions. Badrinath et al. (2016) also provided a general overview of global trends by analysing 1,000 BIM articles from 65 countries published between 1975 and 2015. Torres et al. (2025) also analysed BIM studies (2008–2024) related to construction schedules and found that China leads by publishing 336 articles.

Global BIM research analysis has helped identify branching patterns and the contributions of different countries, universities, and authors. The scientometric and bibliometric analyses in global BIM research reflect a rapid publications surge from fewer than 100 annually in 2010 to over 1,000 by 2019 (Wen et al., 2021). These studies highlighted the transition from theoretical 'early-stage' discussions to a geographically

diverse landscape where China and the US lead in the number of publications (Zhao, 2017; Saka & Chan, 2019).

However, these studies have limitations. Some articles covered only journal papers, while others focused exclusively on top-contributing countries or universities. Consequently, it is difficult to obtain a detailed picture of BIM research for a specific country. Some researchers have conducted country-specific studies; for instance, Li et al. (2020) analysed BIM education and research in China from 2006 to 2020 but limited in terms of scope and level of detail. In terms of New Zealand, none of the previous global BIM review studies provided updated information about New Zealand BIM research contribution and direction. Badrinath et al. (2016) mentioned only 13 articles related to BIM (up to 2016), which offers only a partial view of the New Zealand landscape. To reap the advantages of BIM for the New Zealand construction industry and generate new knowledge, it is crucial to first understand existing studies on the subject. An overview of New Zealand BIM research will help to identify new research gaps and provide opportunities for collaboration.

Therefore, this study aims to identify and highlight all articles related to BIM in New Zealand published between 2010 and 2025. Analysis of global review studies suggests that the majority of BIM articles were published within the last 15 years; thus, this study focuses on the 2010–2025 period. The findings highlight the volume of publications, their subject matter, and the contributions of various New Zealand institutions, including universities, institutes of technology, and polytechnics. As a result, research gaps will be made apparent, assisting current and future researchers in exploring new dimensions of BIM that add value to both New Zealand and global academia and industry.

## 3. RESEARCH METHOD

This study adopted a systematic review approach, comprising both an electronic database search and a manual institutional review to identify BIM-related publications from 2010 to 2025. To ensure relevance, papers were included only if they focused on BIM applications. For methodological transparency, the systematic review process followed a structured protocol divided into two stages: i) article identification and ii) qualitative thematic analysis. In the article identification stage, first, a systematic review was conducted by using academic database search engines, including Scopus, ScienceDirect, Google Scholar, and ASCE. The search was conducted using the Boolean keywords ["BIM" OR "Building Information Modelling"] AND ["New Zealand"], with the timeframe restricted to 2010–2025. Subsequently, to ensure all relevant publications were captured, specific BIM papers were identified by cross-referencing the names of known New Zealand-based BIM researchers within the search systems. In the manual review, researcher initially audited all academic and research staff profiles within the fields of construction, architecture, civil engineering, the built environment, and architectural technology across New Zealand's eight universities and 16 Institutes of Technology and Polytechnics (ITPs). Based on these initial findings, further details and confirmation were sought by reviewing individual researcher profiles on Google Scholar, ORCID, and ResearchGate. Finally, the papers were reviewed via institutional repositories and other research platforms, such as ResearchGate, Academia.

To refine the initial search results into a robust, credible dataset, explicit inclusion and exclusion criteria were applied. The inclusion criteria's publications were excluded if

they were duplicate entries, lacked a primary focus on BIM, or did not explicitly contextually relate to New Zealand research or industry practice. Figure 1 illustrates the screening protocol adopted in this study.

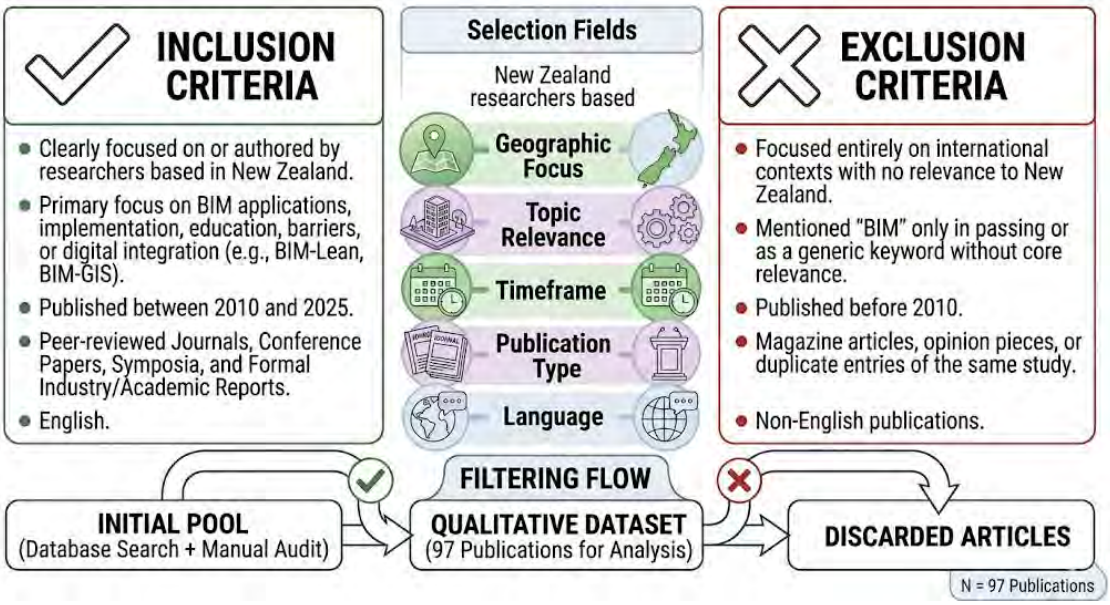



*Figure 1: Systematic screening protocol and inclusion/exclusion criteria for the New Zealand BIM literature selection.*

After identifying the research papers, researcher analysed the paper and categorised them in six themes. To do so, the researcher has followed Reflexive (inductive) Thematic Analysis, developed by Braun and Clarke (2006). This approach involves a six-phase sequential process that guides the analysis in a rigorous process. These phases are i) familiarisation with the data, ii) code the gathered data, iii) generating initial themes, iv) reviewing themes, v) provide names for the themes and, finally, vi) writing up. Besides during the second phase (coding), the researcher utilized Microsoft Excel to analyse the findings and conclusions of each paper. These codes were then cross compared to identify recurring patterns, which were iteratively grouped into broader themes. This reflexive process ensured that the six themes were implemented to ensure robust analysis.

## 4. RESULTS

From the electronic and manual reviews, this study has identified 97 articles published by New Zealand researchers from the 8 universities and 16 ITPs in the period of 2010-2025. Figure 2 presents the annual number of publications from 2010 to 2025. The data demonstrates that BIM research in New Zealand has shifted from a minor area of interest into a major academic focus. During the first few years (2010–2014), the annual output remained low, with fewer than five publications per year. However, BIM publications began to accelerate around 2015, peaking in 2019 with 20 publications. This peak period reflects the academic response to government-led BIM initiatives—notably the publication of the NZ BIM Handbook—as well as broader industry adoption. Following this period, there was a gradual decrease in publications, primarily due to a smaller cohort of active researchers. Conversely, since 2022, BIM research has regained momentum,

driven by expanding research dimensions incorporating emerging digital technologies such as Blockchain and AI.

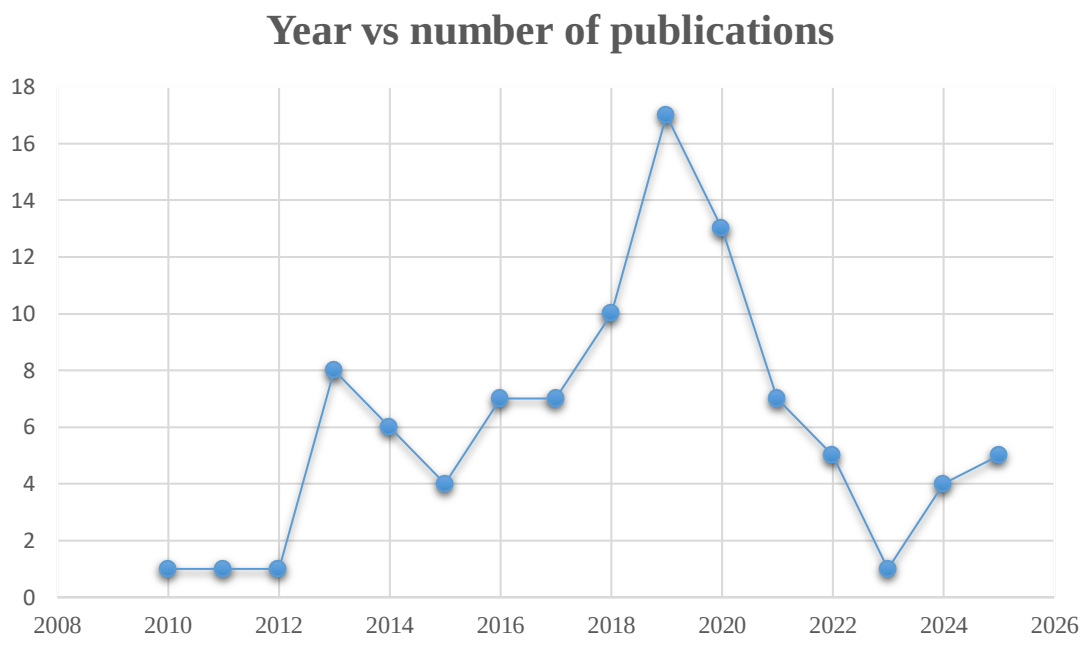



*Figure 2: BIM publications number 2010-2025 by New Zealand researchers*

Figure 3 shows the classification of articles published from 2010 to 2025. According to the data, conference articles accounted for 47% of the total output (45 out of 97). The number of published journal articles was 38, representing 39% of the total publications. Apart from conference and journal articles, seven symposium papers, six reports, one workshop presentation, and one magazine article were published between 2010 and 2025.

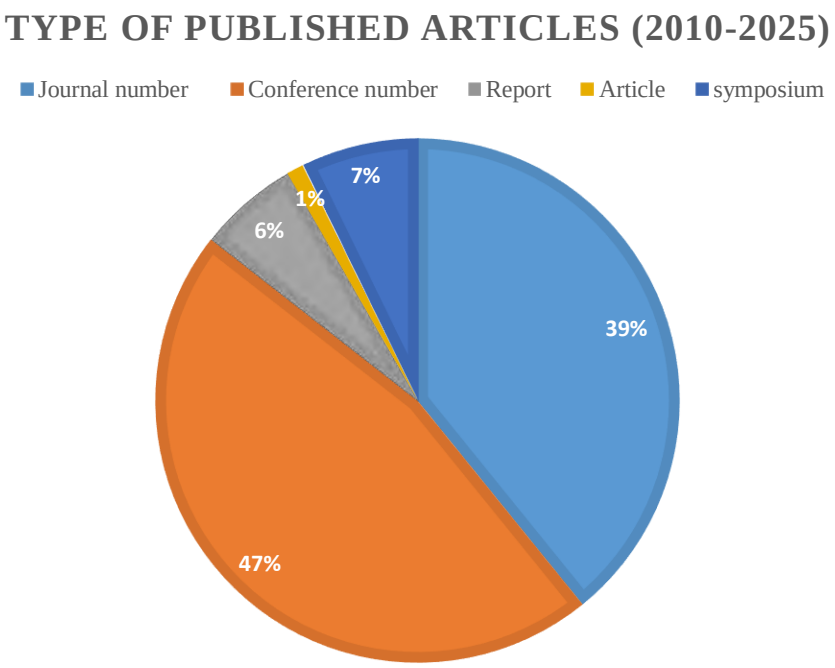



*Figure 3: Type of published papers related to BIM from 2010 to 2025.*

Figure 4 represents the BIM articles published by the different Universities and ITPs in New Zealand. From the findings, the University of Auckland researchers have published 27 papers (28%) between 2010 and 2025.

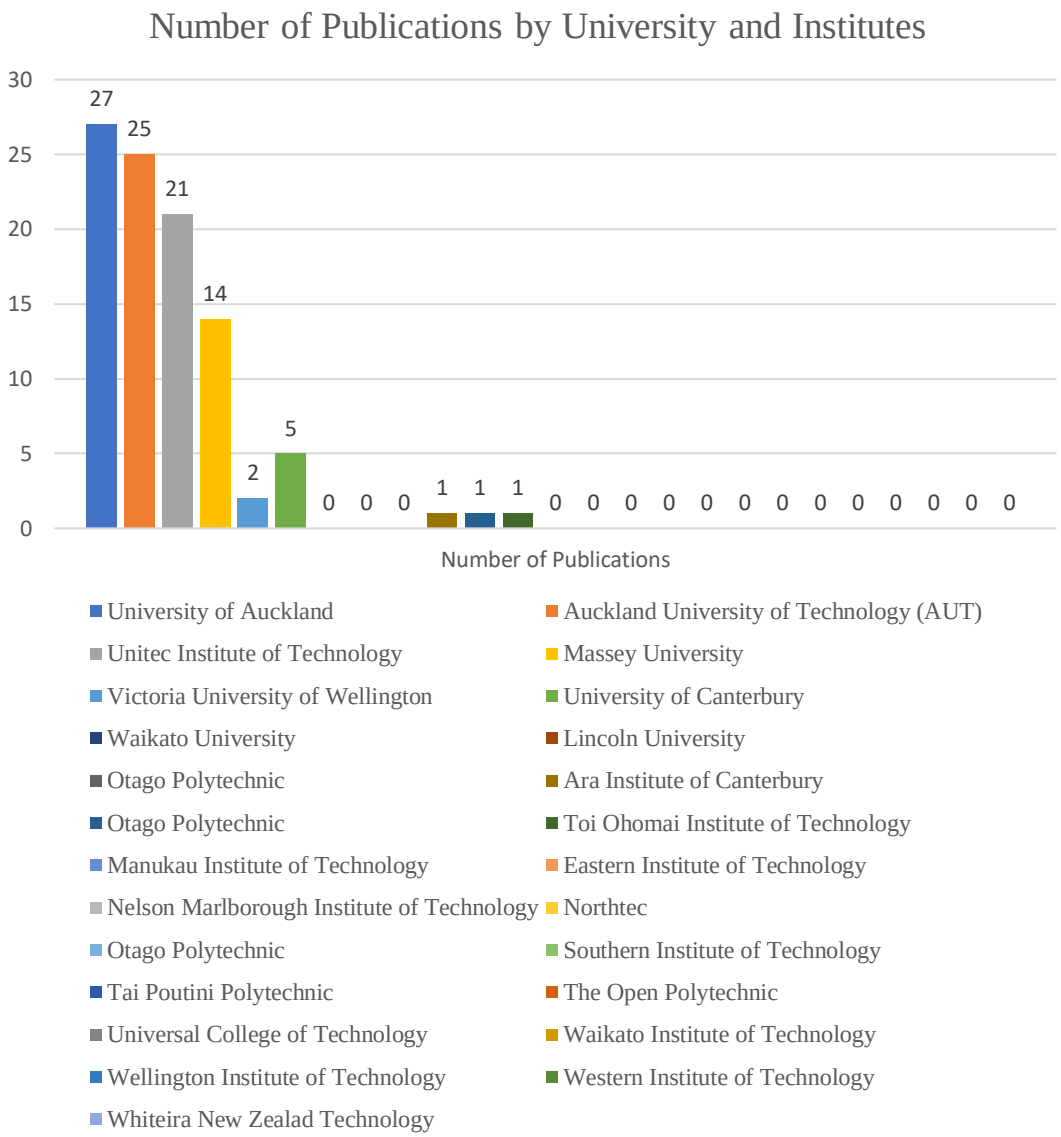



*Figure 4: Number of BIM-related papers published by universities and ITPs (New Zealand).*

Between 2010 and 2025, researchers from the Auckland University of Technology (AUT) published 25 BIM-related articles, accounting for 26% of the 97 total papers. Over the same period, Massey University researchers published 14 articles (14%), University of Canterbury researchers published 5 (5%), and Victoria University of Wellington published one paper. Because the University of Otago, Lincoln University, and the University of Waikato do not offer courses in construction, architecture, or civil engineering, no publications were produced by these institutions. Conversely, among the 16 Institutes of Technology and Polytechnics (ITPs), academic staff at the Unitec Institute of Technology published 21 BIM articles (22%) between 2010 and 2025. The Ara Institute of Canterbury, Otago Polytechnic, and Toi Ohomai Institute of Technology published one BIM article each during this timeframe.

In summary, New Zealand universities contributed 73 articles (70.81% of the total output) while ITPs accounted for 24 articles (23.28%). Notably, over 75% of these publications originated from Auckland-based universities and institutions, specifically the University of Auckland (UoA), AUT, and Unitec. These three institutions are the largest in New Zealand in terms of student and researcher numbers, which explains their higher volume of BIM research compared to other providers.

## 5. THEMES

This section aims to further analyse and synthesize the findings by categorizing the published articles into six key themes (Table 1 and Table 2). The longitudinal analysis of BIM-related publications by New Zealand researchers from 2010 to 2025 indicates a clear evolution from foundational explorations of BIM's utility toward highly specialized, multi-dimensional frameworks. This progression can be categorized into three critical dimensions: the socio-technical challenge of adoption, the integration of sustainable and industrialized construction, and the emergence of Industry 4.0 technologies.

*Table 1: Theme identification*

| Theme | Codes | Total Count |
|---|---|---|
| 1. Adoption & Strategic Frameworks | Quantitative modelling of barriers, SEM adoption models, SME-specific barriers, Regional studies | 28 papers |
| 2. Modular & Offsite Construction | Prefabrication, Standardization, and Modularization. | 15 papers |
| 3. Lean Construction & Process Productivity | Lean and BIM, Productivity | 12 papers |
| 4. Sustainability & Asset Management | Green Star certification, Embodied carbon, Refurbishment of complex buildings, and Energy efficiency (Nd BIM). | 18 papers |
| 5. Industry 4.0 & Automation | Technical applications: Blockchain, UAVs, Computer Vision, AI, and Automated code compliance. | 10 papers |
| 6. Education, Skills & Professional Roles | Tertiary curriculum development, Soft skills, Impact on quantity surveyors and designers. | 13 papers |

Among the 97 publications, 28 are related to adoption and strategic frameworks. Early research (e.g., 2011–2014) focused on identifying fundamental barriers and the impact of BIM on professional roles, particularly in quantity surveying and tertiary education. However, the more recent literature (2020–2025) demonstrates a shift toward methodological sophistication. The use of Structural Equation Modelling (SEM) to quantify the relationships between BIM barriers, usage, and awareness suggests that the discourse has moved beyond merely identifying what the barriers are, to understanding the how and why of institutional resistance. The focus on small-to-medium enterprises (SMEs) is particularly significant, reflecting New Zealand's industrial demographic where smaller firms require adoption strategies tailored specifically to local markets.

A significant cluster of research (33 papers combined) links BIM to sustainability (Theme 4) and modular/offsite construction (Theme 2). This intersection addresses New

Zealand's specific socio-economic concerns, such as the housing crisis and environmental sustainability. Publications within the sustainability and asset management theme largely focus on Green Star certification, framing BIM as an essential facilitator for achieving carbon neutrality and energy efficiency. Simultaneously, publications regarding offsite construction and BIM integration during the 2023–2025 period demonstrate a shift toward "industrialized construction." Researchers increasingly view BIM not merely as a design tool, but as the critical digital infrastructure required to manage the complexities of prefabrication and modular assembly across the project lifecycle.

The themes of Lean Construction (Theme 3) and Industry 4.0 (Theme 5) highlight an industry-wide push for productivity gains and technology adoption. The literature increasingly positions BIM not as a standalone tool, but as a critical enabler of industrialized construction. While the 10 papers on automation covering Blockchain, UAVs, and AI—represent a smaller portion of the total volume, they signify the technological frontier of New Zealand research. Furthermore, the integration of Lean philosophy with BIM indicates a mature understanding that digital tools must be supported by efficient processes to deliver value.

Researchers are now aligning BIM-enabled prefabrication (Theme 2) directly with waste reduction (Theme 3) and carbon accounting (Theme 4). Consequently, the shift from "BIM education" in the early 2010s to "Digital Twin" and "Computer Vision" applications in the 2020s suggests that the New Zealand academic community has successfully transitioned from building capacity to leading innovation.

*Table 2: Research period and dominant themes*

| Research period | Dominant Themes | Focused area |
|---|---|---|
| 2010-2014 | Theme 1 (Adoption & Strategic Frameworks), Theme 6 (Education Skills & Professional Roles) | NZ BIM definition and tertiary curriculum. |
| 2015-2019 | Theme 4 (Sustainability & Asset Management), Theme 1 (Adoption & Strategic Frameworks) | Linking BIM to Green Star and refurbishment of complex buildings. |
| 2020-2025 | Theme 2 (Modular & Offsite Construction), Theme 3 (Lean Construction & Process Productivity), Theme 5 (Industry 4.0 & Automation) | Moving toward AI, Blockchain, and integrated off-site delivery |

## 6. DISCUSSION AND CONCLUSIONS

BIM-related literature has evolved significantly over the last 15 years, both globally and within New Zealand. This study provides a comprehensive review of BIM articles published by New Zealand tertiary education institutions between 2010 and 2025. A total of 97 articles were contributed by five universities and four ITPs. According to the analysis, the University of Auckland was the top contributor overall in terms of total BIM publications, as well as the number of academic researchers engaged in the field. Among the ITPs, the Unitec Institute of Technology was the leading contributor in publishing and driving BIM-related research. These findings indicate that BIM research in New Zealand remains concentrated within a few key institutions, highlighting a clear need and

opportunity for cross-institutional collaboration to broaden the research base and increase publication output. In terms of publication types, the volume of conference articles was higher than that of journal papers, symposiums, or reports. This prevalence of conference papers indicates a focus on emerging ideas rather than the long-term, longitudinal validation typically found in peer-reviewed journals. Additionally, 2019 emerged as the most productive year for New Zealand BIM researchers, yielding the highest number of articles. This spike demonstrates a clear correlation between government-led digitalization initiatives and academic output, proving that policy and industry engagement serve as primary catalysts for domestic BIM research.

Finally, this study synthesizes the landscape of BIM research in New Zealand academia over a transformative 15-year period. The findings confirm that the field has achieved a significant level of maturity, progressing from basic 3D modelling discussions to complex, integrated frameworks that leverage Lean philosophy, sustainable development, and automated technologies. This shift from tool-centric (3D) to process-centric (Lean/automation) research demonstrates a fundamental maturity in New Zealand's academic focus, reflecting a broader movement toward holistic lifecycle management. Furthermore, the research reveals a strong alignment between academic investigation and New Zealand's unique industry requirements, particularly regarding the digitalization of SMEs and the technology-driven construction sector.

Looking forward, a critical need remains for research focusing on the human-centric and cultural shifts required for total digital integration across the supply chain. Future studies can investigate the transformations (behavioural and social) needed to overcome technological barriers across the supply chain, establish collaborative procurement models, and manage workforce upskilling. In addition, SMEs form the backbone of the New Zealand construction industry, research should focus on practical, empirical frameworks designed for small-scale deployment that accommodate specific financial and resource constraints. Finally, there is an urgent need for longitudinal validation and real-world field implementation research to quantify exact productivity gains and return on investment (ROI) on active construction sites. By addressing these interconnected human, organizational, and empirical gaps, future research can provide the robust evidence base required to effectively enhance the long-term productivity and resilience of New Zealand’s built environment.

## 7. REFERENCE

Azhar, S. (2011). Building Information Modelling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, *11*(3), 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Badrinath, A. C., Chang, Y. T., & Hsieh, S. H. (2016). An overview of global research trends in BIM from analysis of BIM publications. In *Proceedings of the 16th International Conference on Computing in Civil and Building Engineering* (pp. 106–140). Osaka University.

BIM Acceleration Committee. (2023). *The New Zealand BIM handbook* (4th ed.). Building-Performance. https://www.biminnz.co.nz/nz-bim-handbook

Chihib, M., Salmerón-Manzano, E., Novas, N., & Manzano-Agugliaro, F. (2019). Bibliometric maps of BIM and BIM in universities: A comparative analysis. *Sustainability*, *11*(16), Article 4398. https://doi.org/10.3390/su11164398

EBOSS. (2021). *BIM in New Zealand: 2021 industry survey report*. https://www.eboss.co.nz/bim-in-nz/

Ghaffarianhoseini, A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., & Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding

its implementation, risks and challenges. *Renewable and Sustainable Energy Reviews*, *75*, 1046–1053. https://doi.org/10.1016/j.rser.2016.11.083

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*, *31*, 241–254. https://doi.org/10.1016/j.autcon.2012.12.005

Li, J., Afsari, K., Li, N., Peng, J., Wu, Z., & Cui, H. (2020). A review for presenting Building Information Modelling education and research in China. *Journal of Cleaner Production*, *259*, Article 120885. https://doi.org/10.1016/j.jclepro.2020.120885

Li, X., Shen, G. Q., Wu, P., & Yue, T. (2019). Integrating building information modelling and prefabrication housing production. *Automation in Construction*, *100*, 46–60. https://doi.org/10.1016/j.autcon.2018.12.024

Mahdjoubi, L., Moobela, C., & Laing, R. (2013). Providing real-estate services through the integration of 3D laser scanning and Building Information Modelling. *Computers in Industry*, *64*(9), 1272–1281. https://doi.org/10.1016/j.compind.2013.09.006

Malagnino, A., Montanaro, T., Lazoi, M., Sergi, I., Corallo, A., & Patrono, L. (2021). Building Information Modelling and Internet of Things integration for smart and sustainable environments: A review. *Journal of Cleaner Production*, *314*, Article 127716. https://doi.org/10.1016/j.jclepro.2021.127716

Saka, A. B., & Chan, D. W. (2019). A global taxonomic review and analysis of the development of BIM research between 2006 and 2017. *Construction Innovation*, *19*(4), 565–596. https://doi.org/10.1108/CI-12-2018-0097

Tak, A. N., Taghaddos, H., Mousaei, A., Bolourani, A., & Hermann, U. (2021). BIM-based 4D mobile crane simulation and onsite operation management. *Automation in Construction*, *128*, Article 103766. https://doi.org/10.1016/j.autcon.2021.103766

Torres, K., Sánchez, O., Castaneda, K., Noguera, M., Carrasco-Beltrán, D., Vidal-Méndez, S., & Lozano-Ramírez, N. E. (2025). Exploring the knowledge structure of Building Information Modelling (BIM) adoption in construction scheduling: A bibliometric analysis from 2008 to 2024. *Ain Shams Engineering Journal*, *16*(8), Article 103446. https://doi.org/10.1016/j.asej.2024.103446

Uddin, M. N., Wei, H. H., Chi, H., Ni, M., & Elumalai, P. (2021). Building Information Modelling (BIM) incorporated green building analysis: An application of local construction materials and sustainable practice in the built environment. *Journal of Building Pathology and Rehabilitation*, *6*(1), Article 25. https://doi.org/10.1007/s41024-021-00120-w

Wang, X., Love, P. E., Kim, M. J., Park, C. S., Sing, C. P., & Hou, L. (2013). A conceptual framework for integrating Building Information Modelling with augmented reality. *Automation in Construction*, *34*, 37–44. https://doi.org/10.1016/j.autcon.2012.10.012

Wen, Q. J., Ren, Z. J., Lu, H., & Wu, J. F. (2021). The progress and trend of BIM research: A bibliometrics-based visualization analysis. *Automation in Construction*, *124*, Article 103558. https://doi.org/10.1016/j.autcon.2021.103558

Zhao, X. (2017). A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction*, *80*, 37–47. https://doi.org/10.1016/j.autcon.2017.04.002

Kithulgodage, S.E. and Kulatunga, U., 2026. A Systematic review to investigate the root causes for variations in infrastructure developments. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 110-120. DOI: https://doi.org/10.31705/WCS.2026.9. Available from: https://ciobwcs.com/papers/

# A SYSTEMATIC REVIEW TO INVESTIGATE THE ROOT CAUSES FOR VARIATIONS IN INFRASTRUCTURE DEVELOPMENTS

**S.E. Kithulgodage[1] and U. Kulatunga[2]**

## *ABSTRACT*

*Infrastructure development projects play a critical role in economic and societal advancement. However, they are frequently affected by variations that influence project cost, time, and performance. Given the limited knowledge about the root causes and impacts specific to infrastructure developments, a systematic literature review conducted using a mixed method approach. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Relevant publications from Scopus, Web of Science, and ScienceDirect databases between 2019 and 2023 were identified using a structured search strategy based on the PICO framework. Following screening and eligibility assessment, fourteen peer-reviewed studies were selected for detailed analysis. The findings reveal that variations arise from interconnected financial, technical, administrative, environmental, institutional, and human-related factors. Key root causes include insufficient budget allocation, regulatory and policy changes, design deficiencies, unforeseen site conditions, material supply disruptions, and coordination failures among stakeholders. These factors contribute to project delays, cost overruns, contractual disputes, and scope modifications, ultimately affecting infrastructure project performance. The review further highlights the complex interactions among stakeholders and emphasizes the need for proactive risk management, improved financial planning, regulatory streamlining, and enhanced communication mechanisms to mitigate variation impacts. By synthesizing recent literature, this study provides a consolidated understanding of the drivers of variations in infrastructure developments and offers insights to support policy makers and practitioners in improving project resilience and delivery outcomes.*

***Keywords:*** *Development Projects; Impacts; Infrastructure; Root Causes; Systematic Literature Review; Variations.*

## 1. INTRODUCTION

Variations in the construction context pertain to the discrepancies between the planned and actual outcomes of events (Kerzner, 2017). Professionals acting in the current construction industry of the twenty-first century have placed a special emphasis on identifying the root causes of variations to reduce the resulting consequences (Alnuaimi et al., 2010). Amendments to the scheduled start time of an activity would unavoidably cause disruptions to other tasks, which could impact the project's quality and/or cost (Ibbs & Chih, 2011). As per the findings of Ali (2008), variations can also result from adding,

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, erandiks24@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

removing or changing the project's objectives, the scope of work, contract drawings, specifications and/or bills of quantities (Cabalag & Silva, 2019). A variation order is issued after the contract starts to approve changes, additions or completions to the original agreement. It updates the original contract and becomes an extra part of the agreement. Because of the complicated activities during construction, it is impossible to finish a construction project without any variations in plans or the construction process (Ssegawa et al., 2002).Variation orders caused by the stakeholders, including owners, consultants, contractors and external factors, impact the project's success (Alkhattabi et al., 2023) The authors further stated that the presence of variation clauses in contracts indicates that no project can be completed without variations. Variation is thus a recurrent problem in the construction sector. Therefore, it is important to assess the root causes for variations in construction industry (Memon et al., 2014).

There is no exception for the occurrence of variations in infrastructure projects as well. Variations in infrastructure projects are high due to several factors including unexpected site conditions, changes in design requirements and unforeseen regulatory issues. Additionally, the complex nature of these projects often leads to difficulties in precise cost and time estimates. Variations are especially high in infrastructure projects due to their large scale, extended timelines and involvement of multiple stakeholders (Karim et al., 2020). Uncertainties such as unforeseen ground conditions, evolving design requirements and coordination challenges across disciplines and contractors can be commonly observed in these projects (Alnuaimi et al., 2010). Additionally, infrastructure developments tend to be more susceptible to regulatory changes, political influences and public consultations, all of which can contribute to frequent scope adjustments and contract modifications. According to Wambeke et al. (2011), infrastructure development project expenses fluctuate because of variations. By examining these variations, it becomes easier to identify and control unforeseen costs and make sure the project stays within budget. Additionally, Infrastructure projects may change in scope as they progress (Althiyabi & Qureshi, 2021). By analysing variations, one can prevent scope creep and preserve alignment with project objectives by ensuring that modifications are justified, regulated and documented (Ahmed & Jawad, 2022).

While variation orders in construction have been extensively studied (Sun et al., 2016; Wambeke et al., 2011; Memon et al., 2014), this review is positioned to address a more specific and underexplored niche. Existing research on variations in infrastructure projects tends to focus on conventional sectors such as road and building construction (Herrera et al., 2020; Alsuliman, 2019), with limited structured synthesis of root causes across diverse infrastructure project types. Moreover, several extant review studies have drawn primarily on older datasets, reducing their relevance to contemporary industry conditions characterized by evolving procurement environments, digitalization, and post-pandemic supply-chain disruptions. Unlike prior reviews that treat variation causes as isolated lists, this study employs a structured PICO-based search strategy and PRISMA-compliant methodology to synthesize causal mechanisms and map their interdependencies, providing a categorized and analytically grounded contribution to the field. Accordingly, this study investigates the root causes of variations in infrastructure developments and examines how interconnectivity develops among the parties responsible for variation initiation in Sri Lanka.

# 2. RESEARCH METHODOLOGY

Literature reviews have gained great importance among scholars since it is believed that "most research can only be understood in context - and a key part of that context consists of the results of other studies" (Petticrew & Roberts, 2006). The systematic reviewing methodology has gained popularity among many sorts of reviews due to its unique qualities that cannot be found in other traditional reviewing approaches (Pahlevan-Sharif et al., 2019). As a result, a systematic literature review (SLR) has been chosen for this study since it gives unbiased results from the literature with a high level of quality and efficiency (Liberati et al., 2009). SLR was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Liberati et al., 2009).

## 2.1 SYSTEMATIC LITERATURE REVIEW

Among the variety of SLR search tools, this study found the PICO framework to be the most suitable. PICO stands for Population (P), Intervention (I), Comparison (C), and Outcome (O), and its structured elements fit well into the context of investigating variations in infrastructure projects. The research question was formulated as, "What are the root causes and impacts related to variations in infrastructure development projects?".

The research question was developed based on an initial manual keyword search. The study identified articles to extract findings about the root causes, impacts, and future directions related to variations in infrastructure projects, aligning these findings with the PICO elements. The elements were defined as follows: Population (P): Construction projects; Intervention (I): Variations, Variation orders; Comparison (C): Road projects, Bridge projects, Infrastructure types; Outcome (O): causes, factors, issues, reasons, impacts, effects, consequences, outcomes. Subsequently, a logic grid was developed to finalize a comprehensive search string incorporating all possible keywords. The keywords used under each PICO element is presented in Table 1.

*Table 1: Systematic literature review logic grid*

| Population (P) | Intervention (I) | Comparison (C) | Outcome (O) |
|---|---|---|---|
| Construction projects | Variations | Infrastructure projects | Causes |
| | Variation orders | Road projects | Impacts |
| | Change Orders | Bridge projects | Outcomes |
| | | Civil Projects | Factors |
| | | | Issues |
| | Variation* | Infrastructure* | |
| | | | Reason* |
| | | | Effect* |
| | | | Consequence* |
| | | | Outcome* |

Database selection is vital to ensure the success of an SLR. This study utilized three databases: Scopus, Web of Science and Science Direct, which are highly regarded for academic research and relevant to the study's context. A "title-abstract-keyword" search was employed to obtain precise and comprehensive results. However, for the intervention

of this study, variations in construction projects, a “title only” search was conducted due to the abundance of articles that mention “variations” in abstracts without relevance to the specific context. Additionally, variations of the word "variation" were used in the search to cover all relevant phrases comprehensively.

Boolean operators (AND, OR) were utilized to enhance the versatility of the search results. The search criteria were limited to the last five years (from 2019) to ensure the results were current and accurate, given the fast-evolving nature of research on root causes, impacts, and future directions of variations in construction projects. Only publications in English were considered. The following search string was used to identify relevant records:

(“construction projects”) AND (“variations” OR “variation orders” OR “Change Orders” OR “variation*”) AND (“infrastructure projects” OR “road projects” OR “bridge projects” OR “Civil Projects” OR “infrastructure*”) AND (“causes” OR “impacts” OR “outcomes” OR “factors” OR “issues” OR “reason*” OR “effect*” OR “consequence*” OR “outcome*”).

## 2.2 SYSTEMATIC LITERATURE REVIEW RECORD RESULTS

As stated in the PRISMA (2020) guidelines for systematic reviews, the flow diagram for “systematic reviews which included searches of databases and registers only” was applied in this study. Figure 1 illustrates the summary of the process followed in this study through the three main stages of the SLR, which included the identification, screening, and inclusion of relevant articles on variations in infrastructure development projects.

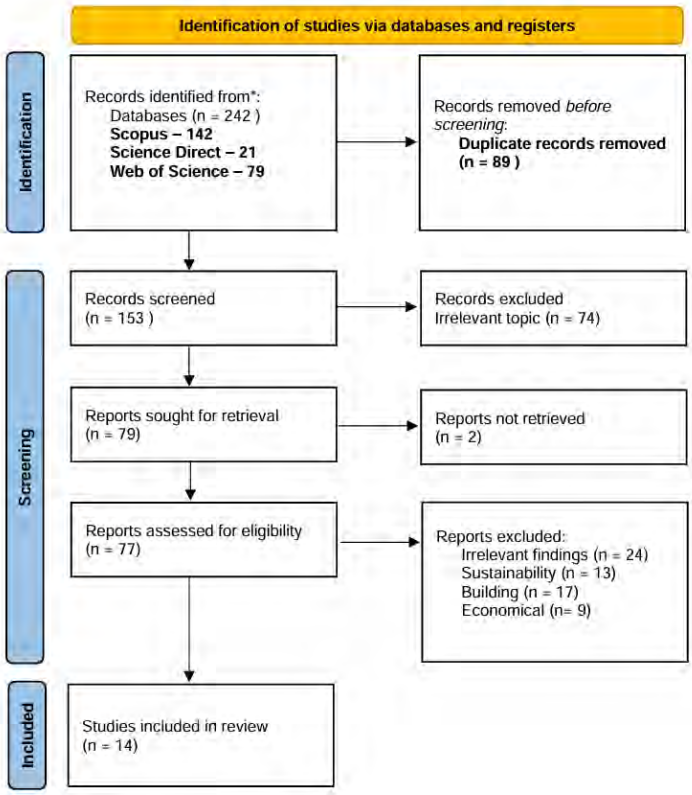



*Figure 1: Identification of studies in the systematic literature review*

Ultimately, 14 studies were included in the final review, comprising both journal articles and conference proceedings published between 2019 and 2023. Most studies were published in 2019 and 2020, with four journal articles and one conference proceeding in 2019, followed by three journal articles and two conference proceedings in 2020. The number of relevant publications gradually declined thereafter, with only journal articles selected from 2021 onward: two in 2021, and one each in 2022 and 2023. No conference proceedings were identified beyond 2020. A summary of the finalised articles, including their main themes and findings, is presented in Table 2.

*Table 2: A summary of the finalised articles*

| No | Citation | Context / Project Type | Main Themes / Findings | Key Root Causes Identified |
|---|---|---|---|---|
| 1 | Herrera et al. (2020) | Road infrastructure, Latin America | Frequency and importance analysis of cost overrun causes in road projects | Design errors, poor planning, regulatory delays |
| 2 | Tran et al. (2020) | Construction projects, Vietnam | Variation order management challenges in developing-country context | Client changes, regulatory issues, unclear scope |
| 3 | Matu et al. (2020) | Urban road transport, Kenya | Stakeholder participation as prerequisite for effective project completion | Poor engagement, coordination failures |
| 4 | Mushato et al. (2020) | Road infrastructure, South Africa | Effects of poor performance on road infrastructure | Unforeseen site conditions, resource constraints |
| 5 | Johnson and Babu (2020) | Construction projects, UAE | Time and cost overruns and their critical causes | Supply chain, labour, financial constraints |
| 6 | Cabalag and Silva (2019) | Port infrastructure, Philippines | Principal component analysis for variation factor extraction | Planning-implementation gap, design deficiencies |
| 7 | Alsuliman (2019) | Public construction, Saudi Arabia | Causes of delay with policy and regulatory dimensions | Political interference, regulatory changes |
| 8 | Marzouk and Enaba (2019) | Construction contracts, Egypt | Text analytics applied to monitor contract correspondence | Administrative, coordination, design issues |
| 9 | Love et al. (2019) | Transportation infrastructure, international | Cost performance and planning fallacy in transport projects | Optimism bias, scope changes, financial disruptions |
| 10 | Belay et al. (2021) | Road construction, Ethiopia | Causes and effects of variation orders on road projects | Design deficiencies, client changes, site conditions |
| 11 | Melaku Belay et al. (2021) | Infrastructure, Ethiopia | Cost overrun and schedule delays in low-income economies | Financial constraints, capacity gaps, institutional failures |

| No | Citation | Context / Project Type | Main Themes / Findings | Key Root Causes Identified |
|---|---|---|---|---|
| 12 | Molinari et al. (2023) | Transport infrastructure, Belgium | Cost overrun variations across land transport modes | Scope changes, regulatory shifts, political factors |
| 13 | Ahmed and Jawad (2022) | Construction projects, systematic review | Causes and impacts of variation orders (systematic review) | Design flaws, owner changes, external environment |
| 14 | Mohammad et al. (2021) | Building & infrastructure, Iraq | Cost and time impact of variation orders | Budget constraints, design changes, coordination issues |

# 3. RESULTS AND DISCUSSION

The next step involved conducting a detailed analysis of the 14 articles selected from the SLR. This analysis aimed to identify the root causes and impacts associated with variations in infrastructure development projects. The following section presents the findings of this analysis.

## 3.1 ROOT CAUSES AND IMPACTS ASSOCIATED WITH VARIATIONS IN CONSTRUCTION AND INFRASTRUCTURE PROJECTS

This section synthesizes findings from the SLR to examine the causal mechanisms through which underlying project conditions generate variations in construction and infrastructure developments. Variations are conceptualized here as deviations from the baseline project scope, cost, schedule, or technical requirements arising from misalignment between planning assumptions and execution realities (Love et al., 2019; Mohammad et al., 2021; Sun et al., 2016). Although such deviations occur across construction sectors, infrastructure projects exhibit heightened susceptibility due to their scale, institutional exposure, regulatory intensity, and stakeholder interdependencies (Flyvbjerg, 2014; Cantarelli et al., 2012; Molinari et al., 2023). These contextual features amplify uncertainty propagation and increase the likelihood of contractual modifications and rework.

Financial constraints constitute a primary driver of variation formation (Abd El-Razek et al., 2008). Insufficient budget allocation or irregular funding flows undermine planned resource mobilization and disrupt activity sequencing, forcing contractors to adjust execution strategies and prompting scope or schedule revisions (Belay et al., 2021; Molinari et al., 2023; Mohammad et al., 2021; Memon et al., 2014). In infrastructure delivery, which relies on sustained capital investment and structured financing, delayed disbursement may halt operations and necessitate renegotiation of contractual terms or implementation sequences (Love et al., 2019; Doloi et al., 2012). Such financial discontinuities therefore translate directly into variations by invalidating baseline planning assumptions and forcing reactive decision-making (Ali et al., 2020).

Regulatory processes generate variations through compliance and temporal misalignment. Infrastructure developments typically require layered approvals from environmental, planning, and safety authorities, and changes or delays in these processes necessitate design revisions or schedule adjustments (Herrera et al., 2020; Tran et al.,

2020). Adaptive compliance requirements often introduce additional technical specifications, or mitigation works that alter project deliverables and contractual obligations (Mohammad et al., 2021; Sun et al., 2016). Consequently, governance-induced uncertainty acts as an institutional mechanism through which external regulatory dynamics materialize as project variations.

Political and policy shifts further intensify variation risk, particularly in long-duration infrastructure initiatives (Alkhattabi, 2023). Changes in governmental priorities or leadership may reshape funding allocations, sustainability targets, or social obligations, thereby altering project scope or timelines after implementation has commenced (Alsuliman, 2019; Love et al., 2019; Flyvbjerg, 2014). These macro-level interventions disrupt planning continuity and necessitate realignment of technical and contractual frameworks, illustrating how political volatility functions as a systemic catalyst for variations.

Design deficiencies and late-stage modifications represent another critical causal pathway. Incomplete preliminary investigations, including inadequate geotechnical surveys or environmental assessments, embed informational uncertainty within design documentation that becomes evident during execution (When discrepancies between assumed and actual conditions emerge, redesign and rework become necessary, resulting in cost and time deviations (Doloi et al., 2012; Love et al., 2019). Furthermore, evolving demand projections or land-use adjustments frequently trigger design alterations that propagate downstream procurement and construction changes (Mohammad et al., 2021; Sun et al., 2016).

Unforeseen site conditions similarly induce variations by invalidating baseline technical assumptions. Encounters with unknown utilities, contaminated soils, or complex subsurface conditions necessitate alternative construction methods or additional mitigation measures, expanding scope and increasing expenditure (Herrera et al., 2020; Mushato et al., 2020; Cantarelli et al., 2012). Such environmental uncertainty is particularly pronounced in infrastructure works due to extensive spatial exposure and limited subsurface predictability, reinforcing its role as a recurring source of variation claims.

Supply-chain disruptions and logistical constraints also contribute to variation formation. Large-scale infrastructure delivery depends on synchronized procurement and material flows, shortages, transportation bottlenecks, or market volatility interrupt planned workflows and compel substitution or resequencing strategies (Johnson & Babu, 2020; Love et al., 2019; Doloi et al., 2012). These adaptive responses alter execution parameters and generate contractual amendments, demonstrating how operational instability translates into measurable project deviations (Assaad et al., 2022).

Supply-chain disruptions and logistical constraints also contribute to variation formation. Large-scale infrastructure delivery depends on synchronized procurement and material flows, shortages, transportation bottlenecks, or market volatility interrupt planned workflows and compel substitution or resequencing strategies (Johnson & Babu, 2020; Love et al., 2019; Doloi et al., 2012). These adaptive responses alter execution parameters and generate contractual amendments, demonstrating how operational instability translates into measurable project deviations (Islamic Development Bank [IsDB], 2020).

Macroeconomic fluctuations and technological transitions represent additional external catalysts. Inflation, exchange-rate volatility, and economic downturns destabilize cost

baselines and procurement forecasts, forcing budget revisions and specification adjustments (Mohammad et al., 2021; Doloi et al., 2012). Meanwhile, technological evolution may require mid-project adoption of new tools or systems, altering workflows and skill requirements (Mushato et al., 2020; Belay et al., 2021). Both phenomena demonstrate how systemic environmental change propagates through project structures to produce variations.

Finally, inadequate stakeholder engagement can generate late-stage scope modifications when community or user concerns emerge after project initiation. Insufficient early consultation results in redesign, mitigation measures, or operational adjustments that disrupt schedules and contractual stability (Tran et al., 2020; Sun et al., 2016). This highlights the socio-institutional dimension of variation formation, wherein participatory deficiencies translate into technical and economic consequences (Ghimire et al., 2023).

Collectively, these mechanisms illustrate that variations are not isolated anomalies but emergent outcomes of structural misalignment between planned assumptions and dynamic execution environments. Infrastructure projects, due to their complexity and exposure to external influences, are particularly vulnerable, underscoring the importance of anticipatory governance, integrative coordination, and adaptive risk management strategies (Love et al., 2019; Molinari et al., 2023).

Following the SLR, identified root causes and impacts associated with variations in infrastructure development projects were linked to the identified issues and is presented in Figure 2.

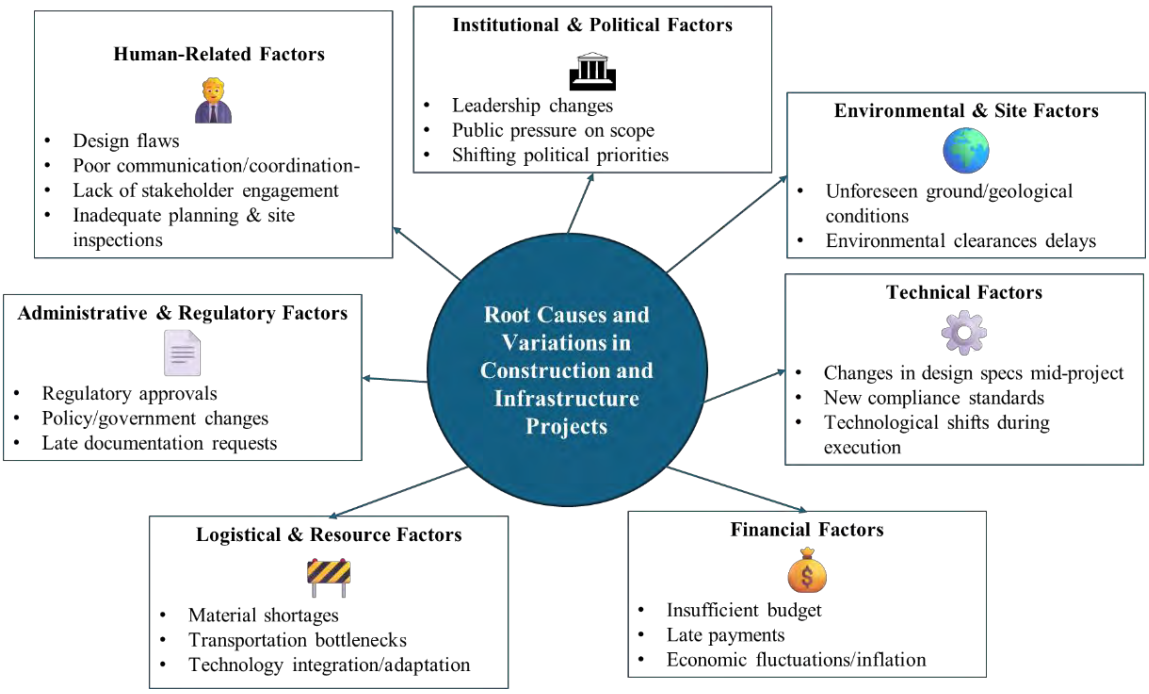



*Figure 2: Root causes and impacts associated with variations in infrastructure development projects*

Figure 2 presents a clear and comprehensive visual summary of the root causes contributing to variations in construction and infrastructure projects. The diagram effectively categorizes the causes into seven thematic groups: human-related, institutional and political, environmental and site, administrative and regulatory, logistical and resource, financial, and technical factors. Key factors contributing to these root causes

are further detailed in this figure demonstrating how interrelated challenges, ranging from design flaws and regulatory delays to budget constraints and unforeseen site conditions, can collectively disrupt project scope, time and cost. The centralized hub-and-spoke layout reinforces the concept that all these factors ultimately feed into the central problem of project variations.

## 4. CONCLUSIONS

The study concludes that variations in infrastructure development projects are a recurring issue that significantly impacts project success, timelines, and costs. The systematic literature review conducted in the study revealed various root causes and impacts associated with these variations.

The research emphasizes the importance of addressing these root causes and mitigating their impacts to ensure the successful completion of infrastructure development projects. It highlights the need for proactive measures such as adequate financial planning, stakeholder engagement, risk management, regulatory streamlining, and resilience building. Additionally, it suggests the implementation of transparent procurement processes, robust anti-corruption measures, and effective project management strategies to minimize variations and enhance project outcomes.

The systematic literature review offers insights into variations in infrastructure projects but has limitations. It focused on recent English articles, possibly excluding relevant older studies and non-English sources. The exclusion of non-peer-reviewed sources might limit its comprehensiveness. Future studies could widen the scope to include a broader range of sources and languages. While the review identified various root causes and impacts, the depth of analysis for each factor may be limited. Future research could delve deeper into specific root causes and impacts to better understand their complexities. Additionally, the review focused on identifying issues rather than exploring solutions. Future studies could investigate effective strategies for mitigating variations and improving project resilience, including the role of emerging technologies. These efforts could enhance the success rate of infrastructure projects.

## 5. REFERENCES

Abd El-Razek, M. E., Bassioni, H. A., & Mobarak, A. M. (2008). Causes of delay in building construction projects in Egypt. *Journal of Construction Engineering and Management, 134*(11), 831–841. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:11(831)

Ahmed, S., & Jawad, S. (2022). Causes and impacts of variation orders in construction projects: A systematic review. *Engineering, Construction and Architectural Management, 29*(8), 3201-3222. https://doi.org/10.5281/zenodo.8120316

Alkhattabi, L., Alkhard, A., & Gouda, A. (2023). Effects of change orders on the budget of the public sector construction projects in the Kingdom of Saudi Arabia. *Results in Engineering, 20*, 101628. https://doi.org/10.1016/j.rineng.2023.101628

Alkhattabi, L. (2023). Effects of change orders on the budget of public sector construction projects in Saudi Arabia. *Results in Engineering, 19*, 101628. https://doi.org/10.1016/j.rineng.2023.101628

Alnuaimi, A. S., Taha, R. A., Al Mohsin, M., & Al-Harthi, A. S. (2010). Causes, effects, benefits, and remedies of change orders on public construction projects in Oman. *Journal of Construction Engineering and Management, 136*(5), 615–622. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000154

Alsuliman, J. A. (2019). Causes of delay in Saudi public construction projects. *Alexandria Engineering Journal, 58*(2), 801–808. https://doi.org/10.1016/j.aej.2019.07.002

Althiyabi, T., & Qureshi, M. R. J. (2021). Predefined project scope changes and its causes for project success. *International Journal of Software Engineering & Applications, 12*(2/3), 45-56. https://doi.org/10.5121/ijsea.2021.12304

Ali, A. Z. (2008). *Causes and steps to minimize variations in construction projects* [Master's thesis, Universiti Teknologi Malaysia]. Malaysian Theses Online. https://ir.upm.edu.my/find/Record/my-utm-ep.31937

Assaad, R. H., Ahmed, M. O., El-adaway, I. H., & Shrestha, P. P. (2022). Management of change orders in infrastructure transportation projects. *Practice Periodical on Structural Design and Construction, 27*(1), 05021006. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000640

Belay, A. M., Tekeste, B. T., & Kebede, T. A. (2021). Causes and effects of variation orders on road construction projects. *Engineering, Construction and Architectural Management, 28*(7), 1793-1811. https://www.academia.edu/73661055/Causes_and_Effects_of_Variation_Orders_in_Road_Construction_Projects_The_Case_of_National_Works_Contract_Administered_by_Addis_Ababa_City_Roads_Authority

Cabalag, M. V., & Silva, D. L. (2019). Variation prognostic model on port infrastructures: Employment of principal component analysis for factor extraction instigating disparity on planning and implementation phase. *IOP Conference Series: Materials Science and Engineering, 652*, 012009. https://doi.org/10.1088/1757-899X/652/1/012009

Cantarelli, C. C., Flyvbjerg, B., Molin, E. J. E., & van Wee, B. (2010). Cost overruns in large-scale transportation infrastructure projects: Explanations and their theoretical embeddedness. *European Journal of Transport and Infrastructure Research, 10*(1), 5–18. https://doi.org/10.18757/ejtir.2010.10.1.2864

Doloi, H., Sawhney, A., Iyer, K. C., & Rentala, S. (2012). Analysing factors affecting delays in Indian construction projects. *International Journal of Project Management, 30*(4), 479-489. https://doi.org/10.1016/j.ijproman.2011.10.004

Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal, 45*(2), 6-19. https://doi.org/10.1002/pmj.21409

Ghimire, S., Bohara, N., & Awasthi, K. D. (2023). Causes and impacts of variation order in building construction projects: A case study of three projects at Bharatpur Metro. *JUEM, 1*(1), 105-114. https://doi.org/10.5281/zenodo.8120316

Herrera, R. F., Sánchez, O., Castañeda, K., & Porras, H. (2020). Cost overrun causative factors in road infrastructure projects: A frequency and importance analysis. *Applied Sciences, 10*(16), Article 5506. https://doi.org/10.3390/app10165506

Ibbs, W., & Chih, Y. (2011). Alternative methods for choosing an appropriate project delivery system (PDS). *Facilities, 29*(13/14), 527–541. https://doi.org/10.1108/02632771111178418

Islamic Development Bank. (2020). Project procurement under Islamic Development Bank: Guidance note on variation orders, contract addendums, and expiration. https://www.isdb.org/project-procurement/sites/pproc/files/media/documents/Guidance%20Note%20on%20Variation%20Orders%2C%20Contract%20Addendums%20and%20Expiration.pdf

Johnson, R. M., & Babu, R. I. I. (2020). Time and cost overruns in the UAE construction industry: A critical analysis. *International Journal of Construction Management, 20*(5), 402–411. https://doi.org/10.1080/15623599.2018.1484864

Karim, K. H. M., Ali, N., & Majeed, B. (2020). The causes of variation orders and their effects on cost and time of projects in Sulaimani governorate. *Kurdistan Journal of Applied Research, 5*(1), 218–235. https://doi.org/10.24017/science.2020.1.16

Kerzner, H. (2017). *Project management: A systems approach to planning, scheduling, and controlling* [12th ed.]. John Wiley & Sons. Retrieved from https://www.scirp.org/reference/referencespapers?referenceid=3400854

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Journal of Clinical Epidemiology, 62*(10), e1–e34. https://doi.org/10.1016/j.jclinepi.2009.06.006

Love, P. E. D., Sing, M. C. P., Ika, L. A., & Newton, S. (2019). The cost performance of transportation projects: The fallacy of the planning fallacy account. *Transportation Research Part A: Policy and Practice, 122*, 1-20. https://doi.org/10.1016/j.tra.2019.02.004

Marzouk, M., & Enaba, M. (2019). Text analytics to analyze and monitor construction project contract and correspondence. *Automation in Construction, 98*, 265-274. https://doi.org/10.1016/j.autcon.2018.11.018

Matu, J., Kyalo, D., Mbugua, J., & Mulwa, A. (2020). Stakeholder participation in project planning: Prerequisite to effective completion of urban road transport infrastructure projects in Kenya. *Journal of Building Construction and Planning Research, 8*(1), 73-91. https://doi.org/10.4236/jbcpr.2020.81006

Melaku Belay, S., Tilahun, S., Yehualaw, M., Matos, J., Sousa, H., & Workneh, E. T. (2021). Analysis of cost overrun and schedule delays of infrastructure projects in low-income economies: Case studies in Ethiopia. *Advances in Civil Engineering, 2021*(1), 4991204. https://doi.org/10.1155/2021/4991204

Memon, A. H., Rahman, I. A., & Hasan, M. F. A. (2014). Significant causes and effects of variation orders in construction projects. *Research Journal of Applied Sciences, Engineering and Technology, 7*(21), 4494–4502. https://doi.org/10.19026/rjaset.7.826

Mohammad, K. H., Ali, N. S., & Najm, B. M. (2021). Assessment of the cost and time impact of variation orders on construction projects in Sulaimani Governorate. *Journal of Engineering, 27*(2), 106–125. https://doi.org/10.31026/j.eng.2021.02.08

Molinari, L., Haezendonck, E., & Mabillard, V. (2023). Cost overruns of Belgian transport infrastructure projects: Analyzing variations over three land transport modes and two project phases. *Transport Policy, 134*, 167-179. https://doi.org/10.1016/j.tranpol.2023.02.017

Mushato, W., Mashwama, N. X., Thwala, D., & Aigbavboa, C. (2020). The effects of poor performance on roads infrastructure project. *Proceedings of International Structural Engineering and Construction, 7*(1), 1-6. https://doi.org/10.14455/ISEC.res.2020.7(1).INF-01

Pahlevan-Sharif, S., Mura, P., & Wijesinghe, S. N. R. (2019). A systematic review of systematic reviews in tourism. *Journal of Hospitality and Tourism Management, 39*, 158–165. https://doi.org/10.1016/j.jhtm.2019.04.001

Petticrew, M., & Roberts, H. (2006). *Systematic reviews in the social sciences*. Wiley. https://doi.org/10.1002/9780470754887

Ssegawa, J. K., Mfolwe, K. M., Makuke, B., and Kutua, B. (2002) Construction variations: A scourge or a necessity?. In *Proceedings of the First International Conference of CIB W107* (pp.87-96). https://pdfcoffee.com/construction-variations-a-scourge-or-a-necessity-pdf-free.html

Sun, M., & Meng, X. (2009). Taxonomy for change causes and effects in construction projects. International *Journal of Project Management, 27*(6), 560–572. https://doi.org/10.1016/j.ijproman.2008.10.005

Tran, N. N. N., Do, S. T., Nguyen, T. A., & Le, L. H. (2020). Variation order management in vietnam construction projects. In J. Reddy, C. Wang, V. Luong, & A. Le (Eds), *ICSCEA 2019* (Vol.80). Springer. https://doi.org/10.1007/978-981-15-5144-4_97

Wambeke, B. W., Hsiang, S. M., & Liu, M. (2011). Causes of variation in construction project task starting times and duration. *Journal of Construction Engineering and Management, 137*(9), 663-677. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000342

Li, R., Oo, B.L., Lim and B.T.H., 2026. A theoretical framework for the adoption of artificial intelligence technologies in the construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 121-134. DOI: https://doi.org/10.31705/WCS.2026.10. Available from: https://ciobwcs.com/papers/

# A THEORETICAL FRAMEWORK FOR THE ADOPTION OF ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN THE CONSTRUCTION INDUSTRY

**R. Li[1], B.L. Oo[2], and B.T.H. Lim[3]**

## *ABSTRACT*

*Despite the extensive research on the applications of Artificial Intelligence (AI) technologies in the construction industry, little attention has been given to the theoretical perspective on varying levels of AI adoption by the industry stakeholders. This research aims to address this gap by proposing a theoretical framework for understanding the adoption of AI technologies in the construction industry. The framework was developed through a review of literature, and it draws on four underpinning theories, namely: the Technology–Organisation–Environment (TOE) framework, the Technology Acceptance Model (TAM), the Innovation Diffusion Theory (IDT) and the Stakeholder Theory (SKT). The TOE framework and IDT shape the influencing factors at the macro-level, while the TAM captures the factors at the micro-level along with SKT for defining the relevant stakeholders of the AI adoption in the construction industry. By connecting individual, organisational, and industrial factors at macro- and micro-levels that impact AI adoptions in the industry, the framework provides a better understanding of the complex interplay of the respective factors in informing future research.*

***Keywords:*** *Artificial Intelligence (AI); Construction Industry; Theoretical Framework.*

## 1. INTRODUCTION

AI technologies have been increasingly developed and adopted in various fields and industries in recent decades. In the Construction Industry (CI), AI applications have been playing an essential role in many aspects, including rendering optimisation (Khan et al., 2024), schedule management (Datta et al., 2024), risk mitigation (Kampelopoulos et al., 2025), and cost estimation (Bhargava et al., 2017). Many researchers opined that introducing AI applications across the entire Construction Project Life Cycle (CPLC) could contribute positively towards construction project deliveries (Regona et al., 2024; Abioye et al., 2021; Khan et al., 2024). Despite the growing expectations of AI technologies toward their potential abilities in construction project deliveries, their applications in the construction industry are still in their initial phase and remain

[1] PhD Candidate, School of Built Environment, The University of New South Wales, Australia, z5380160@ad.unsw.edu.au
[2] Associate Professor, School of Built Environment, The University of New South Wales, Australia, bee.oo@unsw.edu.au
[3] Associate Professor, School of Built Environment, The University of New South Wales, Australia, b.lim@unsw.edu.au

fragmented (Regona et al., 2024). Moreover, various studies reported the trends of resistance to AI adoption (Dauda et al., 2025; Ojha et al., 2022; Omar et al., 2022), suggesting a divergence between the development of new AI technologies and their adoption in practice. To explore the underlying elements or factors behind this discrepancy, existing studies have explored the barriers and challenges of AI applications in the CI. These studies usually summarised the findings from two perspectives. One is the technological limitations, including challenges such as cybersecurity (Olatunde et al., 2023; Maqbool et al., 2022), data integration and collaboration (Wang et al., 2021; Van Tam et al., 2024; Shang et al., 2023), and compatibility and longevity (Gamil et al., 2020). The other aspect is stakeholder- or employee-related factors, involving apprehension among stakeholders (Ojha et al., 2022; Wang et al., 2025; Shang et al., 2023), disinterest in learning a new technology (Musarat et al., 2024), and resistance to change (Musarat et al., 2024; Wang et al., 2021). Although these studies provide an insight into factors influencing AI adoption, little attention has been paid to the roles of key stakeholders who may impact the level of acceptance and application of AI technologies. Specifically, current research on AI applications in the CI lacks sufficient theoretical supports for comprehending the varying levels of adoption by the industry stakeholders. Additionally, the influencing factors and/or elements are often categorised as isolated or scattered, without integrating into a coherent theoretical structure. To address these research gaps, this study aims to propose a theoretical framework that integrates four underpinning theories to better understand the AI adoption in the CI from a multi-level perspective. To achieve this research aim, the research objectives are to: (i) to identify technology diffusion theories and models from different disciplines and explore their applicability to the CI; (ii) establish a theoretical structure for integrating individual, organisational, and industrial factors; and (iii) explore the potential connections of micro- and macro-level factors that affect AI adoption in the CI.

## 2. RESEARCH METHOD

A literature review was performed to investigate theories and models of technology diffusion from different contexts (e.g., technological, organisational, and environmental contexts) in exploring their potential applicability to AI adoption in the CI context. The search for related papers was conducted through Scopus and supplemented by Google Scholar. The criteria of paper selection are: (i) the paper should be a peer-reviewed journal article or conference paper; (ii) the paper should be written in English; and (iii) the paper should focus on AI adoption, advanced technology diffusion, or digital transformation in CI context. However, as limited studies present theoretical perspectives of AI adoption in the CI, the literature review process has selected the relevant theories and models across various disciplines and/or industries [e.g., information and communication technology (ICT) disciplines, and CI], which have been empirically validated. These theories and models cover individual perspectives and attitudes at the micro-level, with environmental, organisational, and technological contents at the macro-level. The insights of the literature review provided the theoretical foundation of the proposed framework.

## 3. NEW TECHNOLOGY ADOPTION THEORIES

Researchers who focus on the technological innovation field have evaluated and recommended several theories, which include the Technology-Organisation-

Environment (TOE) framework, Technology Acceptance Model (TAM), Innovation Diffusion Theory (IDT), and Stakeholder Theory (SKT). These theories are identified as common theories in explaining the technology adoption and utilisation. Furthermore, the integrations of several theories were proposed in previous studies, such as TOE and TAM (Na et al., 2022), TOE and IDT (Wang et al., 2010; Oliveira et al., 2014), and TAM and IDT (Wang et al., 2010; Yuen et al., 2020). The trend implies that a single model or theory may not be sufficient to explain the processes of new technologies' adoption and acceptance. Indeed, with the exponential growth and development of advanced technologies, it is plausible that researchers seek to integrate a combination of diverse theories and/or models in comprehending innovation transmission. Considering these, the review of literature performed in this study presents how existing studies integrated various theories, and how these theories can be applied in the context of AI adoption in the CI.

## 3.1 TOE FRAMEWORK

The TOE framework was proposed by Tornatzky and Fleischer (1990) to explain the implementation of innovation at the organisation or firm level (Nguyen et al., 2022). The advantage of the TOE framework is that it enables the reflection from both internal and external dimensions of the decision-making process of new technologies' acceptance (Nguyen et al., 2022). They categorised the contexts that directly impact technology adoption of entrepreneurs in three aspects, i.e. (i) technology, (ii) organisation, and (iii) environment, as illustrated in Figure 1.

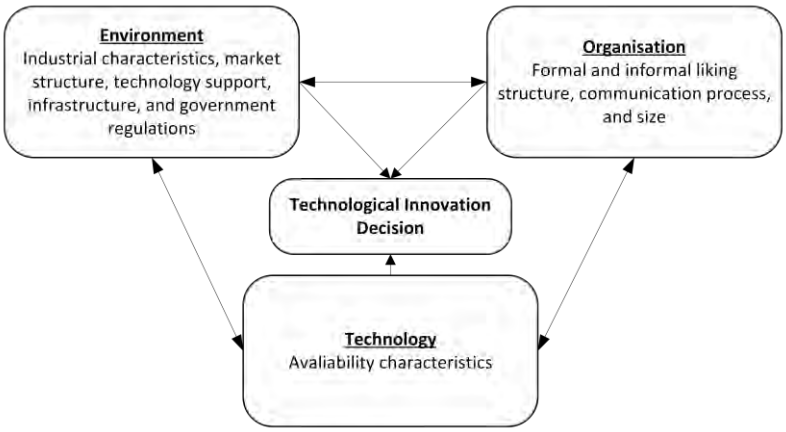



*Figure 1: Technology-Organisation-Environment (TOE) framework*
*Source: Tornatzky and Fleischer (1990)*

This model is identified as an organisation-dimension theory for explaining a firm's decision to utilise new technologies (Baker, 2011). These three elements interact with one another (Tornatzky & Fleischer, 1990), as further detailed below:

**Technological context** - It refers to all related technologies to the firm, including current equipment and systems the firm utilises, as well as the technologies that are currently available in the marketplace but not adopted (Baker, 2011).

**Organisational context** - It refers to resources and characteristics of an organisation or firm, such as firm size, management structure among employees, and the amount of available resources (Baker, 2011). Specifically, these elements can impact a firm's

decision to adopt new systems via various approaches, for instance, connecting internal subunits of an organisation or spanning internal boundaries to promote innovation.

**Environmental context** - It is the field where entrepreneurs operate their businesses, particularly, containing the industrial structure, regulatory status, and technological infrastructure support (Baker, 2011). Furthermore, this context includes the industry, competitors and government factors (Oliveira & Martins, 2011).

Kuan and Chau (2001) adopted the TOE model to explore the factors that led to the successful utilisation of electronic data interchange and verified the usefulness of the TOE framework in evaluating organisational decisions of IT technology adoption. Similarly, Oliveira and Martins (2011) used the TOE framework to compare the different influencing factors of e-business adoption between the telecommunications and tourism industries. The TOE framework has also been identified in other studies explaining various ICT systems adoption statuses (e.g., Malik et al., 2021; Mohammad et al., 2022; Nguyen et al., 2022). According to Hughes et al. (2025), with the adoption of the TOE framework, they proposed that the adoption of Generative AI (GenAI) in the CI is most likely to be driven by employees' talent in using GenAI and blocked by technological complexity. Their study provided an insight into the possibility of applying the TOE framework in research related to AI adoption in the CI. It is noted that the flexibility and comprehensiveness of the TOE model enable its adoption in different industries and technologies, including interdisciplinary research (Sun et al., 2025). Overall, the evidence from previous studies suggests that the TOE model can be well adopted with other theories in comprehending the adoption of new technologies.

## 3.2 TAM

The TAM, which was proposed by Davis et al. (1989), provides a fundamental framework for explaining how new technologies are accepted by individual users. Figure 2 illustrates two essential elements of this model: (i) Perceived Usefulness (PU) and (ii) Perceived Ease Of Use (PEOU). According to Davis (1989), the extend people tend to accept or reject using an advanced technology is related to their belief that it will assist them in completing their tasks better, which is PU in the TAM theory. Accordingly, if users deem that the new system is too hard to master, and the benefits of the application are outweighed by the difficulties of using it, they will prefer to resist the adoption of the advanced system. This is defined as PEOU. Researchers adopted scale development procedures and empirical validation to test the impacts of PU and PEOU on users' willingness to accept new technologies (Hur et al., 2017; Liu & Ye, 2021; Wang et al., 2021). Furthermore, these studies demonstrated that PEOU not only affect the utilisation of new technologies directly but also influences the utilisation through affecting PU.

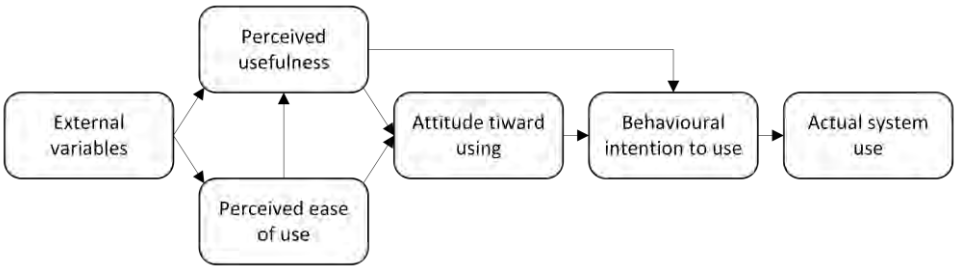



*Figure 2: Technology Acceptance Model (TAM) framework*
*Source: Na et al. (2022)*

The Unified Theory of Acceptance and Use of Technology (UTAUT) proposed by Venkatesh et al. (2003) indicates a significant consolidation of different theories in the investigation of new technology acceptance. By integrating eight models, including the TAM model, the Theory of Planned Behaviour (TPB), and the Model of Personal Computer Utilisation (MPCU), this theory identified four key elements that affect user intention and use behaviour: performance expectancy, effort expectancy, social influences, and facilitating conditions. Venkatesh et al. (2003) claimed that the empirical results demonstrated a higher accuracy in explaining the acceptance extension of users compared to earlier models. Hassan (2025) identified the usage of TAM in evaluating AI adoption in the Egyptian talent acquisition process. This study supported the feasibility of introducing TAM in AI adoption research, despite its research field is outside the CI. Although UTAUT successfully integrated relative models, it primarily retains an individual dimension focus, while providing limited insights into the impacts of multi-dimensional engagement.

## 3.3 IDT

The IDT was proposed to explain how individuals decide to adopt or reject an innovation by identifying five stages of innovation adoption, namely: knowledge, persuasion, decision, implementation, and confirmation (Rogers 1995). However, Moore and Benbasat (1991) demonstrated that IDT should emphasise the characteristics of the innovation, instead of the attitude of potential users. Based on this perspective, they proposed eight elements as the determining factors of IDT i.e. (i) relative advantage, (ii) ease of use, (iii) compatibility, (iv) image, (v) result demonstrability, (vi) visibility, (vii) voluntariness, and (viii) trialability. Similarly, Poong et al. (2009) proposed that result demonstrability, compatibility and relative advantage can positively impact the stakeholders' intention to conduct the innovation. In a statistical model by Yuen et al. (2020), they found that relative advantage, compatibility, complexity, and trialability have a positive influence on users' acceptance level of innovation. They summarised the findings of relevant studies and proposed five elements that can be used to evaluate and predict users' adoption of innovation i.e. (i) relative advantage, (ii) compatibility, (iii) complexity, (iv) experimental, and (v) observability. Steiber et al. (2021) applied the IDT to deepen the understanding of the elements affecting an industrial firm's digital transformation. They suggested that the IDT is effective in identifying factors that affect the adoption level of innovation from its own side. According to the above-mentioned studies, IDT established a connection between technology adoption and acceptance with the innovation itself at the organisational level.

## 3.4 THE INTEGRATIONS OF TOE FRAMEWORK, TAM AND IDT

The TOE framework has been widely adopted to explore organisation-level factors influencing technology adoption and acceptance. At the individual level, TAM provides the perspective of how individuals' intentions impact the new technologies' adoption through PU and PEOU (Davis et al, 1989). Meanwhile, IDT has been used in the field of Information and Communications Technology (ICT) research to evaluate the extension of new technologies in organisations (Meade & Islam, 2006; Yuen et al., 2020). Existing studies attempted to integrate them together to gain a better understanding of the processes of new technologies' adoption from different perspectives. Table 1 illustrates the integration of these frameworks and theories, including TOE with TAM, TAM with IDT, and TOE with IDT.

*Table 1: The summary of models and theories integrations*

| Model or framework | Fields or industries | Reference |
|---|---|---|
| TOE + TAM | CI | Na et al. (2022); Na et al. (2023) |
| TAM + IDT | ICT field | Wang et al. (2010); Al-Rahmi et al. (2019); Yuen et al. (2020) |
| TOE + IDT | ICT field | Soares-Aguiar and Palma-dos-Reis (2008); Wang et al. (2010); Oliveira et al. (2014) |

In the CI context, Na et al. (2022) contributed to the connection between individual and organisational factors by examining the relationships across PU, PEOU, and external factors. Their findings emphasised the importance of PU in shaping user intention of advanced technology, while organisational and environmental factors influenced adoption outcomes at the same time. In addition, they confirmed that PU and PEOU are influenced by external factors, including technological, organisational, and environmental contexts. Specifically, challenges and motivations from the contextual dimension can affect stakeholders' attitudes through PU and PEOU. Additionally, Na et al. (2023) found that PU could positively influence the intention of using new systems, implying the potential utilisation of TAM and TOE models in explaining the adoption of AI technologies in the CI. Despite the wide utilisation and acceptance of the integrated structure of the TOE framework and TAM in explaining new technology adoption, this integration still provides limited consideration of innovation diffusion. Despite the integration of the TOE framework and TAM, researchers also suggested that the integration of the TAM and IDT shows a high level of suitability for examining new technology adoption (Wang et al., 2010; Yuen et al., 2020). By applying a combination of TAM and IDT models, Al-Rahmi et al. (2019) tested the applicability of this integration by investigating the factors affecting the use of the e-learning system among students empirically. Next, Yuen et al. (2020) used the integrated model of IDT and TAM to evaluate the adoption of autonomous vehicles among users and investigate the factors that impact the acceptance intentions of users. Besides, researchers have tried to integrate the TOE framework with IDT theory in the ICT field. The integration was applied in examining the adoption of these advanced technologies' systems: electronic procurement systems (Soares-Aguiar & Palma-dos-Reis, 2008), radio frequency identifications (Wang et al., 2010) and cloud computing systems (Oliveira et al., 2014). Overall, these theoretical integrations have been widely applied across different fields, including the CI context and the ICT fields. By combining organisational, technological, and individual perspectives, previous studies provide a comprehensive explanation of technology adoption processes across different domains. Nevertheless, these studies rarely consider the influences from users or relevant stakeholders of new technologies adoption. This gap is particularly distinct in the CI context, where multiple actors are involved in construction project deliveries. Thus, a clear definition of stakeholders is necessary to provide a comprehensive theoretical perspective.

## 3.5 SKT

The SKT was proposed by Freeman (1984), who demonstrated that the achievement of a firm depends on the value it creates for their various stakeholders. According to this perspective, organisations are required to consider and manage the relationships between both individuals and groups that can affect or are affected by organisational activities.

Freeman (1984) first categorised the different stakeholders based on their level of involvement and influence on the business. Primary (also known as internal) stakeholders are defined as the groups or individuals that directly affect the decision-making process of creating the company's value. In other words, primary stakeholders are directly influenced by a firm's interests or outcomes. For the secondary stakeholder, who is not directly involved in organisational operations but could still influence or be influenced by a firm's decisions and practices. However, Freeman et al. (2010) demonstrated that there is no clear boundary between the primary and secondary stakeholders.

The complex construction project management process indicates that the coordination with stakeholders is a significant challenge (Agyemang et al., 2025). Due to this, the adoption of AI technologies should be considered as a multi-aspect decision, as it is influenced by various stakeholder groups. Newcombe (2003) introduced the SKT into the construction field to identify stakeholders in construction projects by using a case study with power/predictability and power/interest matrices to demonstrate that clients in a construction project include multi-party alliances. Accordingly, in the CI, the primary stakeholders have usually been referred to as investors, employees, contractors, suppliers, clients, and shareholders, as shown in Figure 3.

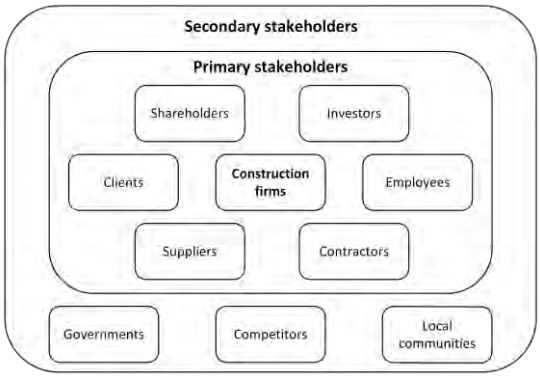



*Figure 3: Stakeholders in the CI context*
*Source: Newcombe (2003)*

The secondary stakeholders in the CI usually include governments, local communities, and competitors. Olander and Landin (2005) applied SKT to construction project management processes by proposing a stakeholder impact analysis method to examine their influences on construction projects. Agyemang et al. (2025) emphasised that the multi-organisational and fragmented natures of construction projects lead to a complex situation of multi-stakeholders. Existing research has conducted SKT to analyse construction interest conflicts (Olander & Landin, 2005), decision-making process influences (Shahbaz et al., 2018), and risk management approaches (Zanjirchi & Moradi, 2012). Evidently, SKT has been widely adopted in construction research to shed light on the coordination of stakeholders' relationships and mitigate conflicts between different parties from a theoretical perspective. However, there is a lack of application of SKT for explaining new technologies' adoption in the CI. In this study, SKT is embedded in the proposed theoretical framework as detailed next.

## 4. THE PROPOSED THEORETICAL FRAMEWORK

As revealed in Section 2, existing studies tend to propose theoretical integrations at a single level. For instance, combining TOE and IDT to represent the macro level, and

using TAM to represent the micro level. Thus, limited studies exist that integrate macro- and micro-dimensional perspectives. Furthermore, SKT has been noted for frequently conducting research in the CI to identify and define stakeholders. However, its collaboration with the theories of technology adoption remains limited. Accordingly, this study proposes an integrated theoretical framework on the adoption of AI technologies in the CI that is underpinned by four theories as illustrated in Figure 4.

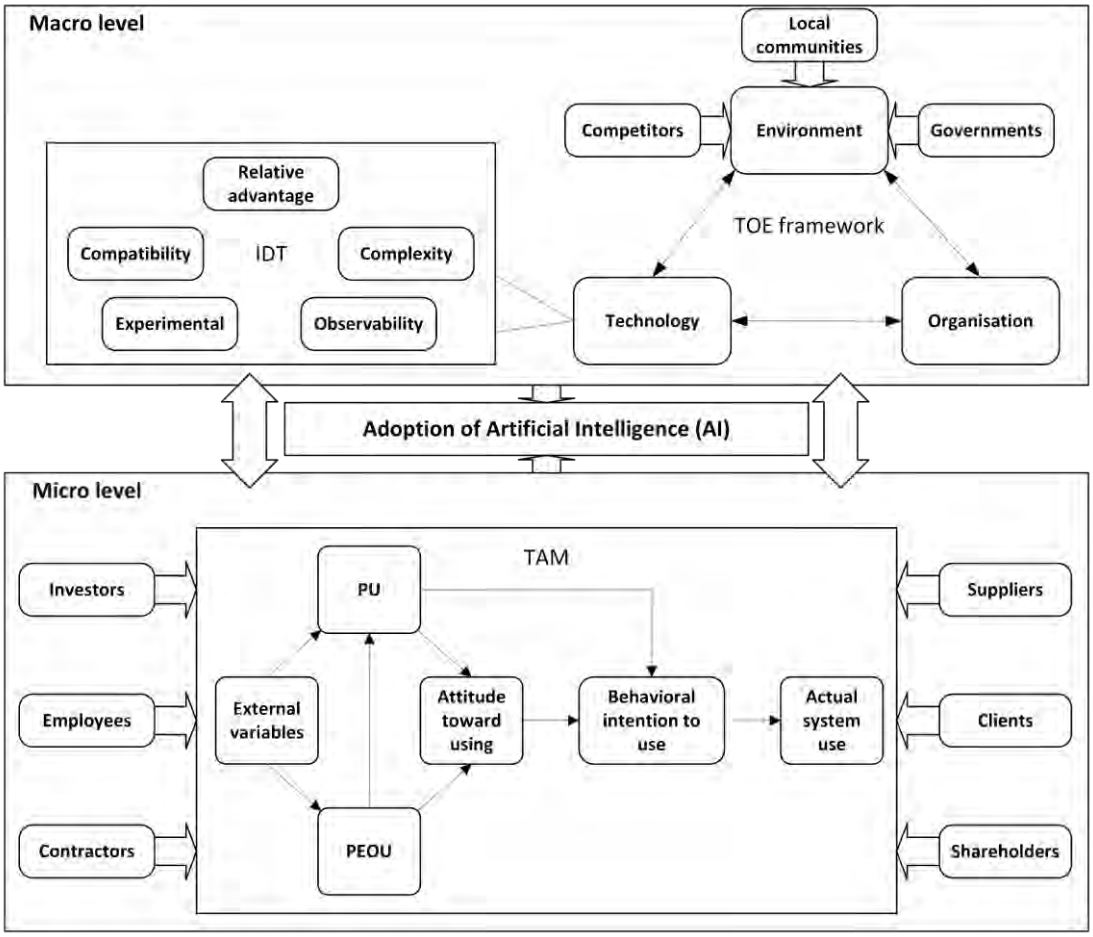



*Figure 4: The proposed theoretical framework*
*Source: Authors' own work*

The framework captures both the micro and macro-level factors from organisational and individual levels that influence the adoption of AI technologies in the CI as discussed next.

## 4.1 MACRO-DIMENSION THEORIES INCORPORATION

To explain the factors that affect the adoption of AI technologies in the CI, the TOE model and IDT are embedded in the macro-level of the structure, which represents the macro-level theories (i.e., the top structure of Figure 4). The TOE framework involves three contexts at the macro level: technology, organisation, and environment. The technological context, which concerns both current utilised and unutilised AI technologies' characteristics that are relevant to construction firms (Na et al., 2023). For instance, the technological context could include immature AI technologies (Ojha et al., 2022), current software limitations to integrate AI systems (Perera et al., 2023), and a

lack of robustness between current technological systems and AI technologies (Gamil et al., 2020). On the other hand, the organisational context refers to the internal characteristics of construction firms that influence their capability to adopt or apply AI technologies. It includes the coordination and communication between different firms' structural levels (Peter, 2023), in the absence of adequate management guidelines (Gamil et al., 2020). This aspect addresses the structural and managerial conditions from construction firms' perspective on AI adoption. Next, the environmental context refers to the external environment surrounding construction firms, incorporating the industry itself, competitors, and government rules and regulations. These include the fragmented and complex natures of the CI (Ojha et al., 2022) and the lack of professional skills toward AI adoption (Peter, 2023). Furthermore, the factors across these three contexts are interdependent (Baker, 2011). For example, in a situation where a construction firm is exploring the opportunity of adopting a new AI technology, which would involve the assessment of the feasibility and compatibility of the new technology with its existing operating system. Managerial support, availability of skilled employees, and cost of new technology adoption determine whether the firms' capacity to adopt the respective new AI technologies. Meanwhile, external environmental impacts, including client requirements, competitive dynamics, and regulatory requirements of compliance, may be referred to as incentives or constraints that influence firms' decision-making process. Although the TOE framework identifies three contexts that influence the adoption of AI technologies, it does not explain how the intrinsic perspective of AI technologies impacts the adoption process. Therefore, to broaden the coverage of factors that influence, the IDT is introduced in this framework.

As a theory that contributes to explaining the characteristics of new technologies, IDT is frequently used in research related to the adoption of advanced technologies as a widely recognised theory (Oliveira et al., 2014; Malik et al., 2021; Na et al., 2022). In this framework, the IDT proposed by Yuen et al. (2020) is applied, which introduces five characteristics i.e. (i) relative advantage, (ii) compatibility, (iii) complexity, (iv) experimental, and (v) observability. The IDT is a refinement of the TOE model in the proposed framework, providing a particular perspective from AI technologies on the macro scale. Additionally, the impact of technologies can diffuse to all contexts at the organisational dimension, which reflects the interdependence of contexts of TOE. Moreover, IDT connects the macro-level and micro-level. For example, the observability of technologies helps users shape their attitude toward adopting AI. Specifically, this factor impacts stakeholders' PU and PEOU of AI technologies, further influencing their intention to adopt AI technologies.

## 4.2 MICRO-DIMENSION THEORIES INCORPORATION

In Figure 4, the bottom structure indicates the micro-level theories involved in this framework. The model adopted at this level is TAM, surrounded by relevant stakeholders. Authors opined that the TAM is the most popular theory for predicting and explaining user acceptance of innovations (Na et al., 2022; Na et al., 2023; Davis & Granic, 2024). TAM suggests that individuals' attitude toward technologies' adoption is based on PU and PEOU. According to Davis and Granic (2024), compared to the PEOU, PU is the primary determinant. Particularly, PEOU affects user acceptance through influencing PU. They also demonstrated that users tend to tolerate the difficulties of the advanced technology, provided it can improve the usefulness of their current operating

technologies. In this study, PU refers to stakeholders' belief in how much AI technologies can enhance the workflow performance and efficiency in construction project deliveries. Taking an example of the diffusion of BIM technology in the CI since the 1990s, given its high efficiency as an all-in-one solution to construction issues in different project phases, including designing, constructing, and operating, stakeholders perceived the adoption of BIM as beneficial for construction project deliveries (Khan et al., 2024). PEOU refers to stakeholders' belief that it is easy to adopt AI technologies without substantial requirements or investments. As a key stakeholder entity, it is expected that investors are more likely to support the adoption of AI technologies, which offer a predictable high Return On Investment (ROI), for those with low ROI, the investor's attitude tends to be apprehensive.

Although the TAM explains the impact of users' intentions and attitudes on AI adoption at the micro level, it does not specify how users or stakeholders should be identified or classified. This gap highlights the necessity of introducing SKT. The embedding of SKT enables the identification of the individuals and groups that are relevant to AI adoption. It is noted that the relationships between SKT and other theories are not singular, it is applied in scattered boxes at both levels to present the stakeholders that are appropriate for the level. It can be observed that competitors, governments, and local communities are identified as being able to affect the environment at the macro level, while investors', employees', contractors', suppliers', clients', and shareholders' influences reflect on the process of TAM at the micro level. The primary stakeholders, also named as the internal stakeholders, are involved at the micro-level, as they influence the adoption of AI technologies through their individual intentions. The secondary stakeholders (external stakeholders) affect the applications of AI technologies by influencing the factors among the TOE. For example, the government requirements of digital transformation can transform into external pressures on construction firms within the environmental context, prompting them to reconsider their decision on AI adoption.

Additionally, the bidirectional arrows crossing the central structure that refers to the AI adoption in the CI represent the interaction between the two structures in Figure 4. Notably, factors for different dimensions are not isolated; they are influenced by each other. Taking an example, the compatibility of AI technologies reflects the characteristics of technologies themselves and further shapes the intentions of adopting these technologies by construction firms. Compatibility reflects the capability of AI technologies to integrate into existing systems. When the management level decides to adopt an AI technology, it must evaluate whether the new technology aligns with the company's current infrastructure and systems. Thus, a higher degree of compatibility reduces the uncertainty of AI adoption' process, thereby accelerating the diffusion of AI adoption within the firm. Thus, this framework provides a multi-dimensional explanation at both the macro- and micro-levels of AI adoption in the CI by combining environmental, organisational and individual elements.

Conclusively, existing frameworks (e.g., TOE-IDT structure) focus on AI adoption primarily explore the adoption intention through single-level influences, rather than conducting cross-level analysis for different factors. However, the proposed framework extends existing integrated structures by combining the focus on individual and system dimensions within the CI. In addition, it incorporates stakeholders' participation to explain the potential interactions from different contexts. This allows for a more dynamic

and sensible explanation of AI adoption in the CI, as different phases of the CPLC may include specific demands of AI applications.

## 5. CONCLUSIONS

This study proposes a theoretical framework for a better understanding of the factors influencing the adoption of AI technologies in the CI. It incorporates the TOE framework, TAM, IDT, and SKT to provide both macro- and micro-level perspectives of influencing factors. Given the complex and fragmented nature of construction projects that would result in heterogeneous technological demands across different phases of CPLC, the AI adoption in the CI is rather unique compared to other sectors. By integrating models and theories from different dimensions, this framework enables a deeper understanding of how influencing factors from different contexts interact, negotiate, and translate into AI adoption in the CI. Furthermore, this framework identifies factors that can be operationalised into measurable variables for quantitative or mixed-method research. For instance, future research may explore stakeholders' trust in AI, ethical concerns of AI utilisation, and resistance to technological innovation, which are influenced by AI technologies complexity from the technological context; management group support from organisational context; and industry competition from environmental context. By integrating these dimensions, the framework enables future research to link and evaluate the interactions of those influencing factors toward AI adoption in the AI. In terms of contribution, theoretically, this study proposes an integrated framework of how environmental contexts, organisational decisions, technological characteristics, and individual intentions interplay in the AI adoption process. It provides a theoretical basis for understanding the AI adoption process from multiple dimensions and a dynamic perspective. Practically, it provides a foundational structure for evaluating the complex AI adoption processes in the CI involving multiple stakeholders. Additionally, the framework deepens the understanding of AI adoption from both macro- and micro-level perspectives. Moreover, this framework provides a fundamental structure for identifying the interactions among various influencing factors, enabling the evaluation of effective points of intervention across multiple levels. Thereby, it supports a well-informed decision-making process of AI adoption from the construction firms' perspective. Meanwhile, the identification of macro-level influences is more inclined to facilitate policy interventions for AI adoption. However, a significant limitation of this framework is that it has not yet been empirically tested, which indicates that its predictive and explanatory capabilities still require validation. To address this limitation, future research can apply Structural Equation Modelling (SEM) or regression-based method to test direct, mediating, and moderating effects among variables to evaluate the generalisability and comprehensiveness of this framework.

## 6. REFERENCES

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Delgado, J. M. D., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*(1), 1–13. https://doi.org/10.1016/j.jobe.2021.103299

Agyemang, E. A., Musonda, I., & Zulu, S. (2025). Stakeholder theory and shareholder theory application in construction field: Systematic scoping review. *Construction Economics and Building*, *25*(2). https://doi.org/10.5130/ajceb.v25i2.9346

Al-Rahmi, W. M., Yahaya, N., Aldraiweesh, A. A., Alamri, M. M., Aljarboa, N. A., Alturki, U., & Aljeraiwi, A. A. (2019). Integrating technology acceptance model with innovation diffusion theory: An empirical investigation on students' intention to use e-learning systems. *IEEE Access*, *7*, 26797–26809. https://doi.org/10.1109/access.2019.2899368

Bhargava, A., Labi, S., Chen, S., Saeed, T. U., & Sinha, K. C. (2017). Predicting cost escalation pathways and deviation severities of infrastructure projects using risk-based econometric models and monte carlo simulation. *Computer-Aided Civil and Infrastructure Engineering*, 32(8), 620-640. https://doi.org/10.1111/mice.12279

Baker, J. (2012). The technology–organization–environment framework. In Y. K. Dwivedi & M. R. Wade (Eds.), *Information systems theory: Explaining and predicting our digital society* (Vol. 1, pp. 231–245). Springer. https://doi.org/10.1007/978-1-4419-6108-2_12

Datta, S. D., Islam, M., Rahman Sobuz, M. H., Ahmed, S., & Kar, M. (2024). Artificial intelligence and machine learning applications in the project lifecycle of the construction industry: A comprehensive review. *Heliyon*, *10*(5), e26888. https://doi.org/10.1016/j.heliyon.2024.e26888

Dauda, J. A., Chavan, N. N., Saka, A. B., Ajayi, S. O., & Oyegoke, A. S. (2025). An appraisal of barriers to digitalisation of construction industry in developing countries: Perspective from India. *International Journal of Construction Management/˜the œInternational Journal of Construction Management*, *25*(7), 1–13. https://doi.org/10.1080/15623599.2024.2362014

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *Journal of Risk and Uncertainty*, *18*(3), 321–325. https://doi.org/10.1023/a:1011156710779

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: A comparison of two theoretical models. *Management Science*, *35*(8), 982–1003. https://doi.org/10.1287/mnsc.35.8.982

Davis, F. D., & Granić, A. (2024). *The technology acceptance model: 30 years of TAM*. Springer Cham. https://doi.org/10.1007/978-3-030-45274-2

Freeman, R. E. (1984). *Strategic Management: A Stakeholder Approach*. Boston, MA: Pitman.

Freeman, R.E., Harrison, J.S., Wicks, A.C., Parmar, B.L., de Colle, S. (2010). *Stakeholder theory: The state of the art*. Cambridge University Press.

Gamil, Y., Abdullah, M.A., Rahman, I. A., & Asad, M. M. (2020). Internet of things in construction industry revolution 4.0. *Journal of Engineering, Design and Technology*, *18*(5), 1091–1102. https://doi.org/10.1108/jedt-06-2019-0164

Hassan, B. F. Y. (2025). Adoption of AI in talent acquisition: A quantitative study on HRM practitioners using the Technology Acceptance Model (TAM). *Scientific Journal for Financial and Commercial Studies and Research*, *6*(1),1289-1316. https://doi.org/10.21608/cfdj.2025.352695.2145

Hughes, L., Davies, F., Li, K., Gunaratnege, S. M., Malik, T., & Dwivedi, Y. K. (2025). Beyond the hype: Organisational adoption of Generative AI through the lens of the TOE framework–A mixed methods perspective. *International Journal of Information Management*, 86, 102982. https://doi.org/10.1016/j.ijinfomgt.2025.102982

Hur, H. J., Lee, H. K., & Choo, H. J. (2017). Understanding usage intention in innovative mobile app service: Comparison between millennial and mature consumers. *Computers in Human Behavior*, *73*, 353–361. https://doi.org/10.1016/j.chb.2017.03.051

Kampelopoulos, D., Tsanousa, A., Vrochidis, S., & Kompatsiaris, I. (2025). A review of LLMs and their applications in the architecture, engineering and construction industry. *Artificial Intelligence Review*, *58*(8). https://doi.org/10.1007/s10462-025-11241-7

Khan, A. A., Bello, A. O., Arqam, M., & Ullah, F. (2024). Integrating building information modelling and artificial intelligence in construction projects: A review of challenges and mitigation strategies. *Technologies*, *12*(10), 185–185. https://doi.org/10.3390/technologies12100185

Kuan, K. K. Y., & Chau, P. Y. K. (2001). A perception-based model for EDI adoption in small businesses using a technology–organization–environment framework. *Information & Management*, *38*(8), 507–521. https://doi.org/10.1016/s0378-7206(01)00073-8

Liu, N., & Ye, Z. (2021). Empirical research on the blockchain adoption – Based on TAM. *Applied Economics*, *53*(37), 4263-4275. https://doi.org/10.1080/00036846.2021.1898535

Malik, S., Chadhar, M., Vatanasakdakul, S., & Chetty, M. (2021). Factors affecting the organizational adoption of blockchain technology: Extending the technology–organization–environment (TOE) framework in the Australian context. *Sustainability*, *13*(16), 9404. https://doi.org/10.3390/su13169404

Maqbool, R., Saiba, M. R., & Ashfaq, S. (2022). Emerging industry 4.0 and Internet of Things (IoT) technologies in the Ghanaian construction industry: Sustainability, implementation challenges, and benefits. *Environmental Science and Pollution Research*, *30*, 37076-37091. https://doi.org/10.1007/s11356-022-24764-1

Meade, N., & Islam, T. (2006). Modelling and forecasting the diffusion of innovation – A 25-year review. *International Journal of Forecasting*, *22*(3), 519–545. https://doi.org/10.1016/j.ijforecast.2006.01.005

Musarat, M. A., Alaloul, W. S., Zainuddin, S.M.B., Qureshi, A. H., & Maqsoom, A. (2024). Digitalization in malaysian construction industry: Awareness, challenges and opportunities. *Results in Engineering*, *21*, 102013–102013. https://doi.org/10.1016/j.rineng.2024.102013

Mohammad, A. B., Al-Okaily, M., Al-Majali, M., & Masa'deh, R. (2022). Business Intelligence and Analytics (BIA) usage in the banking industry sector: An application of the TOE framework. *Journal of Open Innovation: Technology, Market, and Complexity*, *8*(4), 189. https://doi.org/10.3390/joitmc8040189

Moore, G. C., & Benbasat, I. (1991). Development of an instrument to measure the perceptions of adopting an information technology innovation. *Information Systems Research*, *2*(3), 192–222. https://doi.org/10.1287/isre.2.3.192

Na, S., Heo, S., Choi, W., Kim, C., & Whang, S. W. (2023). Artificial Intelligence (AI)-based technology adoption in the construction industry: A cross national perspective using the technology acceptance model. *Buildings*, *13*(10), 2518. https://doi.org/10.3390/buildings13102518

Na, S., Heo, S., Han, S., Shin, Y., & Roh, Y. (2022). Acceptance model of Artificial Intelligence (AI)-based technologies in construction firms: Applying the Technology Acceptance Model (TAM) in combination with the Technology–Organisation–Environment (TOE) framework. *Buildings*, *12*(2), 90. https://doi.org/10.3390/buildings12020090

Newcombe, R. (2003). From client to project stakeholders: A stakeholder mapping approach. *Construction Management and Economics*, *21*(8), 841–848. https://doi.org/10.1080/0144619032000072137

Nguyen, T. H., Le, X. C., & Vu, T. H. L. (2022). An extended Technology-Organization-Environment (TOE) framework for online retailing utilization in digital transformation: Empirical evidence from Vietnam. *Journal of Open Innovation: Technology, Market, and Complexity*, *8*(4), 200. https://www.mdpi.com/2199-8531/8/4/200

Olander, S., & Landin, A. (2005). Evaluation of stakeholder influence in the implementation of construction projects. *International Journal of Project Management*, *23*(4), 321–328. https://doi.org/10.1016/j.ijproman.2005.02.002

Oliveira, T., & Martins, M. F. (2011). Literature review of information technology adoption models at firm level. *Electronic Journal of Information Systems Evaluation*, *14*(1), 110-121. https://academic-publishing.org/index.php/ejise/article/view/389

Oliveira, T., Thomas, M., & Espadanal, M. (2014). Assessing the determinants of cloud computing adoption: An analysis of the manufacturing and services sectors. *Information & Management*, *51*(5), 497–510. https://doi.org/10.1016/j.im.2014.03.006

Ojha, A., Habibnezhad, M., Jebelli, H., & Leicht, R. (2022). Barrier analysis of effective implementation of robotics in the construction industry. In F. Jazizadeh, T. Shealy, & M. J. Garvin (Eds.), *Construction Research Congress 2022: Computer applications, automation, and data analytics* (pp. 661–669). American Society of Civil Engineers. https://doi.org/10.1061/9780784483961.069

Olatunde, N. A., Gento, A. M., Okorie, V. N., Oyewo, O. W., Mewomo, M. C., & Awodele, I. A. (2022). Construction 4.0 technologies in a developing economy: awareness, adoption readiness and challenges. *Frontiers in Engineering and Built Environment*, *3*(2), 108–121. https://doi.org/10.1108/febe-08-2022-0037

Omar, A. F., Zainordin, N., Khoo, S. L., & Peng, J. O. H. (2022). Barriers in implementing artificial intelligence (AI) and Internet of things (IoTs) among Malaysian construction industry. In, *10th International Conference on Applied Science and Technology*, (pp. 030002), https://doi.org/10.1063/5.0111461

Perera, S., Jin, X., Samaratunga, M., & Gunasekara, K. (2023). Drivers and barriers to digitalisation: A cross-analysis of the views of designers and builders in the construction industry. *Journal of Information Technology in Construction*, *28*, 87–106. https://doi.org/10.36680/j.itcon.2023.005

Peter, E. A. V. (2023). Analysis of factors influencing the use of artificial intelligence in the Indian construction industry. In J. Vijayalaxmi (Eds.), *Building Construction and Technology*. *Lecture Notes in Civil Engineering* (pp. 31–44). Springer. https://doi.org/10.1007/978-981-99-3526-0_3

Poong, Y. S., Eze, U. C., & Talha, M. (2009). B2C e-commerce in Malaysia: Perceived characteristics of innovating and trust perspective. *International Journal of Electronic Business*, *7*(4), 392-427. https://doi.org/10.1504/ijeb.2009.027267

Regona, M., Yigitcanlar, T., Hon, C., & Teo, M. (2024). Artificial intelligence and sustainable development goals: systematic literature review of the construction industry. *Sustainable Cities and Society*, *108*, 105499–105499. https://linkinghub.elsevier.com/retrieve/pii/S2210670724003251

Rogers, E. M. (1995). *Diffusion of Innovations* (4th ed.). Free Press.

Shahbaz, M. S., Chandio, A. F., Oad, M., Ahmed, A., & Ullah, R. (2018). Stakeholders' management approaches in construction supply chain: A new perspective of stakeholder's theory. *International Journal of Sustainable Construction Engineering and Technology*, *9*(2), 16-26. https://doi.org/10.30880/ijscet.2018.09.02.002

Shang, G., Low, S. P., & Valen, Y. (2023). Prospects, drivers of and barriers to artificial intelligence adoption in project management. *Built Environment Project and Asset Management*, *13*(5), 629-645. https://doi.org/10.1108/bepam-12-2022-0195

Soares-Aguiar, A., & Palma-dos-Reis, A. (2008). Why do firms adopt e-procurement systems? Using logistic regression to empirically test a conceptual model. *IEEE Transactions on Engineering Management*, *55*(1), 120–133. https://doi.org/10.1109/tem.2007.912806

Steiber, A., Alänge, S., Ghosh, S., & Goncalves, D. (2021). Digital transformation of industrial firms: An innovation diffusion perspective. *European Journal of Innovation Management*, *24*(3), 799-819. https://doi.org/10.1108/ejim-01-2020-0018

Sun, Y., Chen, J., Kong, C., Zheng, X., & Zhang, X. (2025). What factors influence the motivation of logistics enterprises to adopt green technology? An empirical study based on the TOE model. *British Food Journal*, *127*(12), 4742–4766. https://doi.org/10.1108/bfj-01-2025-0061

Tornatzky, L. G., & Fleischer, M. (1990). *The process of technological innovation*. Lexington Books.

Van Tam, N., Quoc Toan, N., & Van Phong, V. (2024). Investigating potential barriers to construction digitalization in emerging economies: A study in Vietnam. *International Journal of Information Management Data Insights*, *4*(1), 100226–100226. https://doi.org/10.1016/j.jjimei.2024.100226

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly*, *27*(3), 425–478. https://doi.org/10.2307/30036540

Wang, G., Zhou, Y., & Cao, D. (2025). Artificial intelligence in construction: Topic-based technology mapping based on patent data. *Automation in Construction*, *172*, 106073. https://doi.org/10.1016/j.autcon.2025.106073

Wang, Y., Kyriakidis, M., & Dang, V. N. (2021). Incorporating human factors in emergency evacuation – An overview of behavioral factors and models. *International Journal of Disaster Risk Reduction*, *60*, 102254. https://doi.org/10.1016/j.ijdrr.2021.102254

Wang, Y.-M., Wang, Y.-S., & Yang, Y.-F. (2010). Understanding the determinants of RFID adoption in the manufacturing industry. *Technological Forecasting and Social Change*, *77*(5), 803–815. https://doi.org/10.1016/j.techfore.2010.03.006

Yuen, K. F., Cai, L., Qi, G., & Wang, X. (2020). Factors influencing autonomous vehicle adoption: An application of the technology acceptance model and innovation diffusion theory. *Technology Analysis & Strategic Management*, *33*(5), 505-519. https://doi.org/10.1080/09537325.2020.1826423

Zanjirchi, S. M., & Moradi, M. (2012). Construction project success analysis from stakeholders' theory perspective. *African Journal of Business Management*, *6*(15), 5218-5225. https://academicjournals.org/journal/AJBM/article-full-text-pdf/61163F022995

Jayakody, J.D.R.A., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Academic workload and mental wellbeing: Perspectives of first-year quantity surveying students at higher education institutions in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 135-148. DOI: https://doi.org/10.31705/WCS.2026.11. Available from: https://ciobwcs.com/papers/

# ACADEMIC WORKLOAD AND MENTAL WELLBEING: PERSPECTIVES OF FIRST-YEAR QUANTITY SURVEYING STUDENTS AT HIGHER EDUCATION INSTITUTIONS IN SRI LANKA

**J.D.R.A. Jayakody[1], K. Thiruchelvam[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Mental well-being plays an important role in the academic success of first-year students during their transition from secondary education to higher education institutes. They often encounter challenges with new social responsibilities, increased academic workload, and an unfamiliar learning environment. These challenges can negatively influence their mental well-being. This study aims to identify the influence of academic workload on the mental well-being of first-year quantity surveying (QS) students in Sri Lanka. A quantitative approach was adopted in the study, beginning with a literature review to identify the challenges that first-year students encounter once they enrol in university. An online questionnaire was administered to collect responses from 80 first-year quantity surveying students studying in Sri Lanka. Data analysis was conducted using Fisher's Exact test and the Mann-Whitney U test to examine perception of workload and its impact on mental wellbeing on first-years QS students. The results of the study revealed that there was no significant difference between gender and the perceived negative impact on the mental well-being of first-year quantity surveying students. Further, the Relative Important Index (RII) was used to rank the academic-related challenges first-year quantity surveying students experience. The findings indicate that balancing extracurricular activities with academic workload is more challenging than studying unfamiliar module content in a new language. The study identifies the key academic challenges influencing the mental well-being of first-year quantity surveying students in Sri Lanka. Addressing these challenges is important for a successful transition from secondary education to university life for first-year quantity surveying students to promote academic success and good mental well-being.*

***Keywords:*** *Academic Workload; First-year students; Mental Wellbeing; Quantity Surveying.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, rashmi.jayakody.12@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

# 1. INTRODUCTION

Education is identified as a fundamental right of all people in a society, which plays a crucial role in shaping the lives of people by ensuring their independence and allowing them to improve the quality of their lives (Sandanayake, 2019; UNESCO, 2025). Within this broad framework of education, Higher Education (HE) is a particularly significant aspect as it facilitates the acquisition of technical knowledge, competencies, and advanced skills in a specified area. The HE institutes provide guidance and education for undergraduates in relation to specific fields to improve their academic and professional growth (Tight, 2024). Additionally, these institutes shape the behaviour of undergraduates, as a centred place that influences a country's development (Bui et al., 2024; Goczek et al., 2021). The HE represents a key transition point in a young person's life (Campbell et al., 2022).

First-year students who are newly enrolled in HE institutes need to successfully adjust themselves to the complex and dynamic university environment, as they might encounter challenges with new academic expectations and independent learning with the transition from secondary education to university (Leonard et al., 2024; Mahees, 2020). HE institutions offer Quantity Surveying (QS) degree programs to prepare quantity surveyors, who are one of the key professionals in the construction industry, to equip them with a wide range of skills and expertise (Ekundayo et al., 2021; Ekundayo, 2020). As QS graduates are highly specialized professionals, ensuring undergraduates maintain both mental and physical well-being is important for their individual success and for meeting the competitive, rapidly evolving industry competencies (Kamarazaly et al., 2021; Samaratunga et al., 2025). However, the intensive workload influences the mental well-being of undergraduates.

Mental well-being has been identified as a clear state of mind that influences the lives of individuals to function effectively, which previous studies have identified as an important factor that influences the better academic performance of undergraduates (Al-Najdi et al., 2025; WHO, 2022). The existing studies have examined the relationship between academic workload and the mental well-being of undergraduates (Praveeni & Herath, 2020), and have indicated that female undergraduates tend to have a higher level of negative mental well-being due to the academic demands compared to male undergraduates (Cen et al., 2024; Zhu et al., 2025).

In Sri Lanka, first-year students encounter challenges with balancing their academic activities and extracurricular activities with their mental well-being (Wickramasinghe et al., 2023). With a challenging degree program such as QS, the pressure on first-year students can be further intensified, which negatively influences their mental well-being. Therefore, it is important to examine the influence of academic workload on the mental well-being of first-year QS students and to understand the role of gender in shaping their perception of workload and mental well-being. Addressing these factors is crucial in promoting a supportive academic environment that encourages both academic and professional success. Therefore, to address these factors, the following objectives were formulated.

1. To examine the relationship between gender and perceived negative mental well-being due to the academic workload of first-year QS students.

2. To investigate the perception of balancing academic workload and extracurricular activities based on gender.
3. To rank academically related challenges which affecting first-year QS students' mental well-being based on perceived importance.

# 2. LITERATURE REVIEW

Academic workload is a common concern of undergraduates who are pursuing their education in HE institutions, with the challenge they face with learning demands and difficulties with adjusting to university life (Akhtar & Akhtar, 2024). According to Samratunga et al (2025), first-year students who pursue their higher education in relation to the construction industry encounter a higher academic workload compared to other undergraduates.

## 2.1 ACADEMIC CONTENT FOR QUANTITY SURVEYING UNDERGRADUATES

The construction industry is recognized as one of the leading sectors that contribute to a country's economic development (Musarat et al., 2023; Thiruchelvam & Uduwage, 2025). In this sector, Quantity surveyors serve as key professionals involved across the entire construction project from planning to construction, maintenance, and demolition (Olanrewajua et al., 2015; RICS, 2025). Considering the level of involvement across all the stages in a construction project, a QS functions as an independent expert who is responsible for handling and providing financial and contractual advice in a construction project (Spellacy et al., 2020). The accuracy of the advice provided by the QS has a significant influence on overall project success (Azizi et al., 2021).

Due to the critical nature of responsibilities, they perform, QSs need to acquire the required knowledge and expertise through formal education (Keung et al., 2022). Therefore, QS degree programs offered by HE institutes are academically demanding, as they aim to develop graduates who are capable of successfully addressing multifaceted challenges encountered in the construction industry (Hui Yap et al., 2022). Considering the complex nature of the construction industry, comprehensive and structured education is essential in delivering QSs with the skills and competencies they require (Padmasiri et al., 2020).

To achieve this, QS's education requires undergraduates to learn a diverse range of professional knowledge and competencies, which are significantly different from what they learned during secondary education. Areas such as construction law, management, finance, risk, and dispute resolution need to be learned by the first-year QS students, which are not generally taught within the school curriculum (Zhang et al., 2024). Therefore, Quantity surveying undergraduates have to study specialized subjects beyond traditional academic modules to cover different knowledge areas, to meet the evolving demands of the construction industry (Wijekoon & Kawmudi, 2024). As a result of this intensive academic demand, fresh QS undergraduates often encounter a heavy academic workload. Continuous assessments, competitive learning environment, examinations, and strict deadlines cause an increased academic workload (Abdullah et al., 2024). These challenges can result in limiting first-year students' ability to manage their academic activities and personal commitments (Samaratunga et al., 2025).

## 2.2 CHALLENGES ENCOUNTERED BY FRESH UNDERGRADUATES

Transition from high school to a higher education institute is widely recognized as a critical and challenging period for first-year QS students. This transition involves a significant environmental and social change where first-year students need to adapt to a new academic environment without their familiar support system, such as family and friends (Chimenya, 2025). Living independently in this unfamiliar environment may be further challenging for first-year students. With this transition, first-year students learn about their own individual development and independence (Mulaudzi, 2023). In adapting to this new environment, first-year QS students often experience difficulties in establishing new friendships and social networks. These difficulties can result to lesser social relationships and academic activities (Gulliver et al., 2023). Therefore, a decline in social adjustment is commonly identified during the early stage of university life for first-year students (Nthabiseng et al., 2024).

In addition to social challenges, first-year QS students often experience academic challenges as well during this transitional period. First-year students often struggle to manage increasing academic workload while simultaneously engaging in extracurricular activities and adapting to new learning expectations (Guo et al., 2022; Mulaudzi, 2023). The structure supervised non-academic activities to which students participate outside their regular classroom hours are known as extracurricular activities. Activities such as sports, student societies, music clubs, and cultural activities that are not part of the standard curriculum are considered extracurricular activities (Zeidan et al., 2025). In addition, studying academic modules delivered in a language that is not their primary language may create additional pressure related to understanding course content and maintaining academic performance (Yu et al., 2025). These challenges can negatively influence the mental wellbeing of first-year students, as they may feel overwhelmed by these challenges (Paul et al., 2019).

## 2.3 IMPORTANCE OF MENTAL WELLBEING

Mental well-being is defined as a state of complete physical, mental, and social wellbeing which is important for the health of individuals (WHO, 2022). It is also recognized as a human right, emphasising its significance at both social and individual levels (United Nations, 2015). Within the HE context, mental wellbeing recognized as a crucial factor that determines undergraduates' development and functioning (Karma et al., 2021). Undergraduates who have positive mental well-being perform well in their academics (Khatri et al., 2024). It can identify that undergraduates who have good mental well-being tend to perform well in their academics (Elkin et al., 2025; Li et al., 2025).

However, first-year QS students may become vulnerable to mental well-being challenges due to the demanding nature of the academic programme. Difficulties associated with unfamiliar subject content may negatively affect their mental well-being (Barbayannis et al., 2022; Samaratunga & Kamardeen, 2025). Furthermore, the transition to a new social and academic environment can negatively influence the mental well-being of both male and female first-year QS students (Haruna et al., 2025).

Importantly, researchers debate whether gender influence the perceived academic stress of undergraduates. Gender has been identified as an important factor that influences how undergraduates perceive academic workload and its impact on mental well-being. According to the studies, female undergraduates experience a higher level of negative

mental well-being compared to male undergraduates (Zhu et al., 2025). Therefore, female first-year students may tend to be more emotionally vulnerable in response to academic workload, with the demand in education (Barbayannis, et al., 2022).

Previous studies have identified that academic demand influences the negative mental well-being and feelings of being overwhelmed among the general undergraduate population. However, limited studies have specifically examined this issue in relation to first-year QS student, specifically in relation to Sri Lankan university education. Therefore, there is a need to investigate the influence of academic workload on the mental well-being of first-year QS students in Sri Lanka.

## 3. METHODOLOGY

This study aimed to investigate the influence of academic workload on the mental well-being of first-year QS students in Sri Lanka by examining gender-based differences in perceptions and identifying the most significant academic-related challenges.

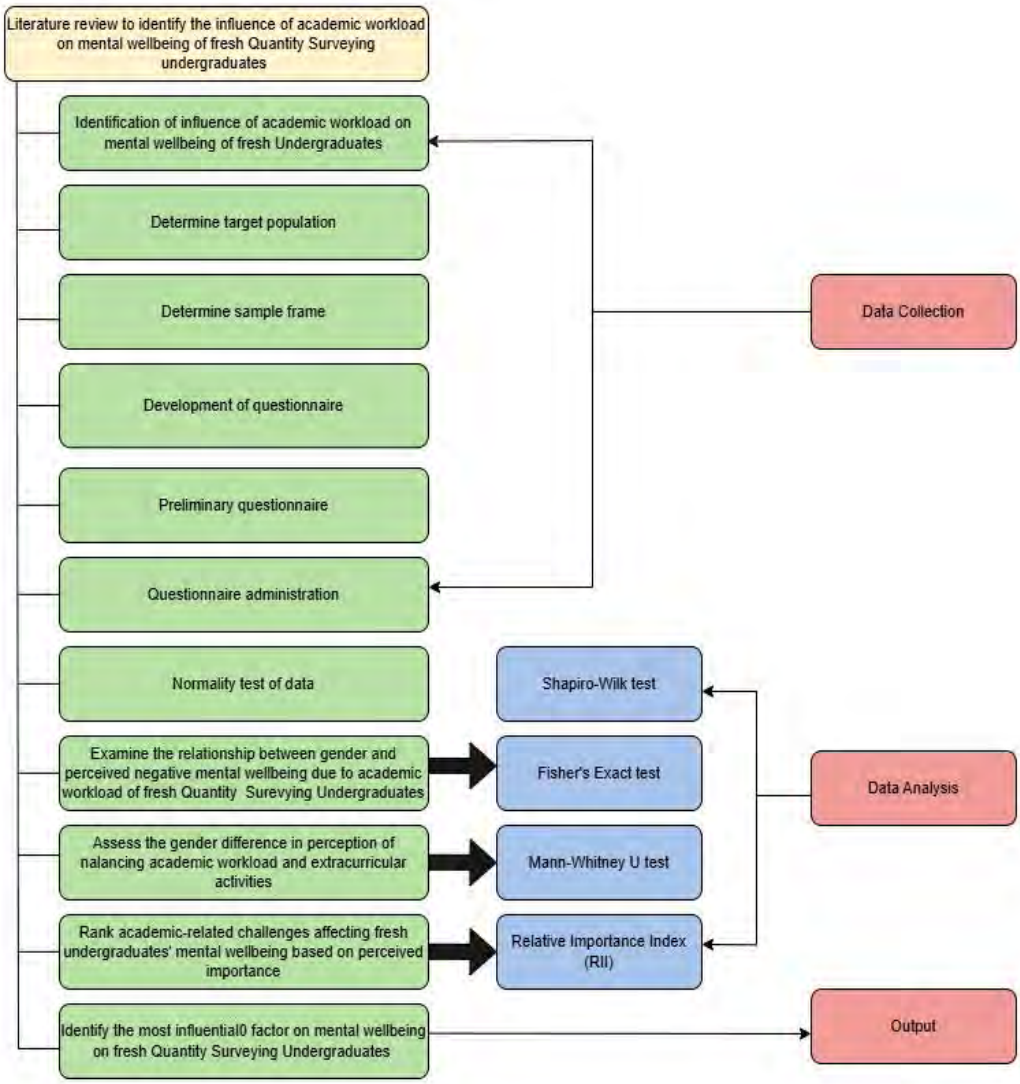



*Figure 1: Research design*

Initially, a literature review was conducted to identify the factors influencing academic workload on first-year students' mental well-being. Then a preliminary survey was conducted to validate the factors identified through the literature review. The target population of the study consist of first-year QS students who are studying in Sri Lanka. The sampling frame of the study consists of first-year QS students enrolled in HE institutes offering Quantity Surveying programmes in Sri Lanka, namely the University of Moratuwa (UOM), Sir John Kothalawala Defence University (KDU), the School of Institute of Quantity Surveyors in Sri Lanka (IQSSL), and the Higher National Diploma (HND). In all these HE institutions, participating in extracurricular activities is entirely voluntary and is not a mandatory requirement. The survey focused on a subjective workload perspective regarding balancing extracurricular activities.

Purposive sampling method was adopted in the study, which is widely used in studies as a method that enables researcher to reach the respondents with required characteristics for the study (Etikan, 2016). Data was collected through an online questionnaire survey via Google Form, which was shared through WhatsApp to the participants. The questionnaire consisted of two sections: demographic information and academic stress factors. The impact on mental wellbeing was evaluated using a binary scale of yes/no, and the specific stress challenges were evaluated using a 5-point Likert scale of 1 = Strongly disagree, 5 = Strongly agree. Before the questionnaire survey, a pilot test was conducted with 20 fresh undergraduates to ensure the clarity of the questionnaire. A total of 80 valid responses were collected from the questionnaire survey.

## 3.1 DATA ANALYSIS

Descriptive statistics techniques were used to analyse the demographic characteristics of the received responses. The normality of the variables was assessed using the Shapiro-Wilk test. The Shapiro-Wilk test is recommended for use with a moderate data sample ($n < 100$) (Mishra et al., 2019). The hypothesis for the Shapiro-Wilk test is as follows.

- Null Hypothesis (Ho) : The data set is normally distributed.
- Alternative Hypothesis (H1) : The data set is not normally distributed.

If $p < 0.05$, reject the null hypothesis. Otherwise, the null hypothesis is accepted.

To achieve objective 1, which aims to determine whether gender is associated with perceptions that academic workload negatively impacts the mental well-being of first-year QS students, Fisher's Exact test was used. This statistical test was used due to the relatively small sample size ($n=80$), as Fisher's Exact test is more appropriate for analysing the relationship between a categorical variable (Nowacki, 2017). Hypothesis for Fisher's Exact test developed as follows.

- Null hypothesis (Ho) : Gender is not associated with the perception of the negative impact of mental well-being due to academic workload
- Alternative hypothesis (H1) : Gender is associated with the perception of a negative impact on mental well-being due to academic workload

If $p < 0.05$, reject the null hypothesis. Otherwise, the null hypothesis is accepted.

To achieve objective 2, which aimed to assess whether the perceptions of balancing academic workload and extracurricular activities differ based on gender, the Mann-Whitney U test was performed. This non-parametric test was employed to examine

whether there was a statistically significant difference between male and female first-year QS students in their perceptions of balancing academic and extracurricular commitments.

- Null hypothesis (Ho) : There is no difference between the gender of students and their perception of balancing extracurricular activities and academics.
- Alternative hypothesis (H1) : There is a difference between the gender of students and their perception of balancing extracurricular activities and academics.

If $p < 0.05$, reject the null hypothesis. Otherwise, the null hypothesis is accepted.

To achieve objective 3, which is to rank academically related challenges affecting the mental well-being of first-year students based on perceived importance, the Relative Importance Index (RII) was used. The Relative Importance Index is a quantitative analysis technique that is used to convert Likert-scale responses into numerical values, which enable easier comparison and ranking of variables (Sourav et al., 2024). Accordingly, the questions which measured using a Likert scale were analysed using RII.

$$\text{RII} = \frac{\Sigma W}{A \times N} \quad (01)$$

*W = Weight assigned by respondents*

*A = Highest weight on the scale*

*N = Total number of respondents.*

The above formula was used to calculate RII. The factor with the highest relative index was ranked first, while the factor with the lowest relative index was ranked last.

# 4. RESULTS AND DISCUSSION

## 4.1 RESPONDENTS' DEMOGRAPHIC INFORMATION

The data was collected among first-year QS students who are studying in 4 higher education institutes known as the University of Moratuwa (UOM), Sir John Kothalawala Defence University (KDU), the School of Institute of Quantity Surveyors in Sri Lanka (IQSSL), and the Higher National Diploma (HND). Initially, a preliminary survey was conducted to identify the clarity and relevance of the questionnaire. In response to the preliminary survey, 20 valid responses were received. Based on the responses, the questionnaire was adjusted. The modified questionnaire was distributed among first-year QS students who are studying the Quantity Surveying degree programme in the above-mentioned higher education institutes. The questionnaire was distributed among 120 fresh quantity surveying undergraduates, and 80 valid responses were collected, resulting 66.67% response rate.

The majority of the responses (87%) were collected from UOM fresh undergraduates, and only 1% were collected from IQSSL fresh undergraduates. The remaining responses were received from KDU (8%) and HND (4%) programmes. This variation in the collection of responses can be identified as the difference in undergraduate intake size across each institute. The annual intake of QS undergraduates in UOM is generally 140 undergraduates, which is higher compared to KDU (34 undergraduates), IQSSL (40 undergraduates), and HND (25 undergraduates). Therefore, the higher representation from UOM reflects its comparatively larger first-year student population. This distribution represents the broader educational context in Sri Lanka, where state

universities have a comparatively larger student intake than private HE institutes offering QS degree programmes.

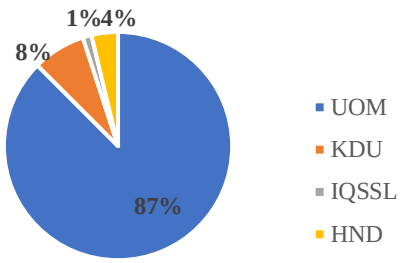



*Figure 2: Respondents institutes*

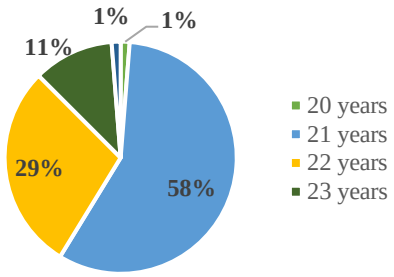



*Figure 3: Respondents age*

Regarding age distribution, the majority of fresh QS undergraduates were 21 years old (58%), with only 1% representing age 20- and 25-years old undergraduates. The mean age of the age sample was 21.55 years. This distribution represents the typical age range of first-year QS students who are entering QS programmes in Sri Lanka. From the total of 80 respondents who completed the questionnaire survey, 45 were female (56%), and 35 were male (44%).

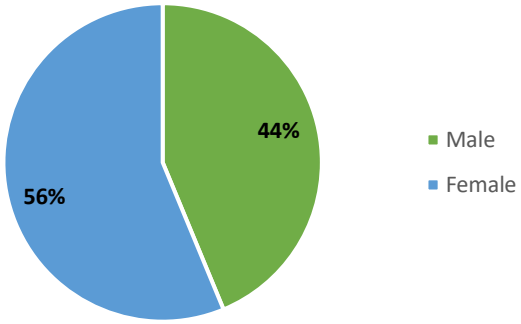



*Figure 2: Respondents gender*

## 4.2 EXAMINE THE RELATIONSHIP BETWEEN GENDER AND PERCEIVED NEGATIVE MENTAL WELL-BEING DUE TO THE ACADEMIC WORKLOAD OF FIRST-YEAR QUANTITY SURVEYING STUDENTS

A Shapiro-Wilk test was performed to identify the normality of the collected data in order to determine the suitable statistical techniques for further analysis. The results of the test are 0.745 with a p-value $< 0.05$. Therefore, the null hypothesis was rejected as the collected data were not normally distributed, and non-parametric tests were further used in the study for the analysis.

A Fisher's Exact test was performed to examine the relationship between gender and the perceived negative impact of academic workload on the mental well-being of first-year QS students. Table 1 outlines the results for Fisher's exact test.

*Table 1: Fisher's exact test result*

| Test | Statistics | P value | N | Result |
|---|---|---|---|---|
| Freeman- Halton Exact Test | 4.514 | 0.338 | 80 | Not significant |

Fisher's Exact Test showed a p-value of 0.338, which is > 0.05; therefore, the null hypothesis (Ho) is not rejected. This indicates that there is no statistically significant relationship between gender and the perceived negative impact of academic workload on the mental well-being of first-year QS students. The results of the study differ from the findings of a few global studies, which indicate that female undergraduates are more vulnerable to academic stress (Cen et al., 2024; Zhu et al., 2025). However, the findings of the study indicate that both male and female first-year students experience a similar impact of academic workload on their mental wellbeing within Sri Lankan context. This may be due to both male and female first-year students experiencing similar transitional challenges once they enter the university, such as social, academic, financial, and emotional challenges (Osafo et al., 2025).

### 4.3 ASSESSING GENDER DIFFERENCES IN PERCEPTIONS OF BALANCING ACADEMIC WORKLOAD AND EXTRACURRICULAR ACTIVITIES

The Mann-Whitney U test was conducted to determine whether perception of balancing academic workload and extracurricular activities differed significantly between male and female first-year QS students. Table 2 presents the results of the Mann-Whitney test.

*Table 2: Mann-Whitney test result*

| Test | U | z value | P value | Result |
|---|---|---|---|---|
| Mann-Whitney U Test | 684.50 | -1.05 | 0.294 | Not significant |

According to the results of the Mann-Whitney U test, the U value represents the test statistics which use to compare the rank distribution between two independent groups of male and female undergraduates. The Z value represents the standardized score of the test statistic, while the p-value represents the statistical significance of the observed difference. Since the p-value (0.294) is greater than the significance level of 0.05, the null hypothesis cannot be rejected. Therefore, there is no statistically significant difference between male and female first-year QS students in their perception of balancing academic workload and extracurricular activities.

The findings of the study show that both male and female first-year students experience similar challenges balancing their extracurricular activities with their academics. The quantity surveying degree programme in Sri Lankan HE institutes is highly demanding in nature, which requires continuous coursework and assignments. Because this heavy workload is identical for all the students regardless of gender, the challenges are the same for both male and female first-year students. The study findings align with existing studies that represent both male and female students encounter similar challenges with balancing their academic and extracurricular activities (Pascoe et al., 2020; Ranasinghe et al., 2017).

## 4.4 RANKING ACADEMICALLY RELATED CHALLENGES AFFECTING FIRST-YEAR STUDENTS' MENTAL WELL-BEING BASED ON PERCEIVED IMPORTANCE

Two academically related challenges affecting first-year students' mental well-being were identified through a comprehensive literature review and ranked using the Relative Importance Index (RII). RII results are presented in Table 3.

*Table 3: Relative importance index test result*

| Academic-related factor | Total weight | RII | Rank |
|---|---|---|---|
| Balancing extracurricular activities with academic workload feels challenging | 303 | 0.7575 | 1 |
| Studying modules in an unfamiliar language makes worry about grades | 287 | 0.7175 | 2 |

The findings represent that balancing extracurricular activities with academic activities had a high perceived impact on first-year students' mental well-being (RII = 0.7575), when compared with the first-year students' concern about academic grades due to studying modules in an unfamiliar language (RII = 0.7175). This suggests that balancing academic and extracurricular activities is perceived as the more significant challenge among the two factors. This can be due to the academic-related difficulties first-year students encounter once they enroll in university. The academic workload, successfully meeting deadlines, and continuous assignments need to be managed along with personal responsibilities. The limited timeline and the new environment that first-year QS students encounter might make it more difficult for them.

Furthermore, the concerns about academic performance due to studying in an unfamiliar language received the lower ranking (RII=0.7175). Even if the language can be challenging, this might be due to the earlier exposure of undergraduates to the English language, as the university academic system is based on the English language. Previous studies also indicate that undergraduates develop their language skills in English over time during their primary and secondary education, that influence good academic performance. Moreover, RII analysis results indicate that difficulties in balancing academic workload with extracurricular activities represent the most significant academically related challenge, which affects the mental well-being of first-year QS students.

The results of the three objectives demonstrate that the study's aim has been achieved. The findings represent that gender does not significantly influence the perceived impact of academic workload on the mental well-being of first-year QS students or perception of balancing academic and extracurricular activities. Anyhow, the results indicate that balancing academic workload with extracurricular activities is the most significant challenge that affects mental wellbeing. Overall, the results indicate that academic workload impacts first-year QS students' mental wellbeing regardless of gender, with workload management difficulties being a main concern.

### 4.5 RECOMMENDATIONS

Providing guidance for first-year QS students about time management during orientation to help them effectively balance their academics with extracurricular activities.

### 4.6 LIMITATIONS

The study considered the subjective perspective of first-year students about the engagement in extracurricular activities with balancing academic workload. Therefore, the study did not explicitly record the allocated time to engage in extracurricular activities or did not isolate the students who did not engage in any extracurricular activity. Additionally, the study findings are heavily dominated by respondents from UOM (87%), which reflects the students' intake in HE institutions in Sri Lanka. This limited the generalizability of the results as the findings specifically reflect the state university environment and curriculum.

## 5. CONCLUSIONS

The study investigates the impact of academic workload on the mental wellbeing of first-year QS students in Sri Lanka, with a relation to the gender-based difference and academic-related challenges. The transition from secondary education to HE results in a sudden increase of academic and social challenges, which influence the mental well-being of first-year QS students. A quantitative method was used in the study. The collected data were analysed using Fisher's Exact test, Mann-Whitney U test, and RII. The findings of the study reveal that gender does not have a statistically significant relationship with the perceived negative impact of academic workload on the mental well-being of first-year QS students. As well, no significant relationship was identified with gender and the perception of balancing academic workload and extracurricular activities. These results indicate that both male and female fresh QS undergraduates experience the same academic pressure and transitional challenges once they enrol in HE institutes. However, RII analysis identified that balancing academic activities with extracurricular activities is the most significant challenge that affects mental well-being. The study concludes that academic workload influences the mental well-being of first-year QS students irrespective of gender. The findings identified the importance of a smooth transition into university life and positive mental well-being among first-year QS students.

## 6. REFERENCES

Abdullah, T., Ali, J., & Alam, A. (2024). Academic stress and its impact on students' emotional well-being and performance at universities. *Journal of Educational Psychology and Pedagogical Sciences*, *4*(1), 13–30. https://doi.org/10.52587/jepps.v4i1.86

Akhtar, S., & Akhtar, N. (2024). Issues and challenges of academic stress among first-year university students: An investigative study. *International Journal of Social Science and Entrepreneurship (IJSSE)*, *4*(1), 2790–7724. https://doi.org/10.58661/ijsse.v4i1.250

Al-Najdi, S., Mansoor, A., Al Hayk, O., Al-Hashimi, N., Ali, K., & Daud, A. (2025). Silent struggles: a qualitative study exploring mental health challenges of undergraduate healthcare students. *BMC Medical Education*, *25*(1). https://doi.org/10.1186/s12909-025-06740-8

Anbesaw, T., Beyene, A., & Kefale, J. (2022). *Adjustment problem and associated factors among first-year undergraduates at Wollo University, Ethiopia*. https://doi.org/https://doi.org/10.3389/feduc.2022.946417

Azizi, N. S. M., Yu, T. Z., & Azizi, Z. (2021). Preliminary study of changes in work practices of quantity surveyors in building information modelling (Bim) projects. *International Journal of Sustainable Construction Engineering and Technology*, *12*(1), 140–152. https://doi.org/10.30880/ijscet.2021.12.01.014

Barbayannis, G., Bandari, M., Zheng, X., Baquerizo, H., Pecor, K. W., & Ming, X. (2022a). Academic stress and mental well-being in college students: Correlations, affected groups, and covid-19. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.886344

Bui, H. T. M., Bui, T., & Pham, B. T. (2024). The role of higher education in achieving sustainable development goals: An evaluation of motivation and capacity of Vietnamese institutions. *International Journal of Management Education*, *22*(3). https://doi.org/10.1016/j.ijme.2024.101088

Campbell, F., Blank, L., Cantrell, A., Baxter, S., Blackmore, C., Dixon, J., & Goyder, E. (2022). Factors that influence mental health of university and college students in the UK: a systematic review. *BMC Public Health*, *22*(1). https://doi.org/10.1186/s12889-022-13943-x

Cen, S., Zhao, M., Wang, F., & Tang, L. (2024). Gender differences in the relationship between mental health and academic performance among undergraduate students at a medical school in Shanghai: a cross-sectional study. *BMC Public Health*. https://doi.org/10.21203/rs.3.rs-5354150/v1

Chimenya, U. M. (2025). Transition from high school to university: First-year students' reading experiences. *Reading & Writing*, *16*(1), Article 517. https://doi.org/10.4102/rw.v16i1.517

Ekundayo, D. O. (2020). *Quantity surveying education and the benchmarking of future needs*.

Ekundayo, D., Shelbourn, M., & Babatunde, S. O. (2021). Collaborative multidisciplinary learning: Quantity surveying students' perspectives. *Industry and Higher Education*, *35*(3), 211–222. https://doi.org/10.1177/0950422220944127

Elkin, N., Mohammed, A. K., Kılınçel, Ş., Soydan, A. M., Tanrıver, S. Ç., Çelik, Ş., & Ranganathan, M. (2025). Mental health literacy and happiness among university students: A social work perspective to promoting well-being. *Frontiers in Psychiatry*, *16*. https://doi.org/10.3389/fpsyt.2025.1541316

Etikan, I. (2016). Comparison of Convenience Sampling and Purposive Sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1. https://doi.org/10.11648/j.ajtas.20160501.11

Goczek, Ł., Witkowska, E., & Witkowski, B. (2021). How does education quality affect economic growth? *Sustainability (Switzerland)*, *13*(11). https://doi.org/10.3390/su13116437

Gulliver, A., Wysoke, T., Calear, A. L., & Farrer, L. M. (2023). Factors associated with engagement in university life, and help-seeking attitudes and behaviour in first year Undergraduate Students. *International Journal of Environmental Research and Public Health*, *20*(1). https://doi.org/10.3390/ijerph20010120

Haruna, U., Mohommed, A.-R., & Braimah, M. (2025). Understanding the burden of depression, anxiety and stress among first-year undergraduate students. *BMC Psychiatry*, *25*(1). https://doi.org/10.1186/s12888-025-07069-8

Hui Yap, J. B., Tin Hew, Q. L., & Skitmore, M. (2022). Student learning experience in higher education: Investigating a quantity surveying program in Malaysia. *Construction Economics and Building*, *22*(1). https://doi.org/https://doi.org/10.5130/AJCEB.v22i1.7835

Kamarazaly, M. A., Yan, T. K., Ramli, M. A., Yaakob, A. M., Tatt, S. L., & Ilmi, H. S. (2021). Stress levels and coping strategies : Case study on quantity surveying students in private university. *Malaysian Construction Research Journal*, *12*(1), 129–148.

Karma, Y., Kezang, S., Pema, C., Sangey, P., & Sonam, D. (2021). Well-being and academic workload: Perceptions of science and technology students. *Educational Research and Reviews*, *16*(11), 418–427. https://doi.org/10.5897/err2021.4197

Keung, C. C. W., Yiu, T. W., & Feng, Z. (2022). Building information modelling in quantity surveying practices: current state and future challenges in hong kong. *Journal of Information Technology in Construction*, *27*, 1060–1074. https://doi.org/10.36680/j.itcon.2022.052

Khatri, P., Duggal, H. K., Lim, W. M., Thomas, A., & Shiva, A. (2024). Student well-being in higher education: Scale development and validation with implications for management education. *International Journal of Management Education*, *22*(1). https://doi.org/10.1016/j.ijme.2024.100933

Leonard, J., Mylonas, A., Parker, P., & Wood, R. (2024). A caring approach to the first-year university student experience. *Journal of University Teaching and Learning Practice*, *21*(1). https://doi.org/https://doi.org/10.53761/q1k5wx84

Li, Q., Li, J., & Fan, Y. (2025). Addressing mental health in university students: A call for action. *Frontiers in Public Health*, *13*. https://doi.org/10.3389/fpubh.2025.1614999

Mahees, M. T. M. (2020). Stress among undergraduates: A case study of University of Colombo, Sri Lanka. *International Educational Applied Research Journal (IEARJ)*, (Volume 4). http://archive.cmb.ac.lk:8080/xmlui/handle/70130/4756

Mishra, P., Pandey, C. M., Singh, U., Gupta, A., Sahu, C., & Keshri, A. (2019). Descriptive statistics and normality tests for statistical data. *Annals of Cardiac Anaesthesia*, *22*(1), 67–72. https://doi.org/10.4103/aca.ACA_157_18

Mulaudzi, I. C. (2023). Challenges faced by first-year university students: Navigating the transition to higher education. *Journal of Education and Human Development*, *12*(2), 79–87. https://doi.org/10.15640/jehd.v12n2a8

Musarat, M. A., Sadiq, A., Alaloul, W. S., & Abdul Wahab, M. M. (2023). A systematic review on enhancement in quality of life through digitalization in the construction industry. In *Sustainability (Switzerland)* (Vol. 15, Number 1). MDPI. https://doi.org/10.3390/su15010202

Nowacki, A. (2017). Chi-square and fisher's exact tests. *Cleveland Clinic Journal of Medicine*, *84*, 20–25. https://doi.org/10.3949/CCJM.84.S2.04

Nthabiseng, S. P., Mphahlele, L. K., & Malatji, K. S. (2024). Transition from high school to university: challenges faced by first-year b.ed. students at a university of technology in south africa. *E-Journal of Humanities, Arts and Social Sciences*, 112–122. https://doi.org/10.38159/ehass.2024524

Olanrewajua, A., Anahveb, P. J., & Barat, B. (2015). Duties and responsibilities of quantity surveyors in the procurement of building services engineering. *Procedia Engineering*, 352–360. https://doi.org/https://doi.org/10.1016/j.proeng.2015.10.046

Osafo, A. B., Ohene-Darko, S., Agormedah, E. K., & Omane-Adjekum, C. (2025). Navigating the Transition to Higher Education: Understanding the Experience among First-Year University Students. *Journal of Tertiary Education and Learning*, *3*(1), 51–64. https://doi.org/10.54536/jtel.v3i1.4192

Padmasiri, N. A. K. . A. S., Rathnasinghe, A. P., & Seneviratne, L. D. I. P. (2020). Appraisal of the competency gap between uom quantity surveying degree programme and iqssl competency standards. *Proceedings of the 17th International Conference on Business Management*, *17*, 770–788. https://doi.org/https://doi.org/10.31357/icbm.v17.5173

Pascoe, M. C., Hetrick, S. E., & Parker, A. G. (2020). The impact of stress on students in secondary school and higher education. In *International Journal of Adolescence and Youth* (Vol. 25, Number 1, pp. 104–112). Routledge. https://doi.org/10.1080/02673843.2019.1596823

Paul, C. A., Jatau, T. S., & Zaki, Y. M. (2019). Stress management strategies among students: A case of quantity surveying students of Kaduna State University, Nigeria. *Journal of Environmental Studies*, *14*(2), 1–14. https://www.researchgate.net/publication/336197203

Praveeni, S. M. N., & Herath, H. M. A. J. (2020). Perceived Academic Stress among University Undergraduates in Sri Lanka. *Wayamba Journal of Management*, *11*(1), 30. https://doi.org/10.4038/wjm.v11i1.7490

Ranasinghe, P., Wathurapatha, W. S., Mathangasinghe, Y., & Ponnamperuma, G. (2017). Emotional intelligence, perceived stress and academic performance of Sri Lankan medical undergraduates. *BMC Medical Education*, *17*(1). https://doi.org/10.1186/s12909-017-0884-5

RICS. (2025). *Quantity surveying*. Royal Institution of Charted Surveyors .

Samaratunga, M., & Kamardeen, I. (2025). Modelling work–study conflict effects on built environment students' well-being, health, and academic performance. *Buildings*, *15*(3). https://doi.org/10.3390/buildings15030406

Samaratunga, M., Kamardeen, I., & Chathurangi, B. N. M. (2025). Work–study conflict stressors and impacts: a cross-disciplinary analysis of built environment undergraduates. *Buildings*, *15*(6). https://doi.org/10.3390/buildings15060973

Sandanayake, T. C. (2019). Promoting open educational resources-based blended learning. *International Journal of Educational Technology in Higher Education*, *16*(1). https://doi.org/10.1186/s41239-019-0133-6

Sourav, Md. M. I., Abeer, A. A., & Bhuiyan, A. H. (2024). Quantifications of service quality factors using the relative importance index method for passenger ferry service in Bangladesh. *Discover Civil Engineering*, *1*(1). https://doi.org/10.1007/s44290-024-00008-8

Spellacy, J., Edwards, D. J., Roberts, C. J., Hayhow, S., & Shelbourri, M. (2020). An investigation into the role of the quantity surveyor in the value management workshop process. *Journal of Engineering, Design and Technology*, *19*(2). https://doi.org/https://doi.org/10.1108/JEDT-07-2020-0289

Thiruchelvam, K., & Uduwage, D. N. L. S. (2025). Assessing sdg 7 performance: identifying relevant kpis for the sri lankan construction industry. *World Construction Symposium*, 203–215. https://doi.org/10.31705/WCS.2025.16

Tight, M. (2024). The idea of the university: Towards a contemporary formulation. *Journal of Higher Education Policy and Management*, *46*(1), 48–62. https://doi.org/10.1080/1360080X.2023.2242080

UNESCO. (2025, February 13). *The right to education*. UNESCO.

United Nations. (2015). *Quality education*. United Nations.

Wickramasinghe, A., Essén, B., Surenthirakumaran, R., & Axemo, P. (2023). Prevalence of depression among students at a Sri Lankan University: A study using the Patient Health Questionnaire-9 (PHQ-9) during the COVID-19 pandemic. *BMC Public Health*, *23*(1). https://doi.org/10.1186/s12889-023-15427-y

Wijekoon, W., & Kawmudi, W. N. (2024). A framework to integrate building information modelling to the curriculum of the quantity surveying undergraduate degree programme in sri lanka. *KDU Journal of Multidisciplinary Studies (KJMS)*, *6*(2). https://doi.org/10.4038/kjms.v6i2.1244

World Health Organiztion. (2022, July 17). *Mental health*. WHO.

Yu, Q., Brunsting, N. C., Smart, J., & Bingham, W. P. (2025). Language Proficiency, Second Language Educational Experience, and Psychological Well-being Among International Students at U.S. Universities. *Research in Higher Education*, *66*(1). https://doi.org/10.1007/s11162-024-09821-7

Zeidan, M., Ballout, R., Al-Akl, N., & Kharroubi, S. A. (2025). Exploring the relationship between extracurricular activities and stress levels among university students: A cross-sectional study. *PLOS ONE*, *20*(8 August). https://doi.org/10.1371/journal.pone.0329888

Zhang, P., Ma, S. G., Sun, Y., & Zhao, Y. N. (2024). Investigating the gaps between engineering graduates and quantity surveyors of construction enterprises. *Sustainability (Switzerland)* , *16*(7). https://doi.org/10.3390/su16072984

Zhu, Y., Liang, W. M., Jiang, K., Truskauskaitė, I., Griškova-Bulanova, I., Bai, Z., & Rukšėnas, O. (2025). Mental well-being of college students: focus on sex differences and psycho physiological indices. *BMC Public Health*, *25*(1). https://doi.org/10.1186/s12889-025-24231-9

Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Adoption of plain language to Sri Lankan construction contracts: A narrative review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 149-160. DOI: https://doi.org/10.31705/WCS.2026.12. Available from: https://ciobwcs.com/papers/

# ADOPTION OF PLAIN LANGUAGE TO SRI LANKAN CONSTRUCTION CONTRACTS: A NARRATIVE REVIEW

**K. Thiruchelvam[1] and D.N.L.S. Uduwage[2]**

## *ABSTRACT*

*Construction contracts serve as legally binding agreement that govern the relationships and obligations of parties involved in construction projects. However, their complex and legalistic language often creates difficulties for contract users. Plain language construction contracts have emerged as an approach to overcome interpretation errors and misunderstandings caused by the traditional legalistic language used in conventional construction contracts. This study adopts a narrative literature review approach, examining literature published over the past fifteen years (2010–2025), focusing on the adoption of plain language in construction contracts, its benefits, challenges, and relevance to the Sri Lankan construction industry. The results indicate that plain language can improve clarity, readability, accessibility, and stakeholder communication, while reducing misinterpretation and potential disputes. Challenges include concerns about legal precision, resistance to change, and the need for specialised drafting skills. Furthermore, the study identifies a research gap, as scholarly attention on plain language construction contracts in Sri Lanka remains limited. The study proposes future research directions including assessing the readiness of the Sri Lankan construction industry to adopt plain language construction contracts, developing contract templates suitable for the Sri Lankan context, and conducting pilot testing to evaluate their practical applicability. This study contributes to the existing body of knowledge by synthesizing global insights on plain language construction contracts and reflecting on their relevance to the Sri Lankan construction industry.*

***Keywords:*** *Construction Contracts; Construction Industry; Contract Clarity; Plain Language; Sri Lanka.*

## 1. INTRODUCTION

The construction industry deals with several stakeholders, including clients, contractors, consultants and subcontractors (Alves & Shah, 2018). Managing interactions among multiple parties and clearly defining their rights, responsibilities and obligations can be challenging without a legally governing agreement (Patrick et al., 2025). In this context, construction contracts play a vital role by acting as the legally binding agreement that specify the obligations of the parties in relation to cost, schedule, quality, and safety performance (Alves & Shah, 2018). Furthermore, construction contracts do not function

[1] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

solely as legal instruments but also serve as critical instruments that guide project execution throughout the project lifecycle (Osifo et al., 2025).

Construction contract users can generally be categorized into primary and secondary users (Masfar, 2017). Primary users refer to those who rely on contracts on a daily basis, such as clients, contractors, and subcontractors. Secondary users are occasional users responsible for resolving disagreements, including lawyers, mediators, and adjudicators (Ali, 2008). Unlike secondary users, primary users may not possess formal legal training (Masfar, 2017). However, standard construction contracts such as Fédération Internationale des Ingénieurs-Conseils (FIDIC), New Engineering Contract (NEC), Joint Contracts Tribunal (JCT) and International Chamber of Commerce (ICC) are traditionally written in a complex style, which can create difficulties for primary users in understanding contractual provisions and may lead to misunderstandings and interpretation errors (Chong & Oon, 2016). Such misunderstandings may escalate into disputes and claims. Consequently, this situation can result in inefficiencies in contract administration and decision-making, ultimately affecting project success (Masfar, 2017).

In recent years, the concept of plain language has gained attention in construction contract drafting as a way to overcome the challenges created by the complex and legalistic language used in typical construction contracts (Chong & Oon, 2016). Plain language refers to writing that is straightforward and presented in a manner that the intended audience can clearly understand without convoluted sentence structures (Ali, 2008). It does not mean removing the legal meaning or reducing contractual protection, rather, it focuses on conveying detailed information clearly and quickly without overloading the audience (United States General Services Administration, n.d.).

Several studies have been conducted on the adoption of plain language in construction contracts. For instance, Chong and Oon (2016) and Ballesteros-Lintao and Ali (2022) conducted a study on Malaysia to check the feasibility of using plain language the Malaysian construction contracts. Similarly, Masfar (2017) assessed the feasibility of using plain language construction contracts in Saudi Arabia. Van Eck (2024) conducted a study on South African perspective on plain language contracts. However, these studies are largely context specific, limiting the direct transferability of their findings to other construction environments.

Sri Lanka, as a country with a construction industry involving diverse language backgrounds (English, Sinhala, and Tamil) and different levels of legal literacy, particularly at the site and operational levels, still follows traditional construction contract drafting practices (Akalanka et al., 2026; Laxsana et al., 2023). The limited legal literacy of site and operational level stakeholders, such as contractors, subcontractors, and suppliers, often leads to disagreements that may escalate into disputes, while dispute resolution processes consume significant time and cost (Hassan & Le, 2020). Even though existing studies have been conducted to examine the feasibility of adopting plain language in construction contracts, their applicability to the Sri Lankan context remains largely unexplored. As noted by Thiruchelvam and Uduwage (2025), countries face unique challenges when adopting practices developed in different contexts. These characteristics suggest that insights from global literature require careful contextual interpretation when considering the Sri Lankan construction industry. Therefore, this paper aims to provide a narrative synthesis of existing literature on the adoption of plain

language in construction contracts and to reflect on its implications for the Sri Lankan construction industry. To achieve this aim, the following objectives were formulated.

1. To identify the publication trend and key application areas of plain language contracts.
2. To scrutinize the key benefits, and challenges associated with the adoption of plain language in construction contracts.
3. To identify research gaps and assess the potential relevance of plain language in construction contracts within the Sri Lankan construction industry.

## 2. MATERIAL AND METHODS

A literature review is a methodology that enables the collection and synthesis of discussions from published works, provides a comprehensive understanding of a particular research area, and establishes a connection between the present study and existing knowledge (Shanahan, 2019). According to Smith and Noble (2015), literature reviews can be broadly categorized into narrative reviews, scoping reviews and systematic reviews. Among these, narrative reviews are suitable for interdisciplinary and emerging topics (Ferrari, 2015). Furthermore, this approach allows for the interpretation of concepts and is valuable for identifying trends, gaps, and emerging themes within the literature (Juntunen & Lehenkari, 2019). Compared to other review types, narrative reviews offer greater flexibility in writing and synthesis (Ferrari, 2015). Since this study addresses an emerging topic, namely the adoption of plain language in construction contracts, and aims to gather insights from diverse studies rather than quantify outcomes, a narrative literature review was adopted. Figure 1 illustrates the research flow of the study.

Publications published over the past fifteen years, from 2010 to 2025, were considered for the review in order to capture recent developments in plain language, as scholarly attention to this topic has increased during the last decade. Publications written in English and available as journal articles, conference proceedings, or book chapters were considered for inclusion. The search query “plain language” AND “contracts” was applied to the article title, abstract, and keywords. The alternative terms such as “contract simplification” or “clear language” were not considered as search queries, as they often are in contexts extending beyond contractual documentation and create an increased likelihood of retrieving irrelevant publications. The initial identification and screening of publications were conducted using the Dimension database to determine the number of available studies related to the research topic. The full texts of the identified studies were subsequently retrieved through Google Scholar, ScienceDirect, and Emerald Insight, as these platforms host extensive collections of high-quality journals and books.

The initial search resulted in 142 publications. After screening the titles and abstracts to assess their relevance to the study, publications that did not explicitly focus on plain language in a contractual, legal, or agreement-related context, duplicate records, and those lacking sufficient information to assess their relevance to the study were excluded. Following this screening process, 36 publications were considered relevant and included in the final analysis. The collected literature was analyzed using thematic analysis, which enables researchers to systematically organize and interpret patterns across multiple sources of information (Kiger & Varpio, 2020). In this study, thematic analysis facilitated

the identification of key themes related to the benefits, challenges, and adaptability of plain language in construction contracts.

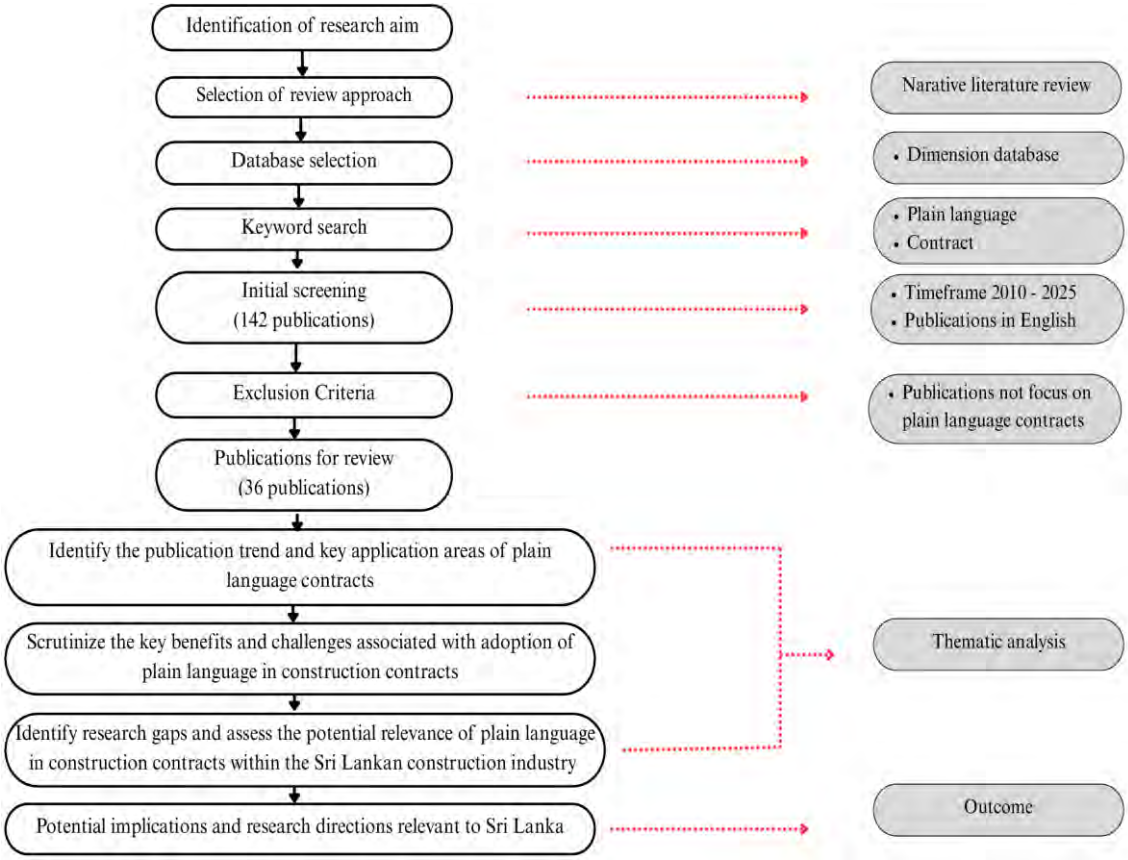



*Figure 1: Research flow*

# 3. FINDINGS AND DISCUSSION

## 3.1 PUBLICATION TREND ON PLAIN LANGUAGE CONTRACTS

Initially, the identified 36 publications were reviewed, and the yearly publication trend on plain language contracts over a 15-year period was analysed. Figure 2 illustrates the publication trend of plain language contracts.

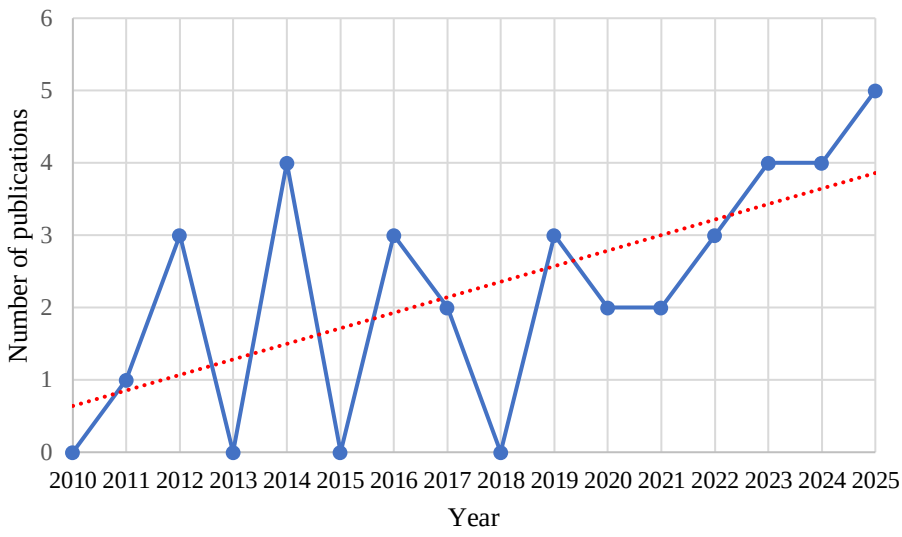



*Figure 2: Publication trend*

As illustrated in Figure 2, the publication trend demonstrates an irregular yet gradually increasing pattern over the 15 year period. During the early phase (2010 - 2020), the number of publications on plain language contracts fluctuated considerably, with no publications recorded in certain years such as 2010, 2013, 2015, and 2018. This suggests that the topic was still emerging and had not yet attracted sustained attention from scholars. However, from 2020 onwards, a more consistent upward trend can be observed. In particular, the period from 2022 to 2025 records the highest number of publications, indicating a growing scholarly interest in plain language contracts in recent years. The upward slope of the trendline, which is marked in red in Figure 2, further supports this pattern, suggesting a gradual increase in research attention over time.

Overall, the observed publication trend implies that, although research on plain language contracts was initially limited and fluctuating, it has increasingly become an area of ongoing scholarly discussion in recent years.

## 3.2 KEY APPLICATION AREAS OF PLAIN LANGUAGE CONTRACT

As per the reviewed publications, plain language contracts were applied in several areas such as legal, consumer, construction and other contexts, as presented in Figure 3.

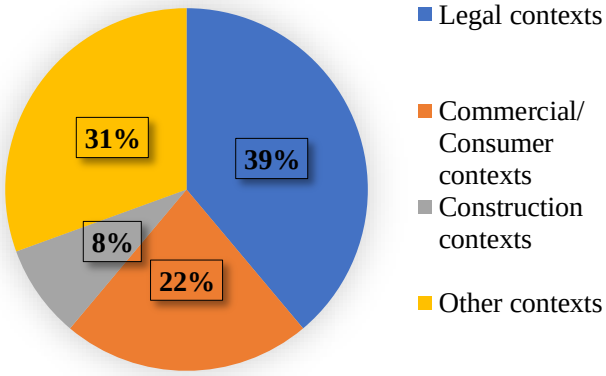



*Figure 3: Key application areas of plain language contracts*

According to Figure 3, the majority of the publications fall under legal contexts (39%). As legal drafting is often criticized for its archaic language, lengthy sentences and difficulty in understanding by individuals who do not have formal legal training (Hassan & Le, 2020), plain language contracts have gained much scholarly attention in law related areas to improve the clarity and comprehensibility of legal documents (Ali, 2008). Plain language was widely discussed within commercial / consumer contexts (22%), where publications have given consideration to adopting plain language in insurance contracts (Van-Boom et al., 2016), electricity bills (Subiela-Hernández et al., 2023), lease agreements (Siebörger & Adendorff, 2011) and other commercial contracts to improve the fairness, accessibility and readability in contracts used by the public.

Publications that focus on digital or smart contracts, medical contracts and other contracts that are not categorized under legal, commercial / consumer or construction contexts were included under the "other contexts" category (31%). However, only 8% of the publications discuss plain language adoption in construction contracts and these studies were conducted in only few countries such as Saudi Arabia (Masfar, 2017), Malaysia (Ballesteros-Lintao & Ali, 2022), the United Kingdom (UK), and Australia (Australian Government, Office of Parliamentary Counsel, 2013), indicating the significant gap in plain language construction contracts.

Given this limited attention, there is a need to further examine plain language adoption in construction contracts in detail. Therefore, the thematic analysis conducted for plain language construction contract related publications revealed two themes: (1) benefits of adopting plain language in construction contracts and (2) challenges associated with plain language adoption. The analysis was further extended to identify recurring sub themes within each of these categories.

### 3.3 SCRUTINIZE THE BENEFITS OF PLAIN LANGUAGE IN CONSTRUCTION CONTRACTS

Focusing specifically on construction contracts, across the reviewed publications, plain language is consistently associated with simplified vocabulary, reduced legal jargon, and improved readability while maintaining legal precision (Cornelius, 2010). Since standard construction contracts such as FIDIC, NEC, JCT, and ICC are often difficult for primary users to interpret, the adoption of plain language in construction contracts has gained attention in recent publications.

Adoption of plain language in construction contracts provides several benefits to both primary and secondary users of the contract and those benefits were identified through the thematic analysis of the reviewed publications. Initially, the publications were carefully read to familiarize the content related to the outcomes of plain language usage in contracts. Then initial codes such as clarity, readability, accessibility and reduced disputes were assigned to the data segments describing outcomes of plain language usage in contracts. Then, the initial codes were examined to identify the sub themes across the reviewed publications and labelled as key benefits of adopting plain language in construction contracts. Table 1 presents the key benefits of adoption of plain language construction contracts in comparison to traditional construction contracts characterised by complex and legalistic language.

*Table 1: Benefits of adopting plain language in construction contracts*

| Benefits of adopting plain language in construction contract | Sources |
|---|---|
| Improved clarity and transparency | [1], [5], [8], [9] |
| Enhancement of readability and comprehension | [1], [2], [3], [4], [5], [6], [7], [8], [9] |
| Greater accessibility for diverse stakeholders | [3], [4], [5], [8], [9] |
| Reduction of misinterpretation | [1], [2], [3], [5], [6], [9] |
| Potential to reduce disputes | [1], [2], [7], [10] |
| Increased efficiency in contract administration | [2], [9] |
| Improved stakeholder communication | [4], [5], [6], [9], [10] |
| Enhanced overall contract quality | [4] |

[1] Ballesteros-Lintao and Ali (2022); [2] Chong and Oon (2016); [3] De Stadler and Van Zyl (2017); [4] Lam (2018); [5] Masfar (2017); [6] Mico (2013); [7] Radzi and Ali (2023); [8] Schriver (2017); [9] Van Eck (2024); [10] Vats and Devi (2025)

Plain language contracts are written in a way that reduces the use of redundant words such as "null and void", where the word "void" alone is sufficient. Therefore, this helps to **improve clarity and transparency** in construction contracts. Plain language contracts do not use legal jargon such as "indemnity" and "force majeure", which can only be understood by secondary users and skilled primary users in construction contract (Van Eck, 2024). Furthermore, plain language contracts use active voice in writing (Masfar, 2017), which **enhances readability and comprehension**. In addition, these contracts are straightforward and presented in a manner that intended audiences can understand, thereby allowing **greater accessibility for diverse stakeholders** (Schriver, 2017).

Chong and Oon (2016) stated that traditional construction contracts contain too many cross- references between clauses, which cause misinterpretation errors between parties, and suggested that the use of plain language in contract allows the **reduction of** such **misinterpretations**. Additionally, Ballesteros-Lintao and Ali (2022) emphasized that construction disputes often originate from specific terms presented in contracts, particularly during variation and claim procedures. However, the use of plain language in construction contracts simplifies these terms and has the **potential to reduce disputes**. Furthermore, easier understanding of construction contracts by intended audiences **increases efficiency in contract administration,** while at the same time **improving stakeholder communication** (Chong & Oon, 2016). Moreover, plain language construction contracts **enhance overall contract quality** by transforming the language into one that is clear, readable, accessible, and usable by all users of the contract (Lam, 2018).

### 3.4 SCRUTINIZE THE CHALLENGES ASSOCIATED WITH ADOPTION OF PLAIN LANGUAGE IN CONSTRUCTION CONTRACTS

Despite the benefits of using plain language construction contracts, the adoption of plain language in construction contracts presents several challenges, where the term challenges in this study refer to the difficulties, limitation or potential risks associated with adopting plain language in construction contracts. These challenges were identified from the publications through comparison with traditional legal drafting practices and analysed using thematic analysis and presented in Table 2.

*Table 2: Challenges associated with adoption of plain language in construction contracts*

| Challenges associated with adoption of plain language in construction contracts | Sources |
|---|---|
| Risk to Legal Precision and Certainty | [1], [2], [4], [5], [6] |
| Fear of Losing Technical Accuracy | [1], [4], [5] |
| Reliance on Professional Jargon | [1], [6] |
| Resistance to Change | [2], [6] |
| High Skill Demands for Plain Legal Writing | [4] |
| Difficulty in Drafting Plain Language Contracts | [6] |
| Limitations of Simplification | [2], [4], [5] |
| Linguistic Density and Structural Complexity | [1] |
| Perceived Threat from the Legal Profession | [4] |

[1] Akal (2022); [2] De Stadler and Van Zyl (2017); [3] Lam (2018); [4] Masfar (2017); [5] Mico (2013); [6] Van Eck (2024)

Masfar (2017), along with highlighting the benefits of adopting plain language in construction contracts, also pointed out the challenges associated with its adoption. According to Masfar (2017), even though plain language improves clarity, oversimplification may create a **risk to legal precision and certainty.** Lam (2018) highlighted that, in order to convey legal ideas to the intended audience, technical wordings are sometimes required. Therefore, the use of plain language creates a **fear of losing technical accuracy**. Van Eck (2024) stated that professional jargon creates a common language among professionals which enriches their communication. Since construction contracts **rely heavily on professional jargon**, converting them into plain language becomes a challenging task. In addition, Masfar (2017) emphasized that some scholars believe disputes occur regardless of language clarity, which leads to **resistance to change** towards plain language construction contracts. Furthermore, drafting a construction contract in plain language **requires high skills to simplify the language** while maintaining legal precision, which is comparatively harder than merely discussing it, and this creates **difficulties in drafting plain language contracts** (Van Eck, 2024). The **limitation of simplification** is identified as another challenge associated with the adoption of plain language in construction contracts, as balancing readability with legal precision should be handled carefully (De Stadler & Van Zyl, 2017). Construction contracts also demonstrate **linguistic density and structural complexity**, meaning that they are often structurally fragmented and grammatically complex, which makes it difficult to convert them into plain language (Akal, 2022). Furthermore, the **critical fear among legal professionals** that plain language contracts may reduce reliance on them plays a crucial role in limiting the acceptance of plain language in construction contracts (Lam, 2018). These findings indicate that, although plain language offers significant advantages, its implementation in construction contracts requires careful balancing between clarity and legal precision.

## 3.5 IMPLICATIONS FOR THE SRI LANKAN CONSTRUCTION INDUSTRY

Contractual practices in the Sri Lankan construction industry largely rely on standard forms of contracts (Wimalasena & Gunatilake, 2018). The most widely used conditions of contracts are part of the Standard Bidding Documents (SBD) which published by the

Construction Industry Development Authority (CIDA) (Janardana et al., 2021), and modified versions of FIDIC standard forms published by the International Federation of Consulting Engineers (Nwogu & Emedosi, 2024). These standard contracts are often characterized by lengthy clauses, complex sentence structures, and extensive use of legal jargon, which may not be easily understood by the primary users of the contract (Walsh, 2017).

The findings of this study indicates that such characteristics may limit the usability of contracts, particularly in contexts where stakeholders possess varying levels of language proficiency and contractual knowledge. As identified in Table 1, plain language contracts improve clarity, readability, accessibility and communication, whereas Table 2 highlights challenges associated with adoption of plain language in construction contracts. Moreover, the findings suggest that the adoption of plain language in construction contracts has practical relevance to the Sri Lankan construction industry, particularly in improving contract usability while requiring careful management of associated challenges.

### 3.5.1 Implications for Industry Practitioners

As identified in Table 1, the use of plain language in construction contracts enhance clarity and accessibility for the intended users, reduce misunderstandings and support smoother contract administration. In the Sri Lankan construction industry where conditions of contracts used for contractual documentation are primarily drafted in English, which is not the first language for many construction professionals, these improvements may be particularly beneficial. Therefore, industry practitioners may consider adopting plain language construction contracts in Sri Lanka. However, the findings also highlighted several challenges in adopting plain language construction contracts (Table 2) including concerns related to legal precisions, resistance to change and difficulty in drafting plain language contracts. Hence, practitioners should focus on drafting plain language construction contracts that enables intended audiences to understand content easily without compromising legal precision.

### 3.5.2 Implications for Institutions and Policy Makers

The study findings highlighted that while plain language offers several practical benefits, adoption of plain language construction contracts may be limited by resistance to change and perceived thread from legal professionals (Table 2). In this context, CIDA and public sector agencies may incorporate plain language principles into construction contracts. Policymakers may also consider developing guidelines or frameworks to support the gradual integration of plain language into contractual practices in Sri Lanka. Pilot projects could be implemented to test simplified contractual wording while maintaining the required level of legal precision (Lam, 2018). In addition, training programmes and awareness initiatives for contract administrators and construction professionals could help improve understanding of plain language drafting and its potential benefits (Wimalasena & Gunatilake, 2018).

### 3.5.3 Implications for Academia

The findings of this study indicate a clear research gap in relation to plain language construction contracts within the Sri Lankan context. As identified in Section 3.2, only a limited number of studies focus on construction specific contexts, indicating the need for further context based research. Future research can examine the readiness for adopting

plain language in construction contracts in Sri Lanka, the potential benefits of adopting plain language in construction contracts, the challenges that may arise when adopting plain language in construction contracts, and possible strategies to overcome the associated challenges. This may help to facilitate the adoption of plain language in construction contracts in Sri Lanka. Future research can also be extended to developing new plain language contract templates applicable to the Sri Lankan construction industry and conducting pilot testing of such contracts. Such research may contribute to improving contractual communication and supporting more effective contract administration within the Sri Lankan construction industry.

## 4. CONCLUSIONS

This study reviewed existing literature on plain language contracts to examine publication trends, key application areas and the benefits and challenges associated with adopting plain language in construction contracts. Although increasing scholarly attention has been given to plain language in contracts, limited focus has been placed on its application within the Sri Lankan construction industry. A total of 36 publications were selected from an initial pool of 142 publications published between 2010 and 2025 for review.

The findings indicate a gradual increase in research attention over time and reveal a clear research gap regarding plain language construction contracts in the Sri Lankan context. Furthermore, the results emphasize that plain language may enhance clarity, improve readability and comprehension, increase accessibility for diverse stakeholders, and reduce misinterpretation. However, several challenges may limit its adoption, including concerns regarding legal precision, reliance on traditional drafting practices, resistance to change, and the high level of skill required for plain legal writing. The study also highlights implications for the Sri Lankan construction industry. The adoption of plain language may improve communication among stakeholders and support more effective contract administration. Institutions and policymakers may consider developing guidelines and pilot initiatives to facilitate its gradual implementation. The countries which have diverse language background within the construction industry similar to Sri Lanka, may use this study findings to support more effective project delivery and contract management.

The literature search was conducted using the search query “plain language” AND “contracts”. Although this term represents the dominant terminology used in the field, studies employing alternative terms such as “clear language”, “plain English”, or “contract simplification” may not have been captured. Future reviews may broaden the search strategy by incorporating additional keyword combinations and Boolean variations to ensure more comprehensive coverage of the literature. Further, this study does not include empirical validation within the Sri Lankan construction industry, which may be necessary to assess the practical applicability of the identified findings. Future studies may examine the readiness of the Sri Lankan construction industry for adopting plain language construction contracts, developing plain language contract templates applicable to the Sri Lankan construction industry, and conducting pilot testing of plain language construction contracts. Overall, the study contributes to improving understanding of contractual communication and encourages further research on plain language in construction contracts.

# 5. REFERENCES


Akal, A. Y. (2022). What are the readability issues in sub-contracting's tender documents? *Buildings*, *12*(6), 839. https://doi.org/10.3390/buildings12060839

Akalanka, A. D., Weerathunge, S. S., & Uduwage Don, N. L. S. U. (2026). Strategies to enhance productivity in multicultural project management teams in Sri Lanka. In C. Aigbavboa, B. Awuzie, D. Aghimien, A.E. Oke & T. Omotayo, (Eds.), *Facilitating inclusivity in multi-, inter-, and transdisciplinary sustainable built environment research in emerging economies* (vol 772, pp. 119-1129). Springer, Cham. https://doi.org/10.1007/978-3-032-08992-2_93

Ali, N. A. N. (2008). Modern plain English drafting and construction: The Malaysian subcontract model terms. *Society of Construction Law D*, *90*(1), 1–67. https://www.scl.org.uk/papers/modern-plain-english-drafting-and-construction-malaysian-subcontract-model-terms

Alves, T., & Shah, N. (2018). Analysis of construction contracts: Searching for collaboration. *Construction Research Congress 2018*, 148–157. https://doi.org/10.1061/9780784481271.015

Ballesteros-Lintao, R., & Ali, N. A. N. A. (2022). Readability and comprehensibility of Malaysian construction contracts. *International Journal of Construction Management*, *23*(15), 2649–2657. https://doi.org/10.1080/15623599.2022.2084598

Chong, H., & Oon, C. K. (2016). A practical approach in clarifying legal drafting: Delphi and case study in Malaysia. *Engineering Construction & Architectural Management*, *23*(5), 610–621. https://doi.org/10.1108/ecam-04-2015-0059

Cornelius, E. (2010). Plain language as alternative textualisation. *Southern African Linguistics and Applied Language Studies*, *28*(2), 171–183. https://doi.org/10.2989/16073614.2010.519106

De Stadler, E., & Van Zyl, L. (2017). Plain-language contracts: challenges and opportunities. *South African Mercantile Law Journal*, *29*(1), 95–127. http://www.jutajournals.co.za/plain-language-contracts-challenges-and-opportunities/

Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing*, *24*(4), 230–235. https://doi.org/10.1179/2047480615z.000000000329

Hassan, F. U., & Le, T. (2020). Automated requirements identification from construction contract documents using natural language processing. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *12*(2). https://doi.org/10.1061/(asce)la.1943-4170.0000379

Janardana, J.A.B., Samaraweera, A., & Jayasena, H. (2021). Suitability of ICTAD Formula and CIDA price indices to calculate the amount of price escalated in construction projects. In Y.G. Sandanayake, S. Gunatilake, & K.G.A.S. Waidyasekara, (eds). *Proceedings of the 9th world construction symposium* (pp. 505–515). Ceylon Institute of Builders. https://doi.org/10.31705/wcs.2021.44

Juntunen, M., & Lehenkari, M. (2019). A narrative literature review process for an academic business research thesis. *Studies in Higher Education*, *46*(2), 330–342. https://doi.org/10.1080/03075079.2019.1630813

Kiger, M. E., & Varpio, L. (2020). Thematic analysis of qualitative data: AMEE guide no. 131. *Medical Teacher*, *42*(8), 846–854. https://doi.org/10.1080/0142159x.2020.1755030

Lam, K. K. L. (2018). *Plain language - A promising tool for quality legislation* [Masters, University of London]. SAS-Space, University College of London. https://sas-space.sas.ac.uk/6279/

Laxsana, S., Abiramy, S., & Fayasa, A. (2023). Measures to mitigate termination of construction contracts in Sri Lanka. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra, & K.A.T.O. Ranadewa (Eds.), *Proceedings of the 11th world construction symposium* (pp. 767–778). Ceylon Institute of Builders. https://doi.org/10.31705/wcs.2023.62

Masfar, Z. M. (2017). Towards a Saudi plain language standard construction contract. *International Journal of Construction Engineering and Management*, *6*(4), 168–179. http://article.sapub.org/10.5923.j.ijcem.20170604.05.html

Mico, A. (2013). Drafting and plain language. *Commonwealth Law Bulletin*, *39*(3), 435–442. https://doi.org/10.1080/03050718.2013.822312

Nwogu, P. C., & Emedosi, A. (2024). FIDIC form of contract: A study review. *British Journal of Environmental Sciences*, *12*(2), 43–48. https://doi.org/10.37745/bjes.2013/vol12n24348

Osifo, E. O., Omumu, E. S., & Alozie, M. (2025). Evolving contractual obligations in construction law: Implications of regulatory changes on project delivery. *World Journal of Advanced Research and Reviews*, *25*(3), 1315–1333. https://doi.org/10.30574/wjarr.2025.25.3.0896

Patrick, I. T., Curbano, R. J. P., Mvuyekure, A. F. N., Hakizamungu, E., & Emmanuella, I. (2025). The influence of knowledge management, total quality management, and worker competencies on construction project performance in Rwanda. *Journal of Management Research and Review*, *1*(05), 135-175. https://doi.org/10.65150/ep-jmrr/v1e5/2025-02

Australian Government, Office of Parliamentary Counsel (2013). *Plain English manual*. https://www.opc.gov.au/sites/default/files/2023-01/plain_english_0_0.pdf

United States General Services Administration. (n.d.) *Principles of plain language*. Digital.gov. Retrieved July 01, 2026, from https://digital.gov/guides/plain-language/principles

Radzi, J., & Ali, N. A. N. A. (2023). 'Meaning' in standard forms of construction contracts: A narrative literature review and a proposal. In M. Smith (Eds.), *AIP Conference Proceedings* (pp. 050019). AIP Publishing. https://doi.org/10.1063/5.0175229

Schriver, K. A. (2017). Plain language in the US gains momentum: 1940–2015. *IEEE Transactions on Professional Communication*, *60*(4), 343–383. https://doi.org/10.1109/tpc.2017.2765118

Shanahan, J. O. (2019). Literature reviews. *In L. Y. Overby, J. O. Shanahan, G. Young (Eds.), Undergraduate Research in Dance* (1st ed., pp. 6–16). Routledge. https://doi.org/10.4324/9781351052986-2

Siebörger, I., & Adendorff, R. D. (2011). Can contracts be both plain and precise? *Southern African Linguistics and Applied Language Studies*, *29*(4), 483–504. https://doi.org/10.2989/16073614.2011.651944

Smith, J., & Noble, H. (2015). Reviewing the literature. *Evidence-Based Nursing*, *19*(1), 2–3. https://doi.org/10.1136/eb-2015-102252

Subiela-Hernández, B., Gálvez-Vidal, A., & González-Conde, M. M. (2023). Plain language and the right to understand in the regulated electricity bill in Spain. *Ibérica*, *45*, 191–214. https://doi.org/10.17398/2340-2784.45.191

Thiruchelvam, K., & Uduwage, D. N. L. S. (2025). Assessing SDG 7 performance: Identifying relevant KPIs for the Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium* (pp. 203-215). Ceylon Institute of Builders. https://doi.org/10.31705/wcs.2025.16

Van Eck, M. (2024). Overcoming language barriers in contracts – A South African perspective. *BRICS Law Journal*, *11*(1), 103–130. https://doi.org/10.21684/2412-2343-2024-11-1-103-130

Van Boom, W. H., Desmet, P., & Van Dam, M. (2016). "If it's easy to read, it's easy to claim"- The effect of the readability of insurance contracts on consumer expectations and conflict behaviour. *Journal of Consumer Policy*, 39(2), 187–197. https://doi.org/10.1007/s10603-016-9317-9

Vats, S., & Devi, R. (2025). Legal language vs. plain English: Clear communication in legal documents. *International Journal of English Language Education and Literature Studies (IJEEL)*, *4*(3), 40–44. https://doi.org/10.22161/ijeel.4.3.5

Walsh, K. P. (2017). Identifying and mitigating the risks created by problematic clauses in construction contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *9*(3). https://doi.org/10.1061/(asce)la.1943-4170.0000225

Wimalasena, N. N., & Gunatilake, S. (2018). The readiness of construction contractors and consultants to adopt E-tendering. *Construction Innovation*, *18*(3), 350–370. https://doi.org/10.1108/ci-03-2017-0025

Dissanayake, W.M.S.S. and Amendra, S., 2026. Age-related variations in spatial cognition and spatial behaviour in botanic gardens: Evidence from the royal botanic gardens, Peradeniya. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 161-175. DOI: https://doi.org/10.31705/WCS.2026.13. Available from: https://ciobwcs.com/papers/

# AGE-RELATED VARIATIONS IN SPATIAL COGNITION AND SPATIAL BEHAVIOUR IN BOTANIC GARDENS: EVIDENCE FROM THE ROYAL BOTANIC GARDENS, PERADENIYA

**W.M.S.S. Dissanayake[1] and S. Amendra[2]**

## *ABSTRACT*

*Botanic gardens have evolved beyond plant conservation and research to serve as multifunctional landscapes. The study emphasises regeneration, sustainability, and resilient design, discovering user interactions and adaptations in these environments, an area that remains underexplored. Spatial cognition is reflected through spatial behaviour. This study examines the spatial behaviours of different age groups in the Royal Botanic Gardens, Peradeniya, Sri Lanka, to understand spatial cognition and its reflective behaviours. The study used the mixed-methods approach. The data collection was conducted based on four main methods to reduce bias and increase validity. A questionnaire survey, Onsite visitor interviews, three expert interviews, and onsite observation and mapping over three days of the peak visiting time. The study revealed that different age groups exhibit different spatial behaviours in the botanical gardens according to their cognitive abilities. The findings indicate that spatial behaviour varies across age groups. Young adults tend to explore more actively and navigate using landmarks, while older adults rely on signage, follow familiar routes, and prefer shaded resting areas. Children engage in educational exploration and can influence family movement patterns. These insights demonstrate the importance of age-responsive landscape design in enhancing navigation, spatial cognition, and overall user experience.*

***Keywords:*** *Botanic Gardens; Spatial behaviour; Spatial cognition.*

## 1. INTRODUCTION

Spatial cognition discusses the cognitive process by which humans can perceive, process, and navigate through their spatial world. It contains the basic components of wayfinding, mobility, and spatial behaviour, all of which change across the human life span and are differentially influenced across all life spans by age. These components do not change equally. It frames how one processes, remembers, and acts on spatial information throughout one's life. Modern neuroscience, particularly that involving single-unit recordings in freely moving animals, has elucidated how spatial information is encoded,

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, shashikadissanayake2000@gmail.com
[2] Senior Consultant, Department of Architecture, University of Moratuwa, Sri Lanka, shereen.amendra@gmail.com

integrated, and maintained over time. Such findings have significant implications for understanding human navigation within large-scale, complex, real-world environments and linking patterns of brain activity to equivalent spatial behaviour. This leads to a perspective of cognition as an embodied dynamic process rather than a static mental one.

International studies have investigated how age impacts spatial cognition and spatial behaviour in botanical gardens, however no studies have assessed the same qualities in Sri Lanka, specifically in the Royal Botanic Gardens, Peradeniya. Sri Lankan literature regarding botanical gardens is limited to botany, conservation, and ecological education, thus leaving the spatial experiences and behaviours of visitors wholly unexplored. Because of this, there is no database to inform the design of landscapes that adapt to the needs of multiple age groups in these types of environments. This research will resolve the gap of empirical knowledge regarding how spatial behaviour exhibits differences amongst visitors in relation to their age, and from this, the inability to design the gardens so that they adequately accommodate visitors of all ages.

# 2. LITERATURE REVIEW

## 2.1 HUMAN AGE

The World Health Organization (WHO) has long categorised individuals into different age groups (refer Table 1).

*Table 1: Human age as a global standard*

| Life stage | Age range | Source |
|---|---|---|
| Children | Under 18 | UNICEF, 2019 |
| Youth | 15–24 | WHO, 2019 |
| Adults | 25–64 | Havighurst, 1972 |

As cognitive development differs across these age groups, variations in spatial cognition and related behaviours can also be expected (refer Table 2).

*Table 2: Human age and cognitive development*

| Life Stage | Age Range | Key Cognitive / Executive Function Developments | Key References |
|---|---|---|---|
| Children | 0–12 years | Emergence of executive functions; development of attention control, cognitive flexibility, goal setting, and information processing. Near-comparative maturity of EF by ~12 years, forming the foundation for later self-regulation and goal-directed behaviours. | Anderson (2002) |
| Adolescence | 12–20 years | Transition to formal operational thinking (12–15 years). Continued diversification of abilities and refinement of cognitive structures (15–20 years). Cognitive development is gradual and not strictly age bound. | Piaget (1972) |
| Adults & Older Adults | Young adulthood onward | Peak cognitive performance is reached in early adulthood. From mid-adulthood onward, processing speed gradually declines, which | Salthouse (1996) |

| Life Stage | Age Range | Key Cognitive / Executive Function Developments | Key References |
|---|---|---|---|
| | | underlies broader reductions in working memory, reasoning, and spatial ability. Cognitive development in adulthood is therefore characterised by a progressive slowing of information processing rather than continued structural growth. | |

The illustration in Figure 1 delineates the progression of cognitive development throughout the human lifespan.

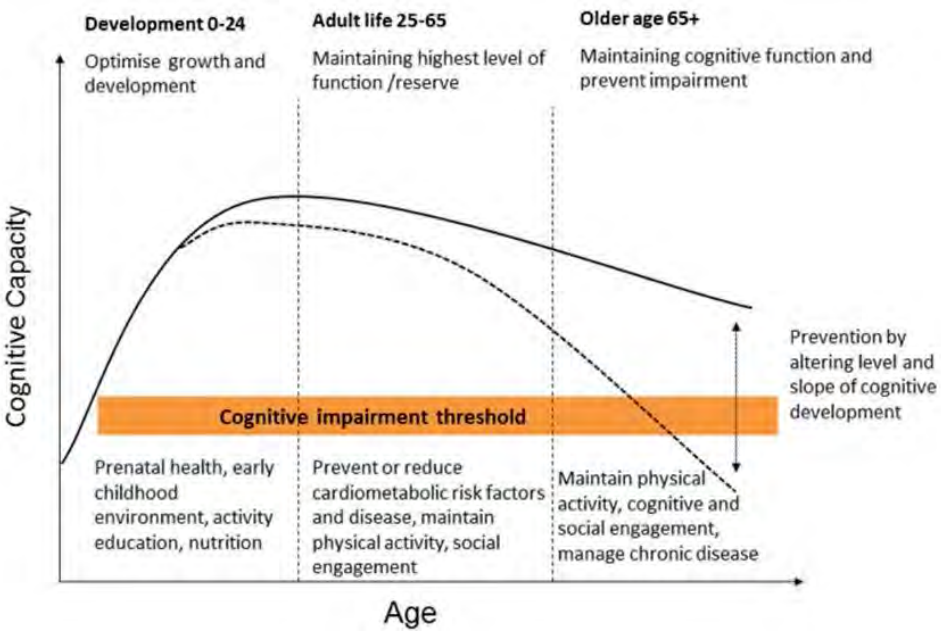



*Figure 1:Schematic representation of the trajectory of cognitive development over the life-course capacity may vary according to lifestyle, environment, education and health*

## 2.2 SPATIAL COGNITION

Environmental perception can be defined as the interpretation of sensory information from the environment, which varies with age. Spatial cognition, according to APA (2018), can be described as the mental process for obtaining and processing information concerning the spatial environment, which includes needs that go beyond the primary needs for survival, decision, orientation, and adaptability in navigating the environment. Research has been conducted on spatial cognition, including the use of environments such as botanical gardens, which provide a mix of both natural and artificial features, providing a better understanding of the relationship between humans and the environment. An example of this can be found in the study by Nori et al. (2009), which found the relationship between visuospatial working memory and the ability to navigate the botanical garden.

## 2.3 SPATIAL BEHAVIOUR

Spatial behaviour across environments varies significantly by age groups, with differences in cognitive abilities, sensory perception, and prior experience. The process

of spatial exploration during childhood exhibits an egocentric nature and is cantered on oneself, with younger children relying more heavily on egocentric strategies than older children or adults, who are increasingly able to shift toward more effective landmark and metric strategies as they age (Yang et al., 2019).The development of spatial skills continues until late adolescence and early adulthood, where one becomes more mobile and exposed to the environment, resulting in an enhanced allocentric approach and improved navigational capacity compared to older people (Hegarty et al., 2024). There is a slight decrease during mid-life years characterised by a switch from allocentric to egocentric approach and reduced environmental exploration (Yu et al., 2021). In old age, significant problems with navigation arise, especially in creating cognitive maps and adopting different perspectives, mostly because of the shrinkage of the hippocampus and decreased activity of the retro splenial cortex (Wiener et al., 2013; Moffat, 2009).

## 2.4 ANALYSIS AND APPLICATION OF THEORIES

Understanding spatial cognition requires examining the theories that explain wayfinding, mobility, and specifically, spatial behaviour. Although Attention Restoration Theory, Spatial Cognition, Place Attachment Theory, and Space Syntax Theory are discussed separately, they overlap through their shared focus on human-environment interaction. Together, these theories explain how spatial form, perception, cognition, and emotional attachment collectively influence human behaviour, movement, and experience within a space, highlighting the multidimensional nature of spatial experience.

### 2.4.1 Attention Restoration Theory (ART)

Exposure to natural environments has shown that it can help restore a limited cognitive resource, which in turn enhances advanced cognitive performance. According to a formal review by Stevenson, Schilhab, and Bentsen (2018), exposure to natural systems, although attention-grabbing, focuses attention on process-related effects that change with low to moderate intensity. According to Neilson et al. (2019), preferred traits for a scene include coherence and legibility. Coherence refers to the way information is organised to be easily understood, while legibility refers to what is next, which allows for better navigation and orientation. These traits contribute to understanding a scene and a sense of safety, which reduces unexpected and threatening events. On the other hand, complexity and mystery traits involve exploration, with complexity being the number of elements, with highly varied environments that are difficult to categorise. Mystery, however, refers to undiscovered elements beyond what is seen. These traits have a link with restorative environments in the ART model, with a preference for natural environments, which has a historical survival advantage. According to Kaplan and Kaplan (1989), spaces that provide a mental map that is easily understood provide a survival and aesthetic advantage, and humans tend to explore and be drawn to it. Four aesthetic variables i.e. (i) Coherence, (ii) Legibility, (iii) Complexity, and (iv) Mystery have been identified for understanding and exploration, which include immediate and inferred information.

### 2.4.2 Space Syntax Theory

Space syntax is a theoretical and methodological framework developed by Hillier and Hanson that analyses spatial configurations and their influence on social and behavioural patterns within urban environments. The core components of space syntax include

indicators such as connectivity, integration, intelligibility, and choice, which collectively assess the accessibility, coherence, and navigability of spatial networks (An et al., 2024).

### 2.4.3 Place Attachment Theory

Emotional and symbolic attachments are formed by people due to common interpretations and common experiences in relation to any location; this process is termed place attachment or space attachment. Emotional attachment is linked to how people see and interact with their physical world. According to Altman and Low (1992), symbolic attachment occurs through common symbols and meanings attached to any given place. Additionally, Stedman (2003) argues that some qualities of the place enhance positive emotional attachment to the place (Hashemnezhad, Heidari, & Hoseini, 2013) (refer Figure 2).

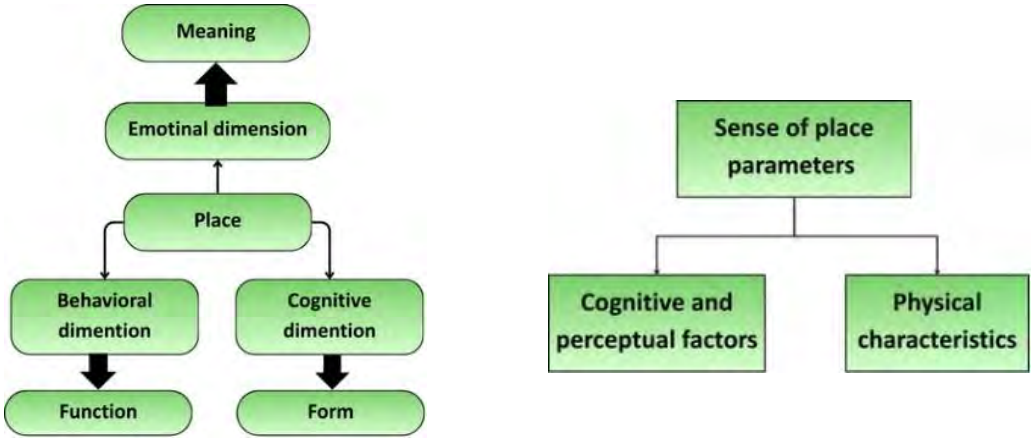



*Figure 2: Sense of place factors and dimensions of creating places- Hashemnezhad, Heidari and Mohammad Hoseini (2013).*

While ART, Spatial Cognition Theory, Place Attachment Theory, and Space Syntax Theory have their basis in distinct disciplines, all four theories are interrelated in their analysis of human behaviour. The configuration of spaces affects the way humans interact with the environment in terms of navigation, spatial cognition, and experience, leading to their emotional attachment and psychological restoration within spaces. It is thus important to note that human behaviour is determined by the interplay between the physical space itself and its psychological effects on the individual at various developmental stages.

## 2.5 PARAMETERS OF THE STUDY

The theoretical framework was developed based on previous studies and theories, highlighting how these theories are interconnected with each other. According to that, developed parameters are defined and detailed further to study in the selected site, as explained in the table below (refer Table 3).

*Table 3: Selected parameters and the definitions*

| Parameter | Definition |
|---|---|
| Visitor Preferences and Interests for key locations of the garden. | Patterns of choices and motivations that influence how visitors engage with environments (Falk & Dierking, 2016). |
| Seating and Rest Areas Usage | Patterns of how people use seating and rest areas as part of their spatial experience (Whyte, 1980). |
| Social Interaction Patterns | Observable behaviours in how individuals and groups communicate and gather within spaces (Gehl, 2011). |
| Engagement Opportunities | The extent to which spaces facilitate active participation, learning, and emotional connection (Packer & Ballantyne, 2002). |

## 3. RESEARCH METHODOLOGY

The study uses a convergent parallel mixed-methods design, gathering and analysing quantitative and qualitative data simultaneously for a comprehensive understanding. The Royal Botanic Gardens at Peradeniya were selected for their extensive land area (refer Table 4) and visitor numbers (refer Figure 3) compared to other botanic gardens in Sri Lanka.

*Table 4: Land area analysis of botanic gardens*

| Botanic Garden | Approximate Land Area (Acres) |
|---|---|
| Royal Botanic Gardens, Peradeniya | 147 |
| Mirijjawila Botanical Garden | 300 |
| Hakgala Botanical Garden | 68 |
| Seethawaka Botanical Garden | 105 |
| Henarathgoda Botanical Garden | 44 |
| Ganewaththa Medicinal Plant Garden | 52 |

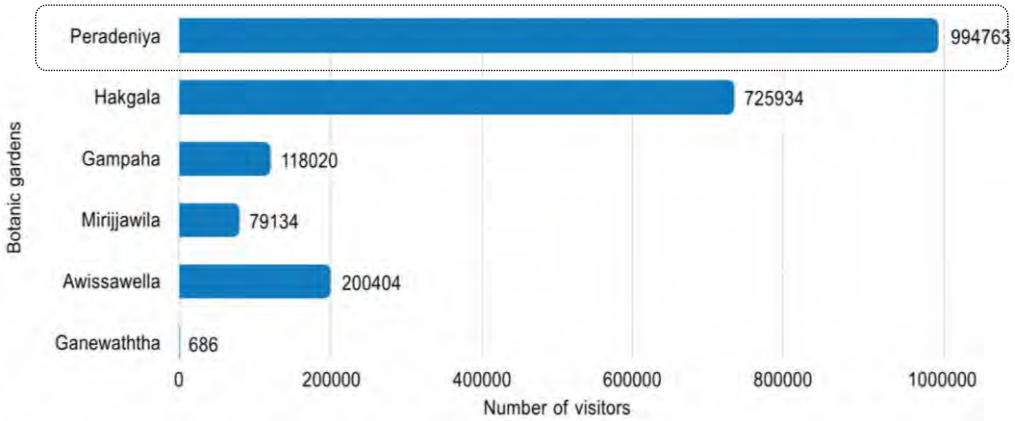



*Figure 3: Annual visitors count for botanic gardens*

The study was conducted in August, a peak arrival month, to understand how patterns of variation arise. The study employed a simple random sampling method to select

participants for onsite interviews, thereby minimising bias and ensuring equal opportunity of selection within the defined target population (Etikan & Bala, 2017). The sample was limited to individuals ranging from youth to pre-seniors, as children and older adults were excluded for methodological reasons. Children's mobility, wayfinding, and spatial experiences are often mediated by caregiver behaviour, which could confound the findings (Cushing & Miller, 2019; van Vliet, 1983). Likewise, older adults may face mobility and accessibility constraints; only residents were included in the study to Prior research indicates that cultural background significantly shapes how individuals perceive, navigate, and interpret spatial environments (Low, 2017; Rapoport, 1982), and familiarity with an environment plays a crucial role in shaping spatial cognition and sense of direction (Piccardi et al., 2011). By focusing exclusively on locals who, by definition, have greater environmental familiarity, the study sought to maintain cultural and cognitive homogeneity, thereby, reducing variability in spatial responses. This approach increases the internal validity of the study, although it may limit the generalisability of findings to non-local populations.

## 3.1 DATA COLLECTION METHODS

Data were collected through four main methods, and the analysis process is summarised in Table 5.

*Table 5: Data collection methods in detail*

| Method | Method in detail |
|---|---|
| Questionnaire Survey | The questionnaire includes both qualitative and quantitative questions about spatial behaviour, covering landscape preferences, user activities, and engagement. It also addresses pathway characteristics, signage, seating areas, and different locations. Data analysis was performed using MS Excel and Jamovi. |
| Site Observation &Photographic Documentation | The site visits were conducted over two weekdays and one weekend day to capture a broader range of visitor behaviours and activity patterns. Systematic observations were conducted of different areas to document spatial behaviours, movement patterns, and visitor preferences. In most areas, people were counted and documented. Highly crowded areas were photographed and documented using head counter software. The data collection was conducted by dividing the site into seven zones and selecting locations for photographic observation. |
| On-site visitor interview | The data collection was conducted outside the premises of the Botanic Garden due to the legal restrictions imposed by the Botanic Garden Ordinance of Sri Lanka. The data was gathered from visitors who had recently exited the garden. The sample comprised 70 participants. In the onsite interview, children's behaviour was analysed based on the caregivers' explanations, but their explanations showed the significant influence of the children on the overall behaviour of the group. |
| Expert's Interview | The questionnaire consists of both qualitative and quantitative questions. Interview conducted as a semi-structured interview with three experts who work in the industry and are engaged with the design aspects of Royal Botanic Gardens, Peradeniya. Two people are landscape architects, and one person is a Senior Agriculture and Landscape Instructor, School of Floriculture and Landscape Gardening, Royal Botanic Garden, Peradeniya, Sri Lanka. |

The methodological framework has been established to provide a comprehensive overview of the study's overall work process (refer Figure 4).

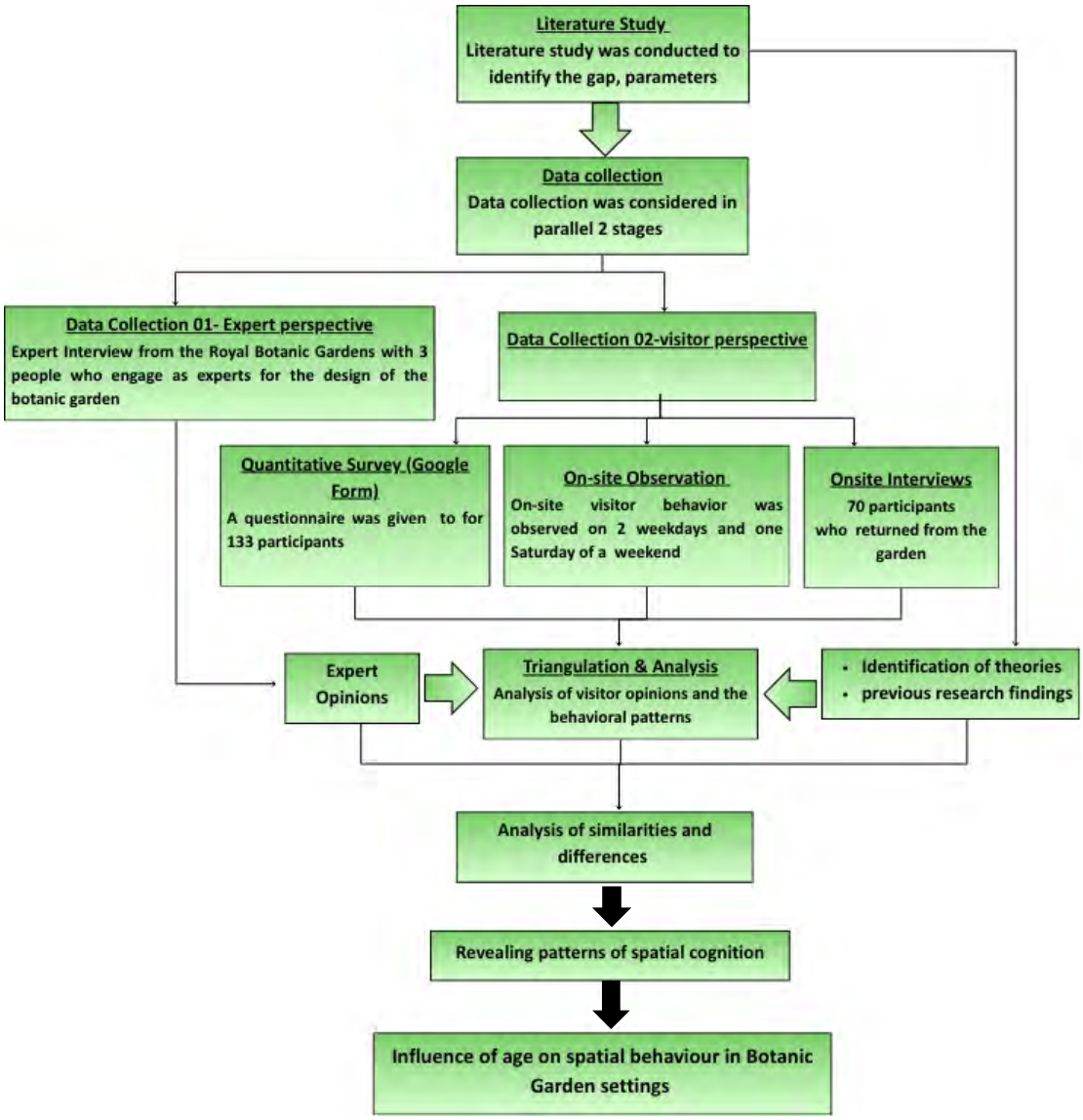



*Figure 4: Methodological framework*

## 4. DATA ANALYSIS

Under the spatial behaviour parameter, there are four sub-parameters considered for the study. According to expert opinions, the selected parameter analysis is given in Table 6. All experts emphasised the need for balanced primary and secondary circulation systems. Visitor movement patterns reveal selective spatial integration shaped by accessibility, visual prominence, and cognitive mapping processes.

*Table 6: Expert opinions analysis of spatial behaviour*

| Parameter | Analysis |
|---|---|
| Visitor Preferences and Interests | Expert responses consistently indicate that spatial preference is structured by group composition, social intention, and environmental recognition. Prominent landscape elements function as cognitive anchors, while exploratory movement patterns reflect higher spatial confidence and adaptive engagement. |
| Seating and Rest Area Usage | Rest-area occupation varied according to desired levels of interaction, enclosure, and psychological comfort. Spatial use demonstrates restorative behaviour patterns influenced by privacy gradients and collective versus passive occupation. |
| Social Interaction Patterns | Social activity concentrated around visually dominant and accessible nodes, whereas peripheral routes supported lower-intensity and semi-private interaction. This reflects the influence of spatial visibility and territorial behaviour on social clustering. |
| Engagement Opportunities | Experts identified differences in navigational behaviour and interpretive engagement across visitor groups. Underutilised zones indicate that spatial legibility and landmark hierarchy strongly influence circulation and experiential depth. |

The onsite observations were systematically collected from pre-selected viewpoints in each zone (refer Figure 5). All gathered data were analysed using Jamovi software. A set of one-way ANOVAS was run, focusing on differences between a group of eight varying age groups, ranging from children to seniors, for all activities measured.

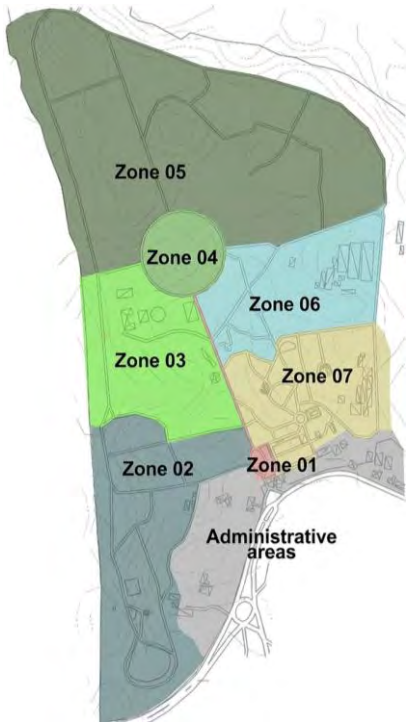



*Figure 5: Zones of the study*

*Table 7: Analysis of observed behaviours*

| Activity | F-Statistic | $df_1$, $df_2$ | p-Value | N (people) | Significance |
|---|---|---|---|---|---|
| Walking | 1.128 | 7, 392 | 0.345 | 570 | |
| **Observing Nature** | **2.611** | **6, 119** | **0.021** | **209** | ✓ |
| Sitting on the Floor | 0.536 | 6, 70 | 0.779 | 170 | |
| Sitting | 0.420 | 5, 12 | 0.826 | 36 | |
| Getting Food (Cafeteria) | 0.552 | 5, 6 | 0.734 | 35 | |
| Photography | 0.495 | 3, 16 | 0.691 | 24 | |
| **Playing** | **6.593** | **2, 21** | **0.006** | **24** | ✓ |
| Standing/Leisure | 0.308 | 5, 12 | 0.899 | 23 | |
| Sitting on a Bench | 2.248 | 2, 15 | 0.140 | 13 | |
| Reading the Map | 1.500 | 2, 6 | 0.296 | 9 | |
| Standing | 0.400 | 1, 2 | 0.592 | 8 | |
| Lying on the Floor | 2.000 | 1, 2 | 0.293 | 4 | |

$p < 0.05$. Significant. Two walking observations with missing age breakdowns (N = 220 people) were imputed using proportional distribution based on observed walking patterns. Total sample: N = 1,125 people across 113 observation records. Highlighted rows indicate statistically significant results.

Significant differences between all age groups were found when comparing how each respective age category engaged in two activities (observing nature: F [6, 119] = 2.611; p = .021; playing: F [2, 21] = 6.593; p = .006). Conversely, the overall pattern of participation was similar for each respective age group in the remaining activities (walking: F [7, 392] = 1.128; p = .345; sitting on the floor: F [6, 70] = 0.536; p = .779; sitting on a bench: F[2, 15] = 2.248; p = .140; all other activities). Activities that had low sample sizes (i.e., < 10 participants) should be considered in their respective context when compared to the rest of the observations (i.e., lying on the floor: N = 4; standing: N = 8).

*Figure 6: Provided seating arrangement references for the questionnaire survey*

Seating and Rest Areas Seating preferences vary across age groups, as analysed using the collected data from the questionnaire survey (refer Figure 6). Adolescents received higher ratings, particularly for Seating 2, 3, and 5 (means = 5.00). Among larger groups, Youth (18–24) and Young Adults (25–34) tended to rate seats moderately, with means mostly

around 3.3– 4.2 and showed relatively low variability (SD ≈ 0.8–1.2). Middle-aged Adults (35–44) and Older Adults (45–54) generally expressed stronger preferences for Seating 1 and 5 (means ≈ 4.0–4.5), with moderate variability (SD ≈ 0.7–1.3). Pre-seniors (55–64) were more inconsistent, showing lower averages (≈ 3.2–3.7) yet higher variability (SD ≈ 1.7), suggesting diverse opinions within this group. Seniors (65+) gave extreme values (means = 2.0–5.0), yet with only one respondent, these results are not reliable. Overall, Seating 1 and 5 received the highest mean ratings across most groups with lower variability, while Seating 3 had the lowest overall ratings with higher variability, indicating less consistent preference (refer Figure 7).

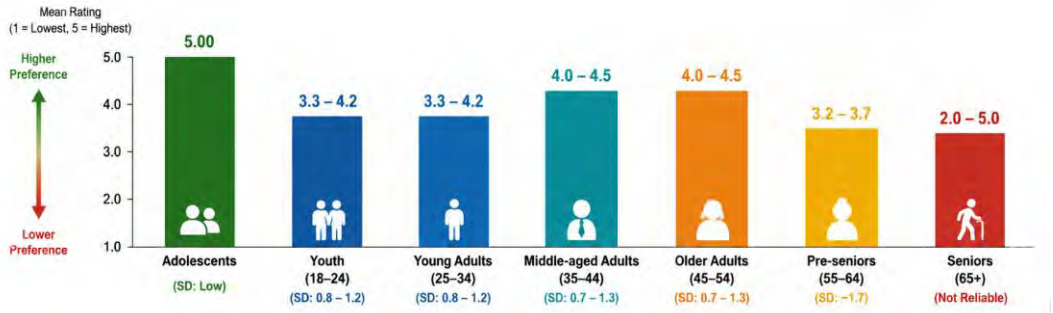



*Figure 7: Mean ratings of seating preferences across different age groups*

Activities and the emotional connections are analysed using the questionnaire survey according to the age groups to gain a deeper understanding of spatial cognition among different age groups. The analysis reveals calmness is the most prominent emotional response across all age categories, particularly among youth (18–24) and young adults (25–34). This highlights a strong confirmation of comfort and relaxation among younger groups. Blends involving calmness, excitement, and nostalgia are more typical among young and middle-aged adult groups, reflecting that in these environments, seating triggers a multi-tiered experience involving balance between tranquillity, excitement, and introspection. Nostalgia by itself or involving calmness runs more among young and older adult groups, signifying introspective experience with space. Seating elicits largely comfort-related feelings, with younger groups displaying wider diversity and older adult groups underlining calmness and introspective states (refer Figure 8).

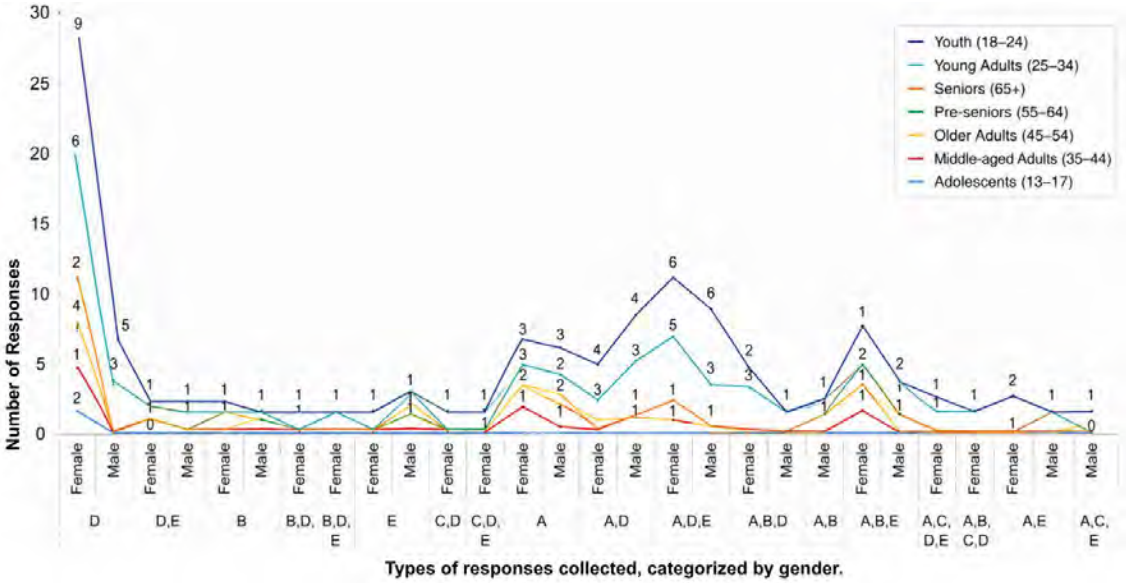



*Figure 8: Age-related patterns of environmental preferences*

The data collected presents an examination of environmental preferences across six age groups i.e. Adolescents, Youth, Young Adults, Middle-aged Adults, Older Adults, Pre-seniors, and Seniors) and gender categories. The environments were classified into five categories: A - Lush vegetation B - Sparse greenery, C - high level of manmade objects D - Natural elements (trees, rocks, streams), and E - Structured landscapes (flowerbeds, lawns).

Among all age and gender groups, the landscapes with natural elements (D) present the highest overall mean preference scores, with adolescents (13–17) and youth (18–24) reaching the highest values. Globally, the distribution of means corroborates a marked and coherent preference for vegetation-rich, nature-dominant environments with minimal artificial components across demographic groups.

## 4.1 DISCUSSION

This study shows that age significantly affects spatial behaviour, landscape use, and emotional responses in the Royal Botanic Gardens, Peradeniya. The findings indicate distinct differences in navigation patterns, activity preferences, and emotional experiences, emphasising the need for age-sensitive botanic gardens.

### 4.1.1 Age and Spatial Navigation

Navigation behaviours vary by age; older people often follow established routes using well-supported signage, compared to younger people who are more likely to explore various routes and areas around the site. There was a tendency for older people to avoid more complex spatial areas, such as peripheral regions; however, younger adults were willing to take more exploratory routes than their older counterparts. This creates support from previous studies that indicate that older adults rely more on following routes for navigation than younger adults and that younger adults exhibit greater flexibility in navigating through an environment while older adults exhibit lower degrees of flexibility in navigating an environment (Moffat, 2009; Wiener et al., 2013; Hegarty et al., 2024). A notable finding was the role of children as “spatial catalysts” within family groups. Children frequently influenced movement decisions by drawing attention to botanical displays, interpretive signage, and less-visited areas. This suggests that educational and heritage landscapes can encourage exploration through child-driven curiosity, extending previous observations of caregiver-child wayfinding dynamics.

### 4.1.2 Age and Landscape Use

There were age differences regarding the different types of landscaping being used. For example, it was found that older and middle-aged individuals tended to congregate more near the entrances, walkways, and activity points within the landscape, whereas younger people were usually found in low-traffic, shaded areas that provided them with privacy and a more natural view of their surroundings. This pattern corresponds to both Whyte’s (1980) social visibility preferences in landscape usage and to the fact that there were age-related differences in the types of landscaping used. Activity type was based on the individual’s age; therefore, age likely influenced the behaviour of an individual in relation to the landscape rather than total mobility. The time spent playing, viewing nature, resting, and reading a map was very different between the three groups; however, there was no significant difference in the amount of time spent walking or standing between the groups. As such, discretionary activities are influenced more (age-discretionary

behaviours) by the individual's age than by their basic movement behaviours (walking/standing).

#### 4.1.3 Emotional Reactions and Restoration

Individuals from all age cohorts felt at peace the most frequently, providing evidence that ART, which states that being in a natural environment produces emotional restoration (Kaplan & Kaplan, 1989), holds true. Older individuals felt nostalgic and reflective to a greater extent than younger individuals, indicating that older individuals had a greater emotional connection to the landscape.

#### 4.1.4 Spatial Configuration and Movement

Visitor patterns closely corresponded with the garden's spatial structure. Highly integrated and visible areas, particularly those containing prominent landmarks, attracted greater numbers of visitors. These results support the conclusion that spatial configuration plays a significant role in shaping movement patterns and space use within the garden. In comparison to the main pathways dominating the garden, the peripheral zones of the garden, which are ecologically valuable areas outside the major pathways, were grossly underutilised (based upon the landscape quality), even though they are ecologically valuable. This indicates that spatial legibility and landmark visibility contribute to the degree of exploration, and for older visitors. Across all age groups, there were clear preferences for areas with dense vegetation and natural features. This consistency supports the theories of the positive relationship between natural environments and restful behaviours, and positive experiences of natural landscapes. Additionally, these results indicate that the Heritage and Cultural Value of the Royal Botanic Gardens contribute to the enjoyment of nature by visitors irrespective of age.

### 4.2 LIMITATIONS

Uncontrolled variables likely confounded age-related findings. For example, visitors' familiarity with the gardens, spatial layout, or social group (family vs peers), education/occupation, and botanical interest were not examined. Prior work shows that higher education predicts better wayfinding, and obesity (high BMI) is linked to restricted mobility and a smaller life-space, suggesting such factors could influence path choices and resting behaviour.

## 5. CONCLUSIONS

This research supports previous evidence that age plays a role in how people think spatially and act during an activity at Royal Botanic Gardens Peradeniya, shows a lack of studies on the influence of age on emotional responses to nature in Sri Lanka; and provides information about how age can affect the discretionary use of land (i.e., where people choose to go) at the botanical gardens, particularly for nature observation and play; while basic behaviours related to movement are similar across all age groups (e.g., walking). Younger visitors tended to prefer environments that were natural and contained a lot of vegetation with an exploratory route to reach their destination, while older adults tended to use well-connected, accessible spaces with places to sit that were enclosed. Children can act as spatial catalysts for family members in creating travel patterns. Calmness was the most frequent emotional reaction across all ages, providing evidence of the restorative nature of the botanical gardens. Nostalgia was more frequently reported among older adults than among younger adults. There was a lack of use of peripheral

areas by all age groups, indicating a need for improved spatial legibility and visibility of landmarks. These results suggest that designers should create age-responsive landscapes using improved signage and seating that is accessible to all and enhanced wayfinding to better serve the diverse visitor population.

# 6. REFERENCES


Altman, I., & Low, S. M. (1992). *Place attachment.* Springer. https://doi.org/10.1007/978-1-4684-8753-4

An, M., Hedayati Marzbali, M., Abdullah, A., & Maghsoodi Tilaki, M. J. (2024). Space syntax and spatial behavior: An integrative review. *Journal of Urban Design, 29*(1), 55–75. https://doi.org/10.1080/13574809.2023.2245107

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology, 8*(2), 71–82. https://doi.org/10.1076/chin.8.2.71.8724

American Psychological Association (2018). Spatial cognition. *APA dictionary of psychology*. https://dictionary.apa.org/spatial-cognition

Cushing, D. F., & Miller, E. (2019). Children's wayfinding in urban environments: A review and synthesis. *Children, Youth and Environments, 29*(1), 24–51. https://doi.org/10.7721/chilyoutenvi.29.1.0024

Etikan, I., & Bala, K. (2017). Sampling and sampling methods. *Biometrics & Biostatistics International Journal, 5*(6), 215–217. https://doi.org/10.15406/bbij.2017.05.00149

Falk, J.H., & Dierking, L.D. (2016). *The Museum Experience Revisited* (1st ed.). Routledge. https://doi.org/10.4324/9781315417851

Gehl, J. (2011). *Life between buildings: Using public space* (6th ed.). Island Press.

Hashem, H., Akbar, H. A., & Parisa, M. H. (2013). "Sense of place" and "place attachment" (A comparative study). *International Journal of Architecture and Urban Development, 3*(1), 5–12. https://www.sid.ir/en/VEWSSID/J_pdf/1036020130101.pdf

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2024). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial layout learning. *Intelligence, 106,* 102858. https://doi.org/10.1016/j.intell.2024.102858

Kaplan, R., & Kaplan, S. (1989). *The experience of nature: A psychological perspective*. Cambridge University Press.

Low, S. M. (2017). *Spatializing culture: The ethnography of space and place*. Routledge.

Moffat, S. D. (2009). Aging and spatial navigation: What do we know and where do we go? *Neuropsychology Review, 19*(4), 478–489. https://doi.org/10.1007/s11065-009-9120-3

Neilson, B. N., Craig, T., Travis, A. T., & Klein, M. I. (2019). Examining attention restoration theory: Theoretical refinements and empirical testing. *Environment and Behavior, 51*(9–10), 1056–1082.

Nori, R., Grandicelli, S., & Giusberti, F. (2009). Individual differences in Visuo-Spatial working memory and Real-World wayfinding. *Swiss Journal of Psychology, 68*(1), 7–16. https://doi.org/10.1024/1421-0185.68.1.7

Packer, J., & Ballantyne, R. (2002). Motivational factors and the visitor experience: A comparison of three sites. *Curator: The Museum Journal, 45*(3), 183–198. https://doi.org/10.1111/j.2151-6952.2002.tb00055.x

Piaget, J. (1972). Intellectual evolution from adolescence to adulthood. *Human Development, 15*(1), 1–12. https://doi.org/10.1159/000271225

Piccardi, L., Risetti, M., & Nori, R. (2011). Familiarity and environmental representations of a city: A self-report study. *Psychological Reports, 109*(1), 309–326. https://doi.org/10.2466/01.13.17.PR0.109.4.309-326

Rapoport, A. (1982). *The meaning of the built environment: A nonverbal communication approach*. The University of Arizona Press.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*(3), 403–428. https://doi.org/10.1037/0033-295X.103.3.403

Stevenson, M. P., Schilhab, T., & Bentsen, P. (2018). Attention Restoration Theory II: a systematic review to clarify attention processes affected by exposure to natural environments. *Journal of Toxicology and Environmental Health Part B, 21*(4), 227–268. https://doi.org/10.1080/10937404.2018.1505571

Stedman, R. C. (2003). Is it really just a social construction?: The contribution of the physical environment to sense of place. *Society & Natural Resources, 16*(8), 671–685. https://doi.org/10.1080/08941920309189

van Vliet, W. (1983). Exploring the fourth environment: An examination of the home range of city and suburban teenagers. *Environment and Behavior, 15*(5), 567–588. https://doi.org/10.1177/0013916583155002

Wiener, J. M., de Condappa, O., Harris, M. A., & Wolbers, T. (2013). Maladaptive bias for extrahippocampal navigation strategies in aging humans. *Journal of Neuroscience, 33*(14), 6012–6017. https://doi.org/10.1523/JNEUROSCI.0717-12.2013

Whyte, W. H. (1980). *The social life of small urban spaces*. Project for Public Spaces.

Yang, Y., Merrill, E. C., & Wang, Q. (2019). Children's response, landmark, and metric strategies in spatial navigation. *Journal of Experimental Child Psychology, 181*, 75–101. https://doi.org/10.1016/j.jecp.2019.01.005

Yu, S., Boone, A. P., He, C., Davis, R. C., Hegarty, M., Chrastil, E. R., & Jacobs, E. G. (2021). Age-related changes in spatial navigation are evident by midlife and differ by sex. *Psychological Science, 32*(5), 692–704. https://doi.org/10.1177/0956797620979185

Jayakodi, S., Senaratne, S., Perera, S. and Bamdad, K., 2026. Analysing key process areas in developing the circular economy maturity model for construction organisations. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 176-190. DOI: https://doi.org/10.31705/WCS.2026.14. Available from: https://ciobwcs.com/papers/

# ANALYSING KEY PROCESS AREAS IN DEVELOPING THE CIRCULAR ECONOMY MATURITY MODEL FOR CONSTRUCTION ORGANISATIONS

**Shashini Jayakodi[1], Sepani Senaratne[2], Srinath Perera[3] and Keivan Bamdad[4]**

## *ABSTRACT*

*Adopting the circular economy (CE) at the individual project level offers only a short-term perspective and neglects strategic, long-term CE transformation in construction. Accordingly, organisation-level CE adoption was identified as the more suitable approach, as it provides strategic, long-term, and consistent results across the construction projects. Consequently, developing a maturity model for construction organisations was identified as a promising approach as it guides organisational processes from the initial to the desired state. Therefore, this study provides a foundation for a CE Maturity Model for Construction Organisations by systematically analysing Key Process Areas (KPAs), addressing a gap in previous studies that focused mainly on conceptual discussions of CE maturity. Initially, CE indicators for construction organisations were identified, providing the basis for identifying KPAs, as explained in the literature review section of this paper. Subsequently, Delphi-based expert interviews were conducted with 20 experts to verify the suitability of the identified KPAs, assess their importance, and justify KPA descriptions. The results identified 19 KPAs relevant to construction organisations, which were categorised into four tiers by importance. Accordingly, the most important KPAs for construction organisations, grouped within the Tier 1 category, were "Circularity in building design", "Material circularity improvement", "Waste circularity improvement", and "Greenhouse gas emissions reduction". The other 15 KPAs are clustered under Tier 2, 3 and 4. Theoretically, this study helps fill the existing research gap on CE adoption in construction organisations, while, practically, it provides a roadmap for construction professionals to adopt CE by focusing on the KPAs.*

***Keywords:*** *Circular economy; Construction Industry; Construction Organisations; Key Process Areas; Maturity Model.*

[1] PhD Researcher, Centre for Smart Modern Construction, School of Built Environment and Design, Western Sydney University, Australia, s.jayakodi@westernsydney.edu.au
[2] Associate Professor, Centre for Smart Modern Construction, School of Built Environment and Design, Western Sydney University, Australia, S.Senaratne@westernsydney.edu.au
[3] Professor, Centre for Smart Modern Construction, School of Built Environment and Design, Western Sydney University, Australia, Srinath.Perera@westernsydney.edu.au
[4] Senior Lecturer, Centre for Smart Modern Construction, School of Built Environment and Design, Western Sydney University, Australia, K.Bamdad@westernsydney.edu.au

# 1. INTRODUCTION

The construction industry is dominated by the Linear Economy (LE) model, based on the "take, make, use, discard" principle (Jayakodi et al., 2024b). In the construction LE model, the process begins with the extraction of raw materials, which are subsequently processed into materials/products and assembled on-site in a manner that cannot be disassembled. As a result, at the end of a building's service life, materials become obsolete and are either disposed of in a landfill or incinerated (Mangialardo & Micelli, 2017). In contrast to the LE model, the circular economy (CE) model has emerged over the past few decades as a prominent alternative, underpinned by the principle of sustainable resource management (Pomponi & Moncaster, 2017). Therefore, in recent years, there has been growing attention from academics, industry practitioners, and policymakers toward transitioning to the CE model in the built environment, which aims to substantially reduce waste generation and alleviate pressure on natural resources (Kirchherr et al., 2023).

In the built environment, substantial research over the past few decades has led to the development of several practical approaches to CE implementation at the various levels. Across these levels, existing literature shows a strong concentration of research at the nano (material) and micro (building or project) levels (Pomponi & Moncaster, 2017). This is largely attributable to the inherent characteristics of the construction industry: it is highly dynamic, project-based, involves numerous stakeholders, and operates through complex, often fragmented supply chains (Jayakodi et al., 2024a; Yang et al., 2023). As a result, circularity in construction has been commonly framed as project-specific rather than systemic. However, this project-centric focus has been increasingly challenged. Scholars argue that limiting CE to individual materials or projects restricts its potential, as it reflects a short-term lens and fails to capture strategic, long-term circular transformation (Gorecki, 2019).

Among several CE adoption approaches, circularity assessment is a prominent approach that facilitates the implementation, improvement, and monitoring of circularity levels (Jayakodi et al., 2024b). There are two types of circularity assessment evidenced: circular flow assessment and impact assessment (De Oliveira et al., 2021). The flow assessment primarily focuses on circularity outcomes using qualitative or quantitative indicators, whereas the impact assessment focuses on the environmental, economic, and social impacts of CE initiatives. Hence, many other sectoral studies have moved beyond output-based assessments at the organisational level by incorporating process-based assessments to ensure consistent circularity performance over time and to support continuous improvement (Uhrenholt et al., 2022). The authors further explained that output-based assessments are limited in their ability to capture complex organisational processes. In this context, the development of maturity models has emerged as a suitable approach for guiding organisational process improvement, as the transition to a CE and the required organisational changes call for a broader, more structured approach to organisational development (Bertassini et al., 2022).

Among these diverse organisations, it is imperative to identify the most effective avenue to achieve maximum circularity outcomes in construction projects. Jayakodi et al. (2024a) asserted that main contractor organisations (referred to as construction organisations in this study) play a crucial role in the adoption of circularity. Several researchers have studied the application of various CE adoption in main contractors, business models

(Jayakodi et al., 2024b; Kjerulf, 2023), waste management performance assessment (Torgautov et al., 2022), quantitative CE assessments (Núñez-Cacho et al., 2018), indicator analysis (Jayakodi et al., 2024a), and CE maturity concepts at higher levels (Gorecki, 2019; Jayakodi et al., 2025). To date, no studies have examined the detailed analysis of the Key Process Areas (KPAs) of maturity models. Hence, this study focuses on fulfilling three research objectives: i) to verify the suitability of identified KPAs (OB1), ii) to identify the level of importance of KPAs (OB2) iii) to justify the description of the KPAs (OB3). To achieve the research aim, this study adopted a qualitative approach through a critical literature review followed by a Delphi-based expert forum.

## 2. DEFINING CIRCULAR ECONOMY KEY PROCESS AREAS FOR CONSTRUCTION ORGANISATIONS

Maturity models assess the prevailing capability level and proffer the necessary capabilities for effective adoption in a systematic roadmap (Adekunle et al., 2022). Further, it can be identified as a tool that helps business transformation from an initial to a desired state by identifying characteristics that determine step-changes from a lower to a higher level of maturity (Becker et al., 2009). A maturity model comprises several components such as Process Categories, KPAs, Maturity Levels, Assessment Attributes and Maturity Characteristics. Maturity levels display the level of maturity of an entity (De Bruin et al., 2005; Paulk et al., 1993). At the core of maturity model design lies the concept of the process, typically defined as a structured sequence of interrelated activities undertaken to achieve a specific organisational purpose. While process-level analysis provides fine-grained analysis, assessing maturity at the level of individual processes is often impractical in large, complex organisations due to the sheer number of processes and their interdependencies. To address this challenge, maturity models aggregate related processes into higher-order constructs commonly referred to as KPAs or process areas (Becker et al., 2009; Paulk et al., 1993).

van Steenbergen et al. (2010) commented distinct from organisations in other sectors, construction organisations require significant attention when developing a maturity model due to their project-based nature. Hence, it is imperative to determine the project and organisational boundaries when implementing CE. Supportively, Jayakodi et al. (2024a) has defined two levels of implementing CE in construction organisations: the construction project level (project-specific processes) and the organisation level (non-project-specific/ organisational ongoing business processes). To identify the project-level KPAs, the scope of the construction organisations involved in the project must be determined. The scope of involvement of a main contractor in a construction project varies based on the procurement route (RIBA, 2020). It was identified that, except for the traditional procurement route, the main contractors are involved in the design and development of the construction project through to handover or the defect liability period. As this study focuses on the organisational perspective, it is crucial to identify the KPAs under the extended project scope to cover the holistic processes. Non-project-specific processes may have less direct impact on circularity in construction than project-specific processes; these processes remain essential, as the organisation drives project execution and influences the project environment (Jayakodi et al., 2024b). Hence, both project-specific and non-project-specific processes were identified to develop a comprehensive, holistic list of KPAs.

*Table 1: Conversion of circular economy indicators to key process areas*

| No | KPA Name | KPA Description | Ref |
|---|---|---|---|
| 01 | Circularity in building design | The ability of the organisation to adopt circular-economy-driven building design techniques and methods to maximise functional use and end-of-life recovery in construction projects. | (1) (2) |
| 02 | Circularity in building construction | The ability of the organisation to adopt circular-economy–driven building construction techniques and methods to maximise functional use and end-of-life recovery in construction projects. | (3) (4) |
| 03 | Material circularity improvement | The ability of the organisation to source secondary (circular) materials, prioritise locally sourced and rapidly renewable materials, substitute hazardous materials with safer alternatives, and procure construction materials with accurate estimations and incorporate end-of-life strategies for the construction projects. | (5) (6) |
| 04 | Waste circularity improvement | The ability of the organisation to direct waste generated from construction projects to a secondary source and reduce overall waste generation. | (7) (8) |
| 05 | Water circularity improvement | The ability of the organisation to source water from circular sources, discharge water to circular systems for treatment and reuse, and reduce water-use intensity in construction projects. | (3) (9) |
| 06 | Energy management and optimisation | The ability of the organisation to generate on-site renewable energy, use renewable energy, and implement energy-efficiency practices in the construction projects. | (3) (8) |
| 07 | Greenhouse gas emissions reduction | The ability of the organisation to reduce energy-direct and energy-indirect greenhouse gas emissions in construction projects. | (1) (10) |
| 08 | Land and biodiversity rehabilitation | The ability of the organisation to adopt adaptive re-use and land-conservation practices enhances land-use efficiency and minimises biodiversity impacts associated with the construction projects. | (10) (11) |
| 09 | Social value creation | The ability of the organisation to create value for the community through the adoption of circular practices in construction projects. | (8) (10) |
| 10 | Economic value creation | The ability of the organisation to create economic value through circularity adoption, including investment in circular capabilities and diversification of revenue streams in construction projects. | (8) (10) |
| 11 | Supplier selection and management | The ability of the organisation to select and manage suppliers in line with circular economy requirements for construction projects. | (12) (13) |
| 12 | Stakeholder collaboration and engagement | The ability of the organisation to foster stakeholder collaboration and management to deliver circular economy objectives in construction projects. | (14) (15) |

| No | KPA Name | KPA Description | Ref |
|---|---|---|---|
| 13 | Client collaboration and guidance | The ability of the organisation to collaborate with clients and guide them to deliver circular economy objectives across construction projects. | (12) (16) |
| 14 | Digital technologies adoption | The ability of the organisation to adopt digital technologies for circular economy–driven processes to enhance efficiency. | (3) (10) |
| 15 | Workforce capacity development and engagement | The ability of the organisation to develop circular economy–driven capacities and increase workforce engagement. | (3) (17) |
| 16 | Circularity-driven strategic directives implementation | The ability of the organisation to develop and adopt circular economy–driven strategic directives. | (9) (11) |
| 17 | Circularity-driven research and innovation | The ability of the organisation to collaborate on research and development and to conduct circular economy–driven innovation projects. | (3) (12) |
| 18 | Establishment of circularity-driven logistics and mobility initiatives | The ability of the organisation to establish circularity driven logistics and sustainable mobility initiatives. | (18) (19) |
| 19 | Circularity-driven business model adoption | The ability of the organisation to adopt circularity driven business models across construction projects. | (4) (13) |
| 20 | Marketing and sharing circular economy initiatives | The ability of the organisation to publicly disclose and market circular economy initiatives in construction projects. | (20) (21) |
| 21 | Circularity driven management systems implementation | The ability of the organisation to adopt and implement circular economy–driven management and certification systems across its construction projects. | (20) (22) |
| 22 | Circularity driven culture establishment | The ability of the organisation to establish a circular economy–driven organisational culture. | (16) (20) |

(1) Huovila and Westerholm (2022), (2) Deselnicu et al. (2018), (3) Tokazhanov et al. (2022), (4) Abadi and Sammuneh (2020), (5) Finch et al. (2021), (6) Beddaa et al. (2023), (7) Medina and Fu (2021), (8) González et al. (2021), (9) Zhang et al. (2021), (10) Piñones et al. (2023), (11) Foster et al. (2020), (12) Torgautov et al. (2022), (13) Antwi-Afari et al. (2023), (14) Kaipainen et al. (2023), (15) Droege et al. (2021), (16) Bianchini et al. (2022), (17) Núñez-Cacho et al. (2020), (18) Zhou et al. (2023), (19) Ding et al. (2023), (20) Ibáñez-Forés et al. (2023), (21) Sacco et al. (2021), (22) De Souza et al. (2022)

When defining the KPAs for maturity models, researchers employ several approaches. Most common approaches draw on maturity models in similar domains, identify the defined KPAs, and verify them against empirical findings (Das et al., 2023). However, when a lack of maturity models in a similar domain, researchers have adopted several other approaches, such as drivers and barriers analysis.

The CE maturity model was developed in the construction context, and a lack of comprehensive studies provides a basis for identifying the KPAs. Hence, this study relied on the circularity indicator approach. Considering the existing CE assessment frameworks developed in the construction context, most indicators focused on circularity

flow or output assessment. Hence, this study used a structured reverse approach, using indicators to identify dedicated CE processes. The current paper builds on these previous studies and extends the already identified CE indicators to derive KPAs, as presented in Table 1. Each column of Table 1, from left to right, respectively, represents the identified CE indicators from previous work, the conversion of each indicator as a KPA, the description of each KPA, and supporting references.

## 3. MATERIALS AND METHODS

To achieve the aim, this study employed a qualitative approach. Most maturity models employ qualitative techniques, such as interviews, Delphi techniques, nominal group studies, and case studies, in addition to quantitative techniques (Adekunle et al., 2022). Among the identified methods, the Delphi method is an iterative procedure that uses multiple data-collection and analysis techniques, along with feedback, to gather and distil the anonymous opinions of experts (Skulmoski et al., 2007). Hence, the study employed Delphi-based expert interviews to achieve its objectives. In the authors' previous study, two systematic literature reviews (SLRs) were conducted to identify CE indicators, which served as the basis for formulating KPAs. Based on the findings of the literature review, the interview guideline was developed and comprised four sections. Section 1 included the experts' demographic details. In Section 2, experts were asked to verify the suitability of KPAs for construction organisations. Section 3 included a 10-point Likert scale to assess the importance of the identified KPAs in delivering the CE outcomes of the construction projects. Section 4 presented the identified KPA descriptions derived from the literature for verification or modification. Afterwards, 20 experts were recruited for the study from the Australian construction industry, considering three expert selection criteria: i) 5 years of experience in the construction industry ii) engages in a role in CE, sustainability or environmental management iii) works in a large building contractor organisation (managing large-scale mega-projects valued over $500 million), a consultant organisation or a sustainability alliance organisation. The experts were recruited through purposive sampling to ensure heterogeneity of the experts (Hasson et al., 2025). The rationale for selecting experts from large building contractor organisations was that the proposed maturity model was specifically developed for them; therefore, their expertise was considered essential. In addition, consultant organisations were included for their significant role as key project stakeholders, while sustainability alliance organisations were selected for their involvement in developing sustainability assessment tools.

Before undertaking the expert interviews, the study has taken necessary ethical approval. Delphi-based semi-structured interviews were conducted until data saturation was reached, as failure to achieve data saturation affects the quality of the research, undermining its validity (Aguboshim, 2021). By comparing experts' consensus rates across articles, Goodarzi et al. (2018) argued that limiting the number of Delphi rounds may hinder the attainment of full consensus; hence, 75% agreement was chosen as the consensus threshold for quantitative data, while consensus of the qualitative data was determined through content analysis. As this consensus threshold was achieved in Round 1 of the interviews, consolidated results from that round were sent to the 20 experts in Round 2 to test their level of agreement again. The study achieved a response rate exceeding 80% and corroborated the consolidated results. In the analysis, two types of data were analysed: qualitative data were analysed using content analyses (Boulkedid et al., 2011), while quantitative data were analysed using the mean (to assess the importance

of KPAs) and standard deviation (to identify outliers) (Harpe, 2015). Although the quantitative analysis was conducted with a relatively small sample size (n = 20), this is considered acceptable in expert-based and Delphi-related studies where participants are selected purposively based on their specialised expertise rather than through probabilistic sampling (Okoli & Pawlowski, 2004). Figure 1 depicts the research process.

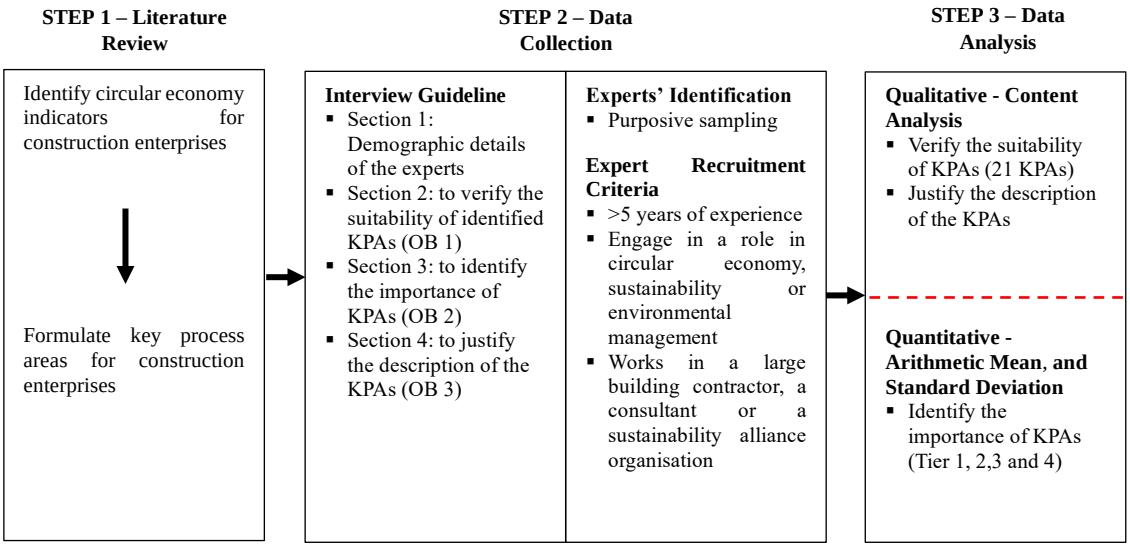



*Figure 1: Research process*

# 4. ANALYSIS

## 4.1 DEMOGRAPHIC DETAILS OF THE EXPERTS

As explained in Section 3, 20 experts were recruited for data collection, and Table 2 presents the experts' codes, roles, years of experience, and the types of organisations they represented.

*Table 2: Demographic details of the experts*

| No | Role | Experience (In Years) | Type of Organisation |
|---|---|---|---|
| E1 | National Sustainability Manager | 08+ | Main Contractor (Tier 1) |
| E2 | Senior Sustainability Advisor | 06+ | Main Contractor (Tier 1) |
| E3 | Senior Sustainability Advisor | 17+ | Main Contractor (Tier 1) |
| E4 | Senior Manager - Environment Sustainability | 18+ | Main Contractor (Tier 1) |
| E5 | Environment and Sustainability Manager | 05+ | Main Contractor (Tier 1) |
| E6 | Sustainability Lead | 17+ | Main Contractor (Tier 1) |
| E7 | Sustainability Manager | 16+ | Main Contractor (Tier 1) |
| E8 | National ESG Coordinator | 05+ | Main Contractor (Tier 1) |
| E9 | State Manager | 20+ | Main Contractor (Tier 1) |
| E10 | Senior Environment Consultant | 07+ | Consultant |
| E11 | Director - Sustainability | 30+ | Consultant |
| E12 | Team Leader - Sustainability and Climate Change | 08+ | Consultant |
| E13 | Associate Sustainability Consultant | 12+ | Consultant |

| No | Role | Experience (In Years) | Type of Organisation |
|---|---|---|---|
| E14 | Senior Construction Consultant | 10+ | Consultant |
| E15 | National Sustainability Lead & Section Manager | 11+ | Consultant |
| E16 | Design Director and Circular Economy Leader | 24+ | Consultant |
| E17 | Environment and Sustainability Manager | 13+ | Consultant |
| E18 | Mining and Environmental Engineer | 06+ | Consultant |
| E19 | Sustainability Design Leader | 19+ | Sustainability alliance |
| E20 | Senior Manager- Sustainable Products and Materials | 10+ | Sustainability alliance |

## 4.2 SUITABILITY AND IMPORTANCE OF KEY PROCESS AREAS

Based on the literature, twenty-two (22) KPAs were initially identified for construction organisations. Following verification of their suitability, nineteen (19) KPAs were retained. “Establishment of circularity-driven logistics and mobility initiatives” was deemed not relevant to construction organisations, as it primarily involves developing waste-infrastructure facilities and other infrastructure that fall outside the typical organisational scope. Accordingly, only sustainable mobility initiatives were incorporated into “Greenhouse Gas Emissions Reduction,” given their materiality to Scope 1 (emissions from sources that an organisation owns or controls directly), Scope 2 (missions that a organisation causes indirectly and come from where the energy it purchases and uses is produced) and, Scope 3 (emissions that occur outside the organisation's boundary as a result of the organisation’s actions). “Client collaboration for circularity,” was subsumed under the broader stakeholder-engagement KPA, as treating it as a standalone area was not suitable, given the client’s role as a principal stakeholder. Finally, KPA 2 “Circularity in construction” was integrated into “Circularity in building design”, reflecting experts' consensus that circular construction methods, particularly modern methods of construction, are largely determined at the design stage.

*Table 3: Importance level of KPAs*

| KPA ID | KPA Name | Importance | Tier | KPA ID | KPA Name | Importance | Tier |
|---|---|---|---|---|---|---|---|
| KPA1 | Material circularity improvement | 9.60 | Tier 1 | KPA11 | Stakeholder collaboration and engagement | 6.92 | Tier 3 |
| KPA2 | Circularity in building design and construction | 9.45 | | KPA12 | Circularity-driven research and innovation | 6.85 | |
| KPA3 | Waste circularity improvement | 9.35 | | KPA13 | Workforce capacity development and engagement | 6.75 | |

| KPA ID | KPA Name | Importance | Tier | KPA ID | KPA Name | Importance | Tier |
|---|---|---|---|---|---|---|---|
| KPA4 | Greenhouse gas emissions reduction | 8.55 | | KPA14 | Circularity-driven business model adoption | 6.65 | |
| KPA5 | Energy management and optimisation | 7.95 | Tier 2 | KPA15 | Circularity-driven culture establishment | 6.54 | |
| KPA6 | Water circularity improvement | 7.85 | | KPA16 | Digital technologies adoption | 6.35 | Tier 4 |
| KPA7 | Circularity-driven management systems implementation | 7.76 | | KPA17 | Land and biodiversity rehabilitation | 6.22 | |
| KPA8 | Circularity-driven strategic directives implementation | 7.25 | | KPA18 | Social value creation | 6.18 | |
| KPA9 | Economic value creation | 6.95 | Tier 3 | KPA19 | Marketing public data disclosure | 6.10 | |
| KPA10 | Supplier, sub-contractor and vendor selection and management | 6.95 | | | | | |

After verifying the suitability of KPAs, a Likert scale was provided to experts to rate the importance of KPAs for CE implementation in construction organisations. Among the various types of Likert scales, it was selected 10 point liker scale is more efficient (Awang et al., 2016). To analyse the collected data, the mean was used, as it was identified that, when the data are at the interval or ratio level, it is statistically valid and meaningful for describing the central tendency. Furthermore, to detect outliers in the dataset, the mean and standard deviation were used. All KPAs reported an importance level greater than 5.5 on the 10-point scale. Based on average importance, KPAs are divided into four tiers: 1 ( >8.5), 2 (7.4 – 8.5), 3 (6.5-5.5), and 4 (6.4-5.5). Tier 1 represents the most important KPAs, with the level of importance decreasing progressively across Tier 2, Tier 3, and Tier 4 KPAs. Since the midpoint of the scale is 5, values above 5.5 indicate that respondents perceived the KPAs as more important than neutral or average. Therefore, all KPAs were considered sufficiently important for improving circularity. Hence, it was decided that all KPAs are important to improve circularity. Table 3 presents the level of importance of each KPA.

## 4.3 JUSTIFICATIONS FOR THE DESCRIPTIONS OF THE KEY PROCESS AREAS

### 4.3.1 Tier 1 Key Process Areas

KPA1 "Material Circularity Improvement" was initially described as the organisation's ability to source secondary (circular) materials, prioritise locally sourced and rapidly renewable materials, substitute hazardous materials with safer alternatives, procure construction materials using accurate estimates, and incorporate end-of-life strategies for construction projects; following review, the 'locally sourced materials' element was removed from this KPA and its implications were relocated to KPA4 "Greenhouse Gas Emissions Reduction" under Scope 3 emissions, while experts recommended elaborating the term 'secondary sources' by referencing R-strategies (Refuse, Rethink, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, Renewable). KPA2 "Circularity in Building Design and Construction" was originally defined as the ability of the organisation to adopt circular-economy–driven building design techniques and methods to maximise functional use and end-of-life recovery in construction projects; however, E9 commented that "*it is practical to elaborate on the type of circularity-driven design and construction techniques which are adopted"*. Therefore, the description was expanded to include design and construction techniques and methods such as modularity, adaptability, maintainability, durability, flexibility, and design for disassembly, and to emphasise maximising resource recovery at the end of the building's life cycle (Alabdulrazzaq et al., 2025). KPA3 "Waste Circularity Improvement" was conceptualised as the organisation's ability to direct generated waste from construction projects to secondary sources and to reduce overall waste generation; the experts agreed with this description, though E1 commented that "*it is better to simplify by what it meant by the secondary sources mentioning the appropriate R strategies such as reuse, recycle, remanufacture, repair, etc*", and E13 also highlighted that diverting waste from landfill is the ultimate goal of waste circularity and should be made explicit (Pilipenets et al., 2024). The experts agreed with the KPA4 description on "Greenhouse Gas Emissions Reduction".

### 4.3.2 Tier 2 - Key Process Areas

Regarding KPA5 "Energy Management and Optimisation", three aspects were initially covered: renewable energy production, renewable energy use, and energy reduction; however, on-site energy production was excluded because it is not feasible for all projects. Furthermore, E20 from the sustainability alliance organisation stated that "*it is required to emphasise the fossil fuel-free construction project concept, as now we are on a journey to replace fossil fuels*". Accordingly, the description was defined as the ability to source renewable energy, reduce energy consumption, and ensure that construction projects are fossil-fuel-free (Simeone et al., 2023). For KPA6 "Water Circularity Improvement", the initial scope considered potable and non-potable water inflows from circular sources and outflows to circular sources; however, E6 highlighted that "*internal water recirculation is critical to consider*", so the description was defined as the ability of the organisation to source water from circular sources, discharge water to circular systems for treatment and reuse, reduce water-use intensity in construction projects, and enhance internal water recirculation in construction projects (Arora et al., 2022). The majority of the experts agreed with the description for KPA7 management systems; however, E1 commented that "*beyond management systems, certification systems should also be included in the description. In addition to adopting circular-economy*

*management systems (e.g., ISO 59000-series standards), organisations can pursue project-level certifications via sustainability rating tools, such as Green Star, which also drive circular-economy outcomes."* The experts agreed with the descriptions for KPA8 "Implementation and Adoption of Circularity-Driven Strategic Directives".

### 4.3.3 Tier 3 - Key Process Areas

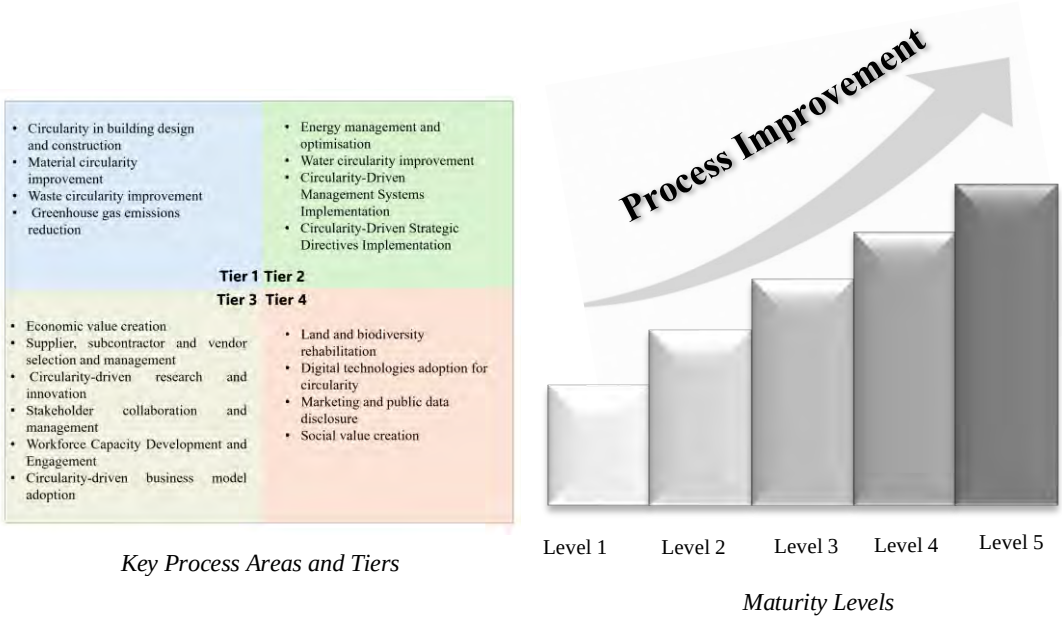
KPA9 "Economic value creation" through circularity was initially defined as the ability to create monetary value through CE adoption and implementation. However, E2 commented that "*as value creation, the ability to capture value is also crucial for contractors. This should be addressed in both economic and social value creation*" (Jayakodi et al., 2024b). Hence, the descriptions for both KPAs were revised accordingly. "Workforce capacity development and engagement", KPA name and scope remained unchanged based on the experts' opinions. Several experts endorsed KPA10, "Supplier Selection and Management," and its description; however, E7, E9, and E13 recommended expanding the scope to explicitly include subcontractors and vendors. Accordingly, the KPA description was revised to: The ability of the organisation to select and manage suppliers, subcontractors, and vendors in line with circular-economy requirements for construction projects. Consequently, the KPA name is also revised. Experts also agreed with the descriptions for KPA11 "Stakeholder collaboration and management", KPA12"Circularity-driven research and innovation", KPA14 "Circularity-driven business model adoption", KPA13 "Workforce capacity development and engagement" and KPA15 "Circularity-driven culture establishment"

### 4.3.4 Tier 4 - Key Process Areas

A review of the literature indicates that KPA17, "Land and biodiversity rehabilitation" remains underexplored in the CE context. The experts agreed with the description derived from the literature. However, E12 noted that, while adaptive reuse is considered, the KPA should also encompass brownfield development and greenfield conservation. Accordingly, greenfield conservation was explicitly incorporated into the KPA description, alongside adaptive reuse, brownfield development, land-use efficiency, and reduced biodiversity impacts. With respect to communication and sharing of CE initiatives, E16 recommended KPA 19 "Marketing and sharing CE initiatives". Substitute the term sharing CE initiatives with the term public data disclosure (Opferkuch et al., 2022). Consequently, the KPA was revised to KPA19"Marketing and public data disclosure". All experts agreed with the descriptions for KPA 16 "Digital technologies adoption", and KPA 18 "Social value creation".

## 4.4 VISUALISING THE IDENTIFIED KEY PROCESS AREAS FOR CONSTRUCTION ORGANISATIONS

Figure 2 depicts the verified KPAs along with the respective tiers. Further, the maturity levels have been indicated to illustrate the structure of the model.




*Key Process Areas and Tiers*

*Maturity Levels*

*Figure 2: Key process areas for construction organisations*

## 5. CONCLUSIONS

The study laid the foundation for the CE maturity model for construction organisations by identifying relevant KPAs to transform their linear practices into circular practices across both project-specific and non-project-specific processes. The key findings revealed 19 KPAs for construction organisations. Further, the identified KPAs were divided into four categories: Tier 1, 2, 3, and 4 KPAs, which clarifies which processes are crucial and need to be considered for a circular built environment. Moreover, the study justified the claim that the description of KPAs provided a clear context for circularity. This study offers significant practical and theoretical implications. Construction professionals use this as a navigation tool to identify the relevant KPAs within construction organisations to implement the CE, while, theoretically, the study contributes to organisational-level CE assessment in construction. This research identifies significant future directions for the construction management research domain. Researchers from other countries and regions may filter the findings of this study to adopt the most relevant KPAs, given that this study is limited to the Australian context. This publication is part of research aimed at developing a maturity model to assess and improve CE in construction organisations. Hence, subsequent publications will focus on developing a detailed maturity model with respective assessment attributes to assess KPAs. While acknowledging that data collection was limited to major stakeholders at this stage of the maturity model, the next stage of developing the detailed model will expand data collection to include additional stakeholders.

## 6. REFERENCES

Abadi, M., & Sammuneh, M. A. (2020). Integrating circular economy and constructability research: An initial development of a lifecycle" circularity" assessment framework and indicators. In L. Scott & C.J Neilson (Eds.), *Proceedings of the institution of civil engineers - Management, procurement and law* (pp.516-525), Association of Researchers in Construction Management.

Adekunle, S. A., Aigbavboa, C., Ejohwomu, O., Ikuabe, M., & Ogunbayo, B. (2022). A critical review of maturity model development in the digitisation era. *Buildings*, *12*(6), 858. https://doi.org/10.3390/buildings12060858

Aguboshim, F. C. (2021). Adequacy of sample size in a qualitative case study and the dilemma of data saturation: A narrative review. *World Journal of Advanced Research and Reviews*, *10*(3), 180-187. https://doi.org/10.30574/wjarr.2021.10.3.0277

Alabdulrazzaq, H., Gasparri, E., Brambilla, A., & Attia, S. (2025). A framework for circular facade design: Systematic review of design strategies and performance indicators. *Journal of Cleaner Production*, *536*, 147140. https://doi.org/10.1016/j.jclepro.2025.147140

Antwi-Afari, P., Ng, S. T., Chen, J., Oluleye, B. I., Antwi-Afari, M. F., & Ababio, B. K. (2023). Enhancing life cycle assessment for circular economy measurement of different case scenarios of modular steel slab. *Building and Environment*, *239*, 110411. https://doi.org/10.1016/j.buildenv.2023.110411

Arora, M., Yeow, L. W., Cheah, L., & Derrible, S. (2022). Assessing water circularity in cities: Methodological framework with a case study. *Resources, Conservation and Recycling*, *178*, 106042. https://doi.org/10.1016/j.resconrec.2021.106042

Awang, Z., Afthanorhan, A., & Mamat, M. (2016). The likert scale analysis using parametric based structural equation modeling (SEM). *Computational Methods in Social Sciences*, *4*(1), 13-21. https://share.google/SQp0REmmRr6YXs6F5

Becker, J., Knackstedt, R., & Pöppelbuß, J. (2009). Developing maturity models for IT management: A procedure model and its application. *Business & Information Systems Engineering*, *1*, 213-222. https://doi.org/10.1007/s12599-009-0044-5

Beddaa, H., Tchiotsop, J., Fraj, A. B., & Somé, C. (2023). Reuse of river sediments in pervious concrete: Towards an adaptation of concrete to the circular economy and climate change challenges. *Construction and Building Materials*, *368*, 130443. https://doi.org/10.1016/j.conbuildmat.2023.130443

Bertassini, A. C., Calache, L. D. D. R., Carpinetti, L. C. R., Ometto, A. R., & Gerolamo, M. C. (2022). CE-oriented culture readiness: An assessment approach based on maturity models and fuzzy set theories. *Sustainable Production and Consumption*, *31*, 615-629. https://doi.org/10.1016/j.spc.2022.03.018

Bianchini, A., Guarnieri, P., & Rossi, J. (2022). A framework to assess social indicators in a circular economy perspective. *Sustainability*, *14*(13), 1-21. https://doi.org/10.3390/su14137970

Boulkedid, R., Abdoul, H., Loustau, M., Sibony, O., & Alberti, C. (2011). Using and reporting the delphi method for selecting healthcare quality indicators: A systematic review. *PloS one*, *6*(6), e20476. https://doi.org/10.1371/journal.pone.0020476

Das, P., Perera, S., Senaratne, S., & Osei-Kyei, R. (2023). A smart modern construction enterprise maturity model for business scenarios leading to industry 4.0. *Smart and Sustainable Built Environment*. *14*(1), 23-49. https://doi.org/10.1108/SASBE-09-2022-0205

De Bruin, T., Rosemann, M., Freeze, R., & Kaulkarni, U. (2005). *Understanding the main phases of developing a maturity assessment model*. Australasian Conference on Information Systems (ACIS), Sydney. https://share.google/7ZXpY5Y40RxLHYi4F

De Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. *Sustainable Production and Consumption*, *26*, 455-468. https://doi.org/10.1016/j.spc.2020.11.024

De Souza, E., Kerber, J., Bouzon, M., & Rodriguez, C. (2022). Performance evaluation of green logistics: Paving the way towards circular economy. *Cleaner Logistics and Supply Chain*, *3*, 100019. https://doi.org/10.1016/j.clscn.2021.100019

Deselnicu, D. C., Militaru, G., Deselnicu, V., Zăinescu, G., & Albu, L. (2018). Towards a circular economy–A zero waste programme for Europe. In *7th international conference on advanced materials and systems (icams)* (pp.563-568). Bucharest. 10.24264/icams-2018.XI.4

Ding, L., Wang, T., & Chan, P. (2023). Forward and reverse logistics for circular economy in construction: A systematic literature review. *Journal of Cleaner Production*, *388*, 135981. https://doi.org/10.1016/j.jclepro.2023.135981

Droege, H., Raggi, A., & Ramos, T. B. (2021). Co-development of a framework for circular economy assessment in organisations: Learnings from the public sector. *Corporate Social Responsibility and Environmental Management*, *28*(6), 1715-1729. DOI: 10.1002/csr.2140

Finch, G., Marriage, G., Pelosi, A., & Gjerde, M. (2021). Building envelope systems for the circular economy; Evaluation parameters, current performance and key challenges. *Sustainable Cities and Society*, *64*, 102561. https://doi.org/10.1016/j.scs.2020.102561

Foster, G., Kreinin, H., & Stagl, S. (2020). The future of circular environmental impact indicators for cultural heritage buildings in Europe. *Environmental Sciences Europe*, *32*, 141. https://doi.org/10.1186/s12302-020-00411-9

Goodarzi, Z., Abbasi, E., & Farhadian, H. (2018). achieving consensus deal with methodological issues in the delphi technique. *International Journal of Agricultural Management and Development*, *8*(2), 219-230. https://share.google/g1dBVGCYW8Itar1fe

González, A., Sendra, C., Herena, A., Rosquillas, M., & Vaz, D. (2021). Methodology to assess the circularity in building construction and refurbishment activities. *Resources, Conservation & Recycling Advances*, *12*, 200051. https://doi.org/10.1016/j.rcradv.2021.200051

Gorecki, J. (2019). Circular Economy maturity in construction companies. *IOP Conference Series: Materials Science and Engineering*, *471*(11), 112090. doi:10.1088/1757-899X/471/11/112090

Harpe, S. E. (2015). How to analyze likert and other rating scale data. *Currents in Pharmacy Teaching and Learning*, *7*(6), 836-850. http://dx.doi.org/10.1016/j.cptl.2015.08.001

Hasson, F., Keeney, S., & McKenna, H. (2025). Revisiting the delphi technique-research thinking and practice: A discussion paper. *International journal of nursing studies*, *168*, 105119. https://doi.org/10.1016/j.ijnurstu.2025.105119

Huovila, P., & Westerholm, N. (2022). Circularity and sustainability in the construction value chain. I*OP Conference Series: Earth and Environmental Science*, *1078*, 012004. doi:10.1088/1755-1315/1078/1/012004

Ibáñez-Forés, V., Alejandrino, C., Bovea, M. D., & Mercante, I. (2023). Prioritising organisational circular economy strategies by applying the partial order set theory: Tool and case study. *Journal of Cleaner Production*, *406*, 136727. https://doi.org/10.1016/j.jclepro.2023.136727

Jayakodi, S., Senaratne, S., & Perera, S. (2024b). Circular economy business model in the construction industry: A systematic review. *Buildings*, *14*(2), 379. https://doi.org/10.3390/buildings14020379

Jayakodi, S., Senaratne, S., Perera, S., & Bamdad, K. (2025). *Conceptual circular economy maturity model for construction organisations*. CIB Conferences, West Lafayette. https://doi.org/10.7771/3067-4883.1678

Jayakodi, S., Senaratne, S., Perera, S., & Bamdad, K. (2024a). Circular economy assessment using project-level and organisation-level indicators for construction organisations: A systematic review. *Sustainable Production and Consumption*, *48*, 324-338. https://doi.org/https://doi.org/10.1016/j.spc.2024.05.025

Kaipainen, J., Uusikartano, J., Aarikka-Stenroos, L., Harala, L., Alakerttula, J., & Pohls, E.-L. (2023). How to engage stakeholders in circular economy ecosystems: The process. In J. Kujala, A. Heikkinen, A. Blomberg. (Eds.), *Stakeholder engagement in a sustainable circular economy: theoretical and practical perspectives* (pp.193-231). Springer. https://share.google/bwtyLYhIRPkhvONiX

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): An analysis of 221 definitions. *Resources, Conservation and Recycling*, *194*, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Kjerulf, L. (2023). Theoretical framework of circular business model innovation for building contractors. In L. Kjerulf and K. Haugbølle (Eds.), *SDGs in construction economics and organization* (pp.77-90), DOI: 10.1007/978-3-031-25498-7_6

Mangialardo, A., & Micelli, E. (2017). Rethinking the construction industry under the circular economy: principles and case studies. In A. Bisello, D. Vettorato, P. Laconte, & S. Costa (Eds.), *Smart and sustainable planning for cities and regions* (pp.333-344). Springer. DOI: 10.1007/978-3-319-75774-2_23

Medina, E. M., & Fu, F. (2021). A new circular economy framework for construction projects. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *174*(6), 304-315. https://doi.org/10.1680/jensu.20.00067

Núñez-Cacho, P., Górecki, J., Molina, V., & Corpas-Iglesias, F. A. (2018). New measures of circular economy thinking in construction companies. *Journal of EU Research in Business*, *2018*, 909360. https://doi.org/10.5171/2018.909360

Núñez-Cacho, U. P., Górecki, J., & Maqueira, J. M. (2020). Simulation-based management of construction companies under the circular economy concept—case study. *Buildings*, *10*(5), 94. https://doi.org/10.3390/buildings10050094

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & Management*, *42*, 15-29. doi:10.1016/j.im.2003.11.002

Opferkuch, K., Caeiro, S., Salomone, R., & Ramos, T. B. (2022). Circular economy disclosure in corporate sustainability reports: The case of European companies in sustainability rankings. *Sustainable Production and Consumption*, *32*, 436-456. https://doi.org/10.1016/j.spc.2022.05.003

Paulk, M., Curtis, B., Chrissis, M., & Weber, C. (1993). *Capability Maturity ModelSM for Software, Version 1.1* (CMU/SEI-93-TR-024). Carnegie Mellon University. https://share.google/RvIYIYdfGENxufNAM

Pilipenets, O., Hui, F. K. P., Gunawardena, T., Mendis, P., & Aye, L. (2024). New circularity indicator for decision making in the stockpile management of construction and demolition waste: Perspectives of Australian practitioners. *Journal of Environmental Management*, *363*, 121345. https://doi.org/10.1016/j.jenvman.2024.121345

Piñones, P., Derpich, I., & Venegas, R. (2023). Circular economy 4.0 evaluation model for urban road infrastructure projects, CIROAD. *Sustainability*, *15*(4), 15043205. https://doi.org/10.3390/su15043205

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710-718. http://dx.doi.org/10.1016/j.jclepro.2016.12.055

RIBA. (2020). *RIBA plan of work 2020 overview*. https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work?srsltid=AfmBOoph9YO53GLiG57Ljz_i0i7CKH4lZlhW4SSMuTUXQ6oyS2BHNmUI

Sacco, P., Vinante, C., Borgianni, Y., & Orzes, G. (2021). Circular economy at the firm level: A new tool for assessing maturity and circularity. *Sustainability*, *13*(9), 5288. https://doi.org/10.3390/su13095288

Simeone, D., Rotilio, M., & Cucchiella, F. (2023). Construction work and utilities in historic centers: strategies for a transition towards fuel-free construction sites. *Energies*, *16*(2), 1-21. https://doi.org/10.3390/en16020700

Skulmoski, G. J., Hartman, F. T., & Krahn, J. (2007). The Delphi method for graduate research. *Journal of Information Technology Education: Research*, *6*(1), 1-21. https://doi.org/10.28945/199

Tokazhanov, G., Galiyev, O., Lukyanenko, A., Nauyryzbay, A., Ismagulov, R., Durdyev, S., Turkyilmaz, A., & Karaca, F. (2022). Circularity assessment tool development for construction projects in emerging economies. *Journal of Cleaner Production*, *362*, 132293. https://doi.org/10.1016/j.jclepro.2022.132293

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Borucki, C., & Karaca, F. (2022). Performance assessment of construction companies for the circular economy: A balanced scorecard approach. *Sustainable Production and Consumption*, *33*, 991-1004. https://doi.org/10.1016/j.spc.2022.08.021

Uhrenholt, J. N., Kristensen, J. H., Rincón, M. C., Adamsen, S., Jensen, S. F., & Waehrens, B. V. (2022). Maturity model as a driver for circular economy transformation. *Sustainability*, *14*(12), 14127483. https://doi.org/10.3390/su14127483

van Steenbergen, M., Bos, R., Brinkkemper, S., van de Weerd, I., & Bekkers, W. (2010). The design of focus area maturity models. In R. Winter, J. L. Zhao & S. Aier (Eds.), *Global perspectives on design science research* (317-332). Springer. https://share.google/CKDlmlnxlzGO6bsBU

Yang, Y., Wei, Z., & Zhang, Z. (2023). Stakeholder relationship in construction projects: A mixed methods review. *Buildings*, *13*(12), 3122. https://doi.org/10.3390/buildings13123122

Zhang, N., Han, Q., & de Vries, B. (2021). Building circularity assessment in the architecture, engineering, and construction industry: A new framework. *Sustainability*, *13*(22), 12466. https://doi.org/10.3390/su132212466

Zhou, B., Siddik, A. B., Zheng, G.-W., & Masukujjaman, M. (2023). Unveiling the role of green logistics management in improving smes' sustainability performance: Do circular economy practices and supply chain traceability matter?. *Systems*, *11*(4), 198. https://doi.org/10.3390/systems11040198

Wimalasuriya, S.A.L., Kulatunga, U., Munasinghe, D. and Dias, N., 2026. Applicability of artificial intelligence for improving infrastructure resilience. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H., and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 191-204. DOI: https://doi.org/10.31705/WCS.2026.15. Available from: https://ciobwcs.com/papers/

# APPLICABILITY OF ARTIFICIAL INTELLIGENCE FOR IMPROVING INFRASTRUCTURE RESILIENCE

**S.A.L. Wimalasuriya[1], U. Kulatunga[2], D. Munasinghe[3] and N. Dias[4]**

## *ABSTRACT*

*Infrastructure systems are susceptible to extreme weather events, climate change, ageing, interdependence and cyber threats, highlighting the inadequacy of conventional resilience approaches. This study aims to review and provide an integrated conceptual perspective on how artificial intelligence (AI) capabilities contribute to infrastructure resilience capacities and resilience lifecycle stages. To examine the relationship between AI capabilities and resilience characteristics, a qualitative narrative literature review was conducted following a thematic analysis. The review proposes an integrated conceptual framework linking AI technologies, AI-enabled capabilities, 4R resilience capacities, and resilience lifecycle stages. The findings imply that AI facilitates capabilities such as hazard prediction, real-time monitoring, damage detection, predictive maintenance, and optimised decision-making, supporting the core resilience capacities (4R: robustness, redundancy, resourcefulness, rapidity) to achieve different resilience lifecycle milestones, including prevention, absorption, recovery and adaptation. The findings also suggest that AI has the potential to bring a transition from conventional reactive, siloed approaches towards a more proactive, adaptive and data-driven resilience system. The findings further reveal the importance of AI integration in infrastructure planning, management, and disaster risk governance to enhance preparedness, monitoring, adaptation and decision-making. However, there are several constraints which limit AI performance in resilience, including data quality and availability, governance issues, cybersecurity risks, system interdependencies and complexity, and a lack of interdisciplinary integration. Future research must focus on ageing infrastructure systems, multi-sector interdependent infrastructure, and explainable AI approaches to enhance transparency and understanding of AI-enabled decision-making.*

***Keywords:*** *Artificial Intelligence; Infrastructure Resilience; Resilience Capacities; Resilience Lifecycle.*

[1] Postgraduate Student, Department of Building Economics, University of Moratuwa, Sri Lanka, lakmaanthony@yahoo.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Senior Scientist/Planner, National Building Research Institute (NBRI), Sri Lanka, dayan.munasinghe@nbro.gov.lk
[4] Lecturer, Humanitarian and Conflict Response Institute (HCRI), University of Manchester, United Kingdom, nuwan.dias@manchester.ac.uk

# 1. INTRODUCTION

Infrastructure systems often become vulnerable to various threats, disrupting their continuous and reliable functioning. This vulnerability arises from increasing stressors, including rapid urbanisation and ageing-induced deterioration (Val et al., 2019). In recent years, climate change has become a major driver of infrastructure vulnerability across various sectors (Zlateva & Hadjitodorov, 2022). These changing environmental conditions can reduce infrastructure performance, preventing systems from operating at the intended design capacity. (Neumann et al., 2015). The interdependence among infrastructure networks further complicates the vulnerability causing cascading failures, where disruption in one system affects multiple other sectors (Little, 2002). Together, these compounding effects increases the complexity of global infrastructure vulnerability.

Therefore, strengthening infrastructure resilience has become increasingly important to ensure the continuity of essential services, public safety and long-term sustainability. Infrastructure resilience is defined as the ability of a system to withstand, adapt and recover from various shocks and stresses whilst remaining operational (Ouyang et al., 2012; Sharma et al., 2018). The level of resilience is modelled using the cost of disruption and the duration it stays inoperable. These factors provide a basis for planning effective recovery (Pant et al., 2014). As a result, resilient infrastructure becomes a contributor for economic stability as well. Moreover, resilience has an interdependent relationship with sustainability. Resilience supports infrastructure to maintain continuous functioning and recovery during and after disruptions, while sustainability, ensures that resources are efficiently used with reduced environmental impact (Trejo & Gardoni, 2023).

There are challenges associated with the existing methods used in infrastructure resilience despite its growing demand and importance. Existing research focuses mostly on technical optimizations and discusses less on interdependent infrastructure systems and the strategies to enhance their resilience (Chang et al., 2014; Tong et al., 2025). Current resilience assessments depend on expert opinions, where the quality of results is affected by the subjective experience and their attitude (Bi et al., 2023). Additionally, the existing resilience assessments also rely on the static characteristics of physical systems, while disregarding their dynamic behaviour (Bi et al., 2023). Furthermore, it is highlighted that the resilience models consider resource allocation less frequently, affecting the overall performance of the system during compounding and cascading disaster events (Wells et al., 2022). Infrastructure retrofitting has often been neglected despite the significant societal benefits it offers. This is largely due to its perceived lack of cost-effectiveness and the limited direct benefits it provides to individual organisations (Chang et al., 2014). Consequently, not having a clear definition of resilience has constrained the understanding and meaningful application of it (Bi et al., 2023).

As a response to these limitations, in recent years, artificial intelligence (AI) and machine learning (ML) have emerged as popular transformative tools with the potential to redefine infrastructure resilience approaches. These technologies can process large datasets to identify patterns, predict failures and support decisions for optimized restoration of services (Afolabi et al., 2025). Unlike conventional techniques, AI and ML enable real-time analysis of data, creating a dynamic environment (Afolabi et al., 2025). AI and ML technologies also enhance resilience by supporting optimized decision-making and reducing socioeconomic losses (Alkhaleel, 2024). This is achieved through the identification and analysis of data patterns using ML enabled modelling. Moreover, these

tools allow proactive decision making and response by recognizing unusual patterns, predicting system response and alerting operators in a timely manner (Alkhaleel, 2024). The integration of AI with digital twin, which are real-time digital replicas of physical systems, can further strengthen continuous monitoring, detection and response (Afolabi et al., 2025).

Accordingly, the focus of this study is on reviewing the applicability of AI in infrastructure resilience to understand how AI tools and techniques support resilience capacities and lifecycle stages to overcome the challenges in conventional methods. Existing studies are mainly built on separate AI applications, address individual resilience capacities, or focus only on a particular infrastructure sector. There is limited understanding of how AI capabilities collectively support infrastructure resilience capacities and lifecycle stages within an integrated infrastructure resilience framework. The paper is structured as follows: first, the research methodology adopted for the study is presented. This is followed by the literature review, a thematic discussion, and the key findings.

## 2. METHODOLOGY

This study adopts a qualitative research approach, grounded in a comprehensive narrative literature review to examine the intersection between infrastructure resilience and AI. Relevant literature was carefully identified from peer-reviewed journal articles and conference proceedings to ensure both academic rigor and inclusion of emerging developments in the field. The literature search was conducted using two primary databases, Scopus and Google Scholar. The search process primarily gathered studies published between 2015 and 2026, while several earlier publications were used for the foundational concepts. An iterative search strategy was used where search terms were refined according to the themes emerged during the search process. Representative search terms are “AI infrastructure resilience”, “critical infrastructure resilience”, “infrastructure vulnerability”, “interdependent infrastructure systems”, “infrastructure resilience lifecycle”, “4R framework”, “cascading failures”, “structural health monitoring”, “infrastructure resilience framework” and “predictive maintenance”. Where appropriate, Boolean operator ‘AND’ was used for search term combinations. The selection process involved screening titles, abstracts, and full texts where necessary to ensure relevance to the research aim, prioritizing the studies based on relevance and recency, with particular attention given to studies addressing resilience characteristics and AI capabilities. The inclusion criteria considered publications related to resilience capacities, infrastructure vulnerability, resilience lifecycle stages and AI capabilities, including predictive analytics, real-time monitoring, damage detection and decision support systems. Studies unrelated to infrastructure resilience, non-English publications and duplicate publications were excluded from the literature review process. Initially, a pool of 183 records were identified. After screening titles and abstracts to remove duplicate and unrelated studies, 87 were reviewed. Ultimately, 49 core studies were selected for the final synthesis. The collected literature was then critically analysed and synthesised using a thematic approach to identify focused areas of the study, thereby providing a structured categorisation of the literature into five key themes, including infrastructure systems and their vulnerabilities, characteristics of resilience, conventional methods of ensuring infrastructure resilience and limitations, applications of AI enhancing infrastructure resilience and challenges and limitations of AI in infrastructure resilience.

# 3. LITERATURE REVIEW

## 3.1 INFRASTRUCTURE SYSTEMS AND THEIR VULNERABILITIES

Infrastructure systems are interdependent networks that improve economic stability and societal well-being (Rinaldi et al., 2001). These systems comprise both physical assets—such as transportation networks, energy supply systems, water and sanitation facilities, and communication networks, as well as the organizational and institutional frameworks required for their operation, management, and maintenance. The interdependency and interconnectedness of modern infrastructure systems lead to system vulnerability, as it has become difficult to isolate an individual infrastructure system when seeking solutions after disruptions (Jayasinghe et al., 2023). Interdependencies are classified into four principal types, physical (material or physical flow from one entity to another), cyber (transfer of information), geographic (physical proximity affecting components across multiple infrastructure systems) and logical (dependencies other than the above three categories). This indicates that there are multiple pathways for a disruption to occur (Jayasinghe et al., 2023; Rinaldi et al., 2001). Therefore, the functionality of interdependent infrastructure systems depends on the strength and stability of the connections between them (Mottahedi et al., 2021). However, the interdependency also increases vulnerability, since a failure in one system can trigger cascading impacts across the entire network. A prominent historical example occurred in 2011, when the Tohoku earthquake and tsunami in Japan damaged energy infrastructure, leaving 4.4 million households without electricity. This cascaded into water systems as well, affecting 1.5 million consumers without safe drinking water (Mottahedi et al., 2021). However, as shown by Jayasinghe et al. (2023), most research has focused on the bilateral relationship between infrastructure systems and has neglected the multi-directional dependence among them. Thus, in complex urban network systems, such approaches cannot fully capture the scale and dynamics of cascading effects. Importantly, the conventional silo-based approach used for infrastructure planning, design and operation is inadequate to achieve resilience and sustainability (Jayasinghe et al., 2023) in modern dynamic, and interdependent infrastructure systems.

The performance of infrastructure systems is affected by changing climatic conditions. Extreme events trigger floods, droughts and heatwaves, which may reduce the electricity generation and lead to cascading failures (Val et al., 2019). Although most research focuses on climate hazards, another important issue is the physical deterioration of infrastructure over time. However, the structural state due to ageing-related deterioration is often neglected in resilience assessment frameworks. Studies on seismic resilience of ageing bridges subjected to severe environmental conditions have reported a 52.64% reduction in resilience (Forcellini & Mitoulis, 2025). More recently, compounding threats, where two or more hazards occur simultaneously, have gained attention due to their impact on interdependent infrastructure systems. Yet, questions remain on how current models assess infrastructure resilience under such compounding threats (Wells et al., 2022).

Cyber-attacks can further complicate the infrastructure vulnerability, causing direct physical infrastructure degradation. As stated by Stellios et al. (2018), the Stuxnet attack in 2010 was a computer worm targeting Iran's nuclear program. It infected many industrial control systems and physically degraded approximately 1000 machines. Similarly, the Aurora attack in 2009 caused the circuit breakers to open and close at a fast

rate, disrupting the operation of electric power generators that lead to physical damage. As a result of the increasing interdependency between cyber and physical networks, infrastructure becomes more vulnerable to both natural and man-made attacks (Islam et al., 2023).

## 3.2 CHARACTERISTICS OF RESILIENCE

The growing vulnerabilities of infrastructure highlight the importance of understanding resilience, a concept still with unclear and diverse theoretical foundations across different disciplines and perspectives. Bruneau et al. (2003) provide a definition for community seismic resilience from a functional and social perspective. It is viewed as the ability of systems and communities to mitigate hazards, absorb them and recover effectively to reduce social and economic impacts while limiting future risks. From a broader and more comprehensive perspective, resilience is a quality that controls vulnerability to threats, improving response and recovery, whilst enabling adaptation to disruptive events (Rehak et al., 2018). However, infrastructure resilience is often misapplied and overused in safety management concepts such as risk, reliability, robustness and vulnerability, where existing methods are merely relabelled as resilience (Bi et al., 2023a). Thus, existing methods, often lack strategies for recovery and adaptation after failure. Therefore, carrying out pre- and post-disaster planning with inadequate boundaries and scope can lead to insufficient and ineffective results, especially when using new concepts such as technological infrastructure resilience (Mottahedi et al., 2021).

Despite the many different definitions, there is some agreement across studies on four key resilience capacities. Bruneau et al. (2003) introduced the '4R' concept, which consists of robustness, redundancy, resourcefulness and rapidity as the key properties for physical and social resilience systems. Robustness is the ability to withstand stress without the loss of function, redundancy is the extent to which the systems and units are substitutable, resourcefulness is the capacity to identify problems, prioritize them and use resources efficiently. Rapidity is the ability to achieve recovery in a timely manner while preventing future disruption (Bruneau et al., 2003). Despite the wide use of 4R across studies, the framework faces most of the same limitations as existing resilience assessments. It often neglects the role of society (Mottahedi et al., 2021), and the challenges faced in quantifying resilience metrics, which can affect the accuracy of decision making (Mehvar et al., 2021).

The operation of the 4R capacities is explained in frameworks that view infrastructure resilience as a cyclic process. They propose a similar structure consisting of pre-event prevention, absorption, recovery and adaptation to enable the continual improvement of resilience (Ouyang et al., 2012; Rehak et al., 2018). Prevention is part of preparedness and refers to measures taken to resist potential impacts. Absorption is determined by robustness, which is the ability to absorb disruptive events without causing disturbance to services. Recovery is the ability to return to the original state and is governed by the available resources. Adaptation is the potential to withstand the recurrence of disruptive event (Rehak et al., 2018). When integrating these structured stages, important practical and conceptual challenges arise. Over time, resilience studies have evolved from a "bounce back" to a "bounce forward" approach. Bruneau et al. (2003) define rapidity as a step taken to recover and return to the original state upon disruption. In contrast, more recent studies emphasize transformative resilience which supports absorption, recovery and a bounce forward approach (Zhao et al., 2026). Another issue is the theory- practice

gap, which is amplified by the lack of quantifiable resilience metrics (Mehvar et al., 2021). Similarly, many frameworks and principles are difficult to apply to practical scenarios due to the heavy theoretical nature (Labaka et al., 2016).

### 3.3 CONVENTIONAL METHODS OF ENSURING RESILIENCE OF INFRASTRUCTURE AND THEIR LIMITATIONS

One of the most common conventional approaches to improving infrastructure resilience is engineering design that achieves robustness and redundancy. Robustness allows the system to stay operational even during failure events (Bi et al., 2023), while redundancy brings backup components that support robustness (Bruneau et al., 2003). In practice, this is achieved through a notional infrastructure system with N-1 reliablility (a conceptual modelling used for system reliability, where N denotes the total number of components), where the loss of a single link does not interrupt the operation of other nodes in the network (Alderson et al., 2015). As a result, additional components and safety subsystems are implemented into the system (Labaka et al., 2016).

Another dominant approach is hazard-based risk assessment. This assumes that disruptions are from identifiable causes that can be eliminated or neutralized (Bi et al., 2023). To measure the risk associated with non-deliberate hazards, probabilistic risk analysis is widely used. It considers possible future scenarios, assigns probabilities and estimates their consequences (Alderson et al., 2015). Life-cycle management approaches can be used in three categories, condition-based Markov decision processes, reliability- and risk-based life-cycle management and renewal theory-based life-cycle cost models. These require intervention actions such as inspection, maintenance, repair and replacement during their design service life (Yang & Frangopol, 2019).

Despite the effectiveness of these methods, limitations can be seen due to their static, hazard-specific nature and their limited consideration of interdependent systems. Oversimplified disruption scenarios and the use of random failures to simulate disruptions are common across studies. Such approaches assume that all nodes face the same level of failure probability and successive failures. It is unfavourable in understanding location-specific hazard effects such as flooding (Bi et al., 2023). Moreover, the regulatory structure in most countries is based on a ’siloed’ approach that focuses on individual systems, with minimal consideration on interdependence among them (Val et al., 2019). This can lead to cascading failures and unexpected disruptions across infrastructure systems. For instance, the Northeast blackout in 2003 was caused by a local software failure, which resulted in power outages, approximately affecting 50 million people (Bi et al., 2023). Modelling these cascading failures remains complex due to the scale of infrastructure systems and the lack of suitable benchmark studies for comparisons (Val et al., 2019).

A lack of adaptability and uncertainty is another limitation in conventional ex-post analysis approaches, where dynamic system behaviour is difficult to capture, particularly in climate change adaptation context (Mostafavi, 2018). Similarly, the growing digitalization, expose infrastructure systems to new risks, and increase interdependence. This makes them liable to cyber threats that are not addressed within conventional resilience frameworks (Osei-Kyei et al., 2021; Rathnayaka et al., 2022). Additionally, studies have shown that, severe deterioration significantly reduces the resilience performance within a few decades. Hence, the deterioration is neglected in resilience modelling (Forcellini & Mitoulis, 2025).

### 3.4 APPLICATIONS OF AI IN ENHANCING INFRASTRUCTURE RESILIENCE

This section covers the applicability of AI across five sectors that assist in improving infrastructure resilience, hazard prediction, monitoring, predictive maintenance, disaster response, recovery and adaptive systems. These represent key stages of the resilience lifecycle, including, prevention, absorption, recovery and adaptation (Ouyang et al., 2012; Rehak et al., 2018).

Hazard prediction and risk assessment have improved with the emergence of machine learning techniques. Particularly because AI identify and analyse complex, non-linear hazard patterns. In the context of risks associated with extreme weather events, AI can analyse historical climate data and real-time weather information to predict extreme rainfall events. This supports the planning and designing of infrastructure systems (Habib et al., 2024) by strengthening the proactive preparedness and prevention strategies. In flood assessments, Advanced Decision Tree models have shown significant predictive potential, compared with conventional models such as Frequency Ratio, Weights-of-Evidence and Analytical Hierarchy Process. However, they have limited ability to capture temporal variations (Khosravi et al., 2018), indicating the challenges AI models still face under dynamic environmental conditions. Similarly, in seismic hazard assessments, the integration of Internet of Things (IoT) and AI improves preparedness and early warning, through real-time data collection and analysis. This reduces the potential damage to infrastructure systems (Rosca & Stancu, 2024). These advancements demonstrate the emerging paradigm shift from conventional reactive approaches to proactive monitoring and risk management.

Continuous monitoring and automated observation of structures have become more efficient and accurate with the current advancements in AI, particularly due to its capability to process large datasets under minimal human involvement. In structural health monitoring, AI approaches such as machine learning, deep learning, and artificial neural networks analyse vast amounts of data to support data processing, damage detection and predictive maintenance. Furthermore, these approaches identify critical regions for optimal sensor placement to monitor the structural behaviour (Plevris & Papazafeiropoulos, 2024). This improves the speed and accuracy of infrastructure condition assessments, optimizing the monitoring efficiency and resource utilization. AI and IoT sensor systems support in proactive detection of infrastructure issues requiring maintenance, reducing response time compared with manual processes (Forkan et al., 2024). This supports the adaptive resilience and infrastructure management. Additionally, using deep learning with remote sensing broaden the field by allowing a wider spatial observation of infrastructure (Zhu et al., 2017). Although machine learning techniques using sensor data are widely used across studies, deep learning-based monitoring shows stronger performance, particularly in image-based damage detection (Plevris & Papazafeiropoulos, 2024; Zhu et al., 2017).

AI uses real-time and historical data for predictive maintenance analysis. In railway infrastructure, it is used to identify degradation trends and supports maintenance decision-making processes. Such efficient planning and reduced interventions lead to a greater system stability (Bris-Peñalver et al., 2026). Compared to degradation trend-based models, a more effective technique can be seen in water distribution networks. To identify water pipe deteriorations, artificial neural networks are widely studied due to its ability to cope with nonlinear relationships and uncertainty (Dawood et al., 2020). In addition,

machine learning algorithms are promising for early detection of leaks and bursts in pipelines (Joseph et al., 2024). Unlike degradation and deterioration focused predictive maintenance models, anomaly detection models support faster identification and response, reducing the service disruptions.

AI has also enhanced the effectiveness of disaster response and recovery activities compared with conventional manual techniques. In damage assessment, AI-driven Geographic Information System (GIS) platforms automate the analysis of satellite and drone imagery for efficient and accurate damage detection. Similarly, machine learning and computer vision techniques use semantic segmentation, a pixel-based image classification, to rapidly assess the condition of damaged infrastructure (Kopiika et al., 2025). Deep learning-based frameworks such as ChangeOS demonstrate higher speed and accuracy in automated post-disaster damage assessments. This is done using remote sensing images and detecting semantic changes (Zheng et al., 2021). Therefore, deep learning techniques demonstrate strong potential for complex large-scale image analysis in post-disaster damage assessment. Following damage identification, reinforcement learning supports adaptive, sequential decision-making under dynamic, uncertain disaster environments. This facilitates optimized resource allocation and rescue operations during disaster relief activities (Xu et al., 2025).

Recent studies also highlight for the role of AI in adaptive and smart infrastructure systems for long-term resilience. Among them, AI-enabled smart grids optimise urban energy systems by managing the supply and demand in real-time (Almulhim, 2025). This becomes useful in improving operational and energy management in highly interconnected systems. Extending this, AI integrated digital twin systems enables adaptation to dynamic conditions through continuous monitoring, automated damage detection, dynamic hazard modelling and adaptive responses (Afolabi et al., 2025; Argyroudis et al., 2022). Unlike conventional static approaches, digital twin allows continuously updating system behaviour under changing environmental and operational conditions. However, implementation challenges such as data requirement, scalability and computational complexity exist in different scales.

### 3.5 CHALLENGES AND LIMITATIONS OF AI IN INFRASTRUCTURE RESILIENCE

Despite the capabilities AI provides, several interconnected challenges exist when incorporating AI for infrastructure resilience. Many studies highlight data quality and availability as a main constraint. Alkhaleel (2024) states that modelling complexity increases in interdependent systems when incomplete and uncertainty of data exists. Such issues arise when failure data goes unrecorded or unreported due to perceived insignificance or liability concerns (Val et al., 2019). In addition, Mostafavi (2018) claims that the complex adaptive behaviours and uncertainty of infrastructure systems, may pose challenges when AI-based models accurately represent real-world system behaviour. Weak governance further compounds the effective use of AI. The rapid growth of AI has surpassed regulatory frameworks, leading to governance uncertainties. Particularly, in AI-driven decision-making, there is lack of defined rules regarding responsibility (Androutsopoulou et al., 2025). This limits trust and creates barriers to AI implementation. Similarly, the lack of reporting of AI-related incidents constraints the use of such information for future learning (Agarwal & Nene, 2024). This can lead to repetitive occurrence of such issues. Moreover, AI with IoT increases cybersecurity risks,

creating new vulnerabilities. For example, the attackers can manipulate input data, misleading AI models, causing inaccuracy in decision-making (Bonsu & Akekudaga, 2025).

Infrastructure resilience decisions require an interdisciplinary understanding of various sectors. Therefore, machine learning alone is insufficient to maintain such integrations. AI models often lack contextual knowledge required to represent the real-world scenarios. This requires expertise from a variety of disciplines to ensure that the AI model is tailored to the specific context (Ghaffarian et al., 2023). These challenges may become severe in the developing regions, where policy frameworks have not evolved with growing digitalization. In such environments, limited financial resources and technical skills further intensify the issue, slowing the progress and limiting the AI-based systems effectiveness (Ndiaye et al., 2025).

## 4. DISCUSSION

The conceptual framework illustrated in Figure 1 presents how AI technologies support infrastructure resilience through a sequential and interconnected process.

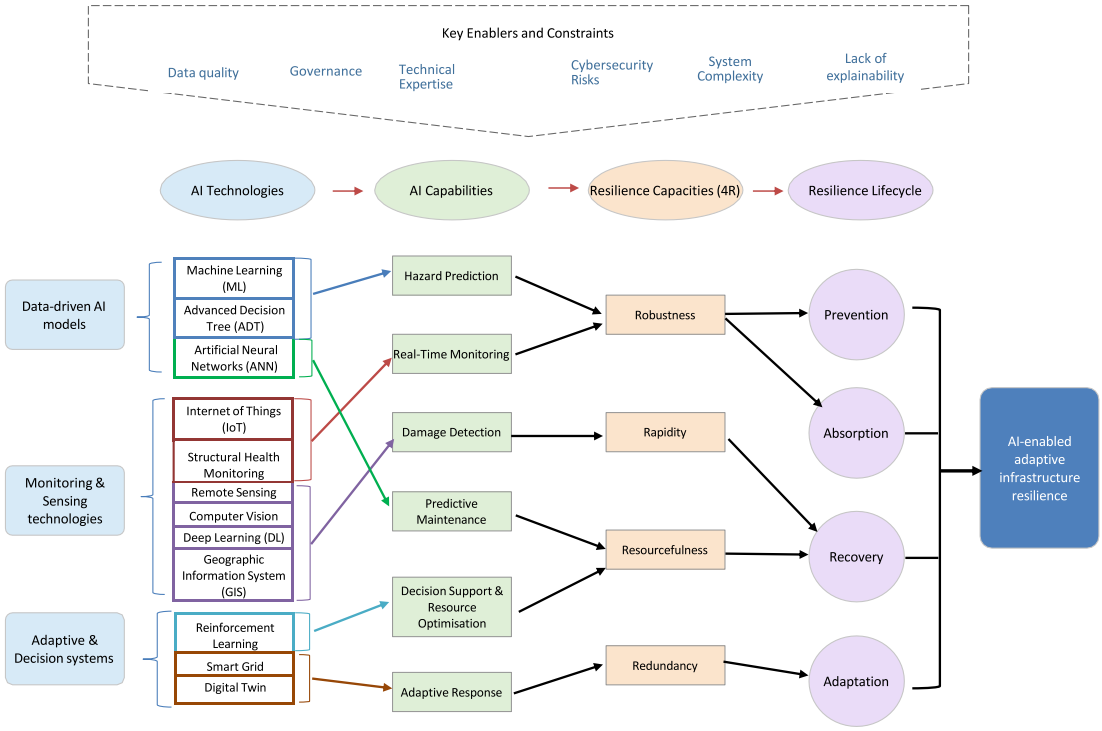



*Figure 1: Conceptual framework for AI-enabled infrastructure resilience*

The identified AI technologies were categorised based on their function, into data-driven AI models, monitoring and sensing technologies, and adaptive and decision systems. Collectively, these technologies enable six AI capabilities including hazard prediction, predictive maintenance, real-time monitoring, damage detection, decision support and resource optimisation, and adaptive response. These capabilities enhance 4R resilience capacities to achieve milestones across resilience lifecycle stages. The framework enables dynamic, adaptive, real-time resilience system compared to static, silo-based, hazard-specific conventional resilience approaches (Bi et al., 2023; Val et al., 2019).

The initial stages of the resilience lifecycle, prevention and absorption are primarily driven by the robustness of the system. As shown in figure 1, hazard prediction and real-time monitoring enhance the robustness by improving the system ability to withstand stress without a loss of function. In hazard prediction, machine learning and advanced decision tree models identify complex non-linear hazard patterns and deterioration trends (Bris-Peñalver et al., 2026; Habib et al., 2024; Khosravi et al., 2018), allowing proactive preparedness and prevention. This improves robustness allowing the system to prevent impacts before they occur and absorb disruptive events with less service interruptions (Ouyang et al., 2012; Rehak et al., 2018). Similarly, IoT and sensing technologies enable real-time monitoring, facilitating continuous situational awareness and identifies operational risks with minimal human involvement (Forkan et al., 2024; Plevris & Papazafeiropoulos, 2024; Zhu et al., 2017). This strengthens robustness by preventing cascading failures through early intervention and ensures that system absorb shocks through real-time system performance awareness.

The recovery stage is primarily supported by the resilience capacities of rapidity and resourcefulness. Figure 1 links damage detection to rapidity, which is the ability to achieve the timely recovery. This is achieved by reducing response time as a result of early identification of operational risks. For such identifications, deep learning, computer vision, remote sensing and AI-driven geographic information systems enable rapid, pixel-based assessment of damage using satellite and drone images (Kopiika et al., 2025; Zheng et al., 2021). Predictive maintenance and decision support and resource optimisation improve resourcefulness. Artificial neural networks help identify degradation trends and reinforcement learning enables organized decision-making under uncertain conditions (Dawood et al., 2020; Xu et al., 2025). These help to optimize resource allocation and maintenance planning.

The final stage of the lifecycle, adaptation, involves a “bounce forward” approach. Adaptation is the ability of infrastructure to withstand shocks in the future disruptive events (Rehak et al., 2018). This is supported by the adaptive response capability, which enables the redundancy. This can be achieved by smart grids and digital twins as they help manage supply and demand in real-time while adapting the system to changing operational and environmental conditions (Afolabi et al., 2025; Almulhim, 2025; Argyroudis et al., 2022). This reduces service interruptions and improves operational flexibility.

The reviewed literature also indicates a shift in infrastructure resilience, moving from “bounce-back” model toward an AI-enabled “bounce-forward” approach. AI supports transformative resilience through continuous learning, real-time analysis and proactive decision-making. This is particularly beneficial in highly interdependent systems where conventional approaches fail to capture cascading risks (Mottahedi et al., 2021). However, the reliability of AI-driven systems depends on data quality, governance, cybersecurity and system complexities (Alkhaleel, 2024; Androutsopoulou et al., 2025; Bonsu & Akekudaga, 2025). Despite the increasing adaptive capacity and system efficiency, digitalized infrastructure also becomes vulnerable to cyber threats and cascading risks due to system interdependencies (Androutsopoulou et al., 2025; Bonsu & Akekudaga, 2025; Islam et al., 2023; Stellios et al., 2018). Moreover, highly complex digitalized infrastructure may reduce transparency in decision-making (Ghaffarian et al., 2023; Alkhaleel, 2024) and requires interdisciplinary technical expertise and explainable AI for effective implementation (Androutsopoulou et al., 2025; Ghaffarian et al., 2023;

Ndiaye et al., 2025). Therefore, although AI shows greater potential for enabling proactive and resilience, its technological capabilities alone are insufficient for its successful implementation.

The findings highlight the importance of AI technologies in integrated infrastructure resilience planning, disaster risk governance processes and infrastructure management (Androutsopoulou et al., 2025; Argyroudis et al., 2022; Val et al., 2019). AI technologies have significant value when incorporated throughout the entire resilience lifecycle, rather than being limited to the recovery stage. This has the potential to create more integrated, adaptive infrastructure resilience systems capable of handling complex environmental, institutional and operational uncertainties (Argyroudis et al., 2022; Mostafavi, 2018). The review further indicates that AI applications are mature in disaster damage assessment, transportation and energy infrastructures. In contrast, ageing infrastructure and cross-sector infrastructure networks are underexplored, highlighting the need for future research.

## 5. CONCLUSIONS

The study reviews current literature to understand the applicability of AI in enhancing the resilience of infrastructure systems. The findings indicate that AI technologies bring strong potential to data-driven, dynamic, adaptive decision-making processes, which can be used to improve infrastructure resilience. The proposed framework demonstrates how AI capabilities such as hazard prediction, real-time monitoring, damage detection, predictive maintenance, and decision support link with 4R resilience capacities and resilience lifecycle, including prevention, absorption, recovery, and adaptation. The identified AI capabilities support continuous monitoring, predictive analysis, adaptive response, and decision-making, under dynamic environmental and operational conditions and uncertainties. Thus, AI tools facilitate both “bounce back” and “bounce forward”, addressing the conventional silo-based techniques by marking a transition in resilience paradigm. In practice, integration of AI technologies into infrastructure planning, management, and governance processes can advance and optimize preparedness, monitoring, adaptive resilience, and decision-making across the entire resilience lifecycle, rather than limiting them only to the conventional recovery stage. However, the performance of these AI models depends on the data quality, governance issues, cybersecurity risks, system complexities and resource limitations. Incorporating governance frameworks, strengthening cybersecurity, maintaining data quality and availability and understanding the system interconnectedness are essential to implement AI in infrastructure resilience successfully. Future research should examine AI-assisted resilience frameworks while addressing governance, cybersecurity, and data quality challenges. More attention is also needed in AI behaviour on ageing infrastructure and interdependent cross-sector systems, and on approaches such as explainable AI, to improve the transparency and AI-driven decision-making understanding.

## 6. REFERENCES

Afolabi, A., Ogunrinde, O., & Zabihollah, A. (2025). Digital twin and AI models for infrastructure resilience: A Systematic Knowledge Mapping. *Applied Sciences*, *15*(24). https://doi.org/10.3390/app152413135

Agarwal, A., & Nene, M. J. (2024). Addressing AI risks in critical infrastructure: Formalising the AI incident reporting process. In *Proceedings of the 2024 10th IEEE international conference on*

*electronics, computing and communication technologies (CONECCT)*. https://doi.org/10.1109/CONECCT62155.2024.10677312

Alderson, D. L., Brown, G. G., & Carlyle, W. M. (2015). Operational models of infrastructure resilience. *Risk Analysis, 35*(4), 562–586. https://doi.org/10.1111/risa.12333

Alkhaleel, B. A. (2024). Machine learning applications in the resilience of interdependent critical infrastructure systems: A systematic literature review. *International Journal of Critical Infrastructure Protection, 44*, 100646. https://doi.org/10.1016/j.ijcip.2023.100646

Almulhim, A. I. (2025). Integrating artificial intelligence into smart infrastructure management for sustainable urban planning. *Technologies, 13*(11). https://doi.org/10.3390/technologies13110481

Androutsopoulou, M., Carayannis, E. G., Askounis, D., & Zotas, N. (2025). Towards AI-enabled cyber-physical infrastructures—Challenges, opportunities, and implications for a data-driven eGovernment theory, policy, and practice. *Journal of the Knowledge Economy*. https://doi.org/10.1007/s13132-025-02726-5

Argyroudis, S. A., Mitoulis, S. A., Chatzi, E., Baker, J. W., Brilakis, I., Gkoumas, K., Vousdoukas, M., Hynes, W., Carluccio, S., Keou, O., Frangopol, D. M., & Linkov, I. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management, 35*, 100387. https://doi.org/10.1016/j.crm.2021.100387

Bi, W., MacAskill, K., & Schooling, J. (2023). Old wine in new bottles? Understanding infrastructure resilience: Foundations, assessment, and limitations. *Transportation Research Part D: Transport and Environment, 120*, 103793. https://doi.org/10.1016/j.trd.2023.103793

Bonsu, M. A., & Akekudaga, P. (2025). Enhancing critical infrastructure security: Addressing cybersecurity risks and regulatory gaps in AI-enabled IoT systems. In *Proceedings of the UEMCON 2025 IEEE annual ubiquitous computing, electronics & mobile communication conference* (pp. 627–633). https://doi.org/10.1109/uemcon67449.2025.11267559

Bris-Peñalver, F. J., Verdecia-Peña, R., & Alonso, J. I. (2026). A survey of AI-enabled predictive maintenance for railway infrastructure: Models, data sources, and research challenges. *Sensors, 26*(3). https://doi.org/10.3390/s26030906

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra, 19*(4), 733–752. https://doi.org/10.1193/1.1623497.

Chang, S. E., Mcdaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2014). Toward disaster-resilient cities: Characterizing resilience of infrastructure systems with expert judgments. *Risk Analysis, 34*(3), 416–434. https://doi.org/10.1111/risa.12133

Dawood, T., Elwakil, E., Novoa, H. M., & Delgado, J. F. G. (2020). Artificial intelligence for the modeling of water pipes deterioration mechanisms. *Automation in Construction, 120*, 103398. https://doi.org/10.1016/j.autcon.2020.103398

Forcellini, D., & Mitoulis, S. A. (2025). Effect of deterioration on critical infrastructure resilience—Framework and application on bridges. *Results in Engineering, 25*, 103834. https://doi.org/10.1016/j.rineng.2024.103834

Forkan, A. R. M., Kang, Y. Bin, Marti, F., Banerjee, A., McCarthy, C., Ghaderi, H., Costa, B., Dawod, A., Georgakopolous, D., & Jayaraman, P. P. (2024). AIoT-CitySense: AI and IoT-driven city-scale sensing for roadside infrastructure maintenance. *Data Science and Engineering, 9*(1), 26–40. https://doi.org/10.1007/s41019-023-00236-5

Ghaffarian, S., Taghikhah, F. R., & Maier, H. R. (2023). Explainable artificial intelligence in disaster risk management: Achievements and prospective futures. *International Journal of Disaster Risk Reduction, 98*, 104123. https://doi.org/10.1016/j.ijdrr.2023.104123

Habib, M., Habib, A., Albzaie, M., & Farghal, A. (2024). Sustainability benefits of AI-based engineering solutions for infrastructure resilience in arid regions against extreme rainfall events. *Discover Sustainability, 5*(1). https://doi.org/10.1007/s43621-024-00500-2

Islam, M. Z., Lin, Y., Vokkarane, V. M., & Venkataramanan, V. (2023). Cyber-physical cascading failure and resilience of power grid: A comprehensive review. *Frontiers in Energy Research, 11*. https://doi.org/10.3389/fenrg.2023.1095303

Jayasinghe, P. A., Derrible, S., & Kattan, L. (2023). Interdependencies between urban transport, water, and solid waste infrastructure systems. *Infrastructures, 8*(4). https://doi.org/10.3390/infrastructures8040076

Joseph, K., Shetty, J., Sharma, A. K., van Staden, R., Wasantha, P. L. P., Small, S., & Bennett, N. (2024). Leak and burst detection in water distribution network using logic- and machine learning-based approaches. *Water, 16*(14). https://doi.org/10.3390/w16141935

Khosravi, K., Pham, B. T., Chapi, K., Shirzadi, A., Shahabi, H., Revhaug, I., Prakash, I., & Tien Bui, D. (2018). A comparative assessment of decision trees algorithms for flash flood susceptibility modeling at Haraz watershed, northern Iran. *Science of the Total Environment, 627*, 744–755. https://doi.org/10.1016/j.scitotenv.2018.01.266

Kopiika, N., Karavias, A., Krassakis, P., Ye, Z., Ninic, J., Shakhovska, N., Argyroudis, S., & Mitoulis, S. A. (2025). Rapid post-disaster infrastructure damage characterisation using remote sensing and deep learning technologies: A tiered approach. *Automation in Construction, 170*, 105955. https://doi.org/10.1016/j.autcon.2024.105955

Labaka, L., Hernantes, J., & Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change, 103*, 21–33. https://doi.org/10.1016/j.techfore.2015.11.005

Little, R. G. (2010). Controlling cascading failure: Understanding the vulnerabilities of interconnected infrastructures. *Journal of Urban Technology, 9*(1), 109–123. https://doi.org/10.1080/106307302317379855

Mehvar, S., Wijnberg, K., Borsje, B., Kerle, N., Maarten Schraagen, J., Vinke-De Kruijf, J., Geurs, K., Hartmann, A., Hogeboom, R., & Hulscher, S. (2021). Review article: Towards resilient vital infrastructure systems—Challenges, opportunities, and future research agenda. *Natural Hazards and Earth System Sciences, 21*(5), 1383–1407. https://doi.org/10.5194/nhess-21-1383-2021

Mostafavi, A. (2018). A system-of-systems framework for exploratory analysis of climate change impacts on civil infrastructure resilience. *Sustainable and Resilient Infrastructure, 3*(4), 175–192. https://doi.org/10.1080/23789689.2017.1416845

Mottahedi, A., Sereshki, F., Ataei, M., Qarahasanlou, A. N., & Barabadi, A. (2021). The resilience of critical infrastructure systems: A systematic literature review. *Energies, 14*(6). https://doi.org/10.3390/en14061571

Ndiaye, S., Diop, I., Faye, D., & Dione, D. (2025). Critical infrastructures security in developing countries: Survey and challenges. In *2025 international conference on circuit, systems and communication (ICCSC 2025)*. https://doi.org/10.1109/ICCSC66714.2025.11134923

Neumann, J. E., Price, J., Chinowsky, P., Wright, L., Ludwig, L., Streeter, R., Jones, R., Smith, J. B., Perkins, W., Jantarasami, L., & Martinich, J. (2015). Climate change risks to US infrastructure: Impacts on roads, bridges, coastal development, and urban drainage. https://doi.org/10.1007/s10584-013-1037-4

Osei-Kyei, R., Tam, V., Ma, M., & Mashiri, F. (2021). Critical review of the threats affecting the building of critical infrastructure resilience. *International Journal of Disaster Risk Reduction, 60*, 102316. https://doi.org/10.1016/j.ijdrr.2021.102316

Ouyang, M., Dueñas-Osorio, L., & Min, X. (2012). A three-stage resilience analysis framework for urban infrastructure systems. *Structural Safety, 36–37*, 23–31. https://doi.org/10.1016/j.strusafe.2011.12.004

Pant, R., Barker, K., & Zobel, C. W. (2014). Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. *Reliability Engineering and System Safety, 125*, 92–102. https://doi.org/10.1016/j.ress.2013.09.007

Plevris, V., & Papazafeiropoulos, G. (2024). AI in structural health monitoring for infrastructure maintenance and safety. *Infrastructures, 9*(12). https://doi.org/10.3390/infrastructures9120225

Rathnayaka, B., Siriwardana, C., Robert, D., Amaratunga, D., & Setunge, S. (2022). Improving the resilience of critical infrastructures: Evidence-based insights from a systematic literature review. *International Journal of Disaster Risk Reduction, 78*, 103123. https://doi.org/10.1016/j.ijdrr.2022.103123

Rehak, D., Senovsky, P., & Slivkova, S. (2018). Resilience of critical infrastructure elements and its main factors. *Systems, 6*(2). https://doi.org/10.3390/systems6020021

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine, 21*(6), 11–25. https://doi.org/10.1109/37.969131

Rosca, C. M., & Stancu, A. (2024). Earthquake prediction and alert system using IoT infrastructure and cloud-based environmental data analysis. *Applied Sciences, 14*(22). https://doi.org/10.3390/app142210169

Sharma, N., Tabandeh, A., & Gardoni, P. (2018). Resilience analysis: A mathematical formulation to model resilience of engineering systems. *Sustainable and Resilient Infrastructure, 3*(2), 49–67. https://doi.org/10.1080/23789689.2017.1345257

Stellios, I., Kotzanikolaou, P., Psarakis, M., Alcaraz, C., & Lopez, J. (2018). A survey of IoT-enabled cyberattacks: Assessing attack paths to critical infrastructures and services. *IEEE Communications Surveys and Tutorials, 20*(4), 3453–3495. https://doi.org/10.1109/COMST.2018.2855563

Tong, W., Li, H. X., Nasirzadeh, F., Yao, F., & Ji, Y. (2025). Resilience of interdependent infrastructure networks: Review and future directions. *International Journal of Critical Infrastructure Protection, 51*, 100793. https://doi.org/10.1016/j.ijcip.2025.100793

Trejo, D., & Gardoni, P. (2023). Special issue on adaptive pathways for resilient infrastructure: An introduction. *Sustainable and Resilient Infrastructure, 8*(sup1), 1–2. https://doi.org/10.1080/23789689.2022.2139564

Val, D. V., Yurchenko, D., Nogal, M., & O'Connor, A. (2019). Climate change-related risks and adaptation of interdependent infrastructure systems. In *Climate adaptation engineering: Risks and economics for infrastructure decision-making* (pp. 207–242). Elsevier. https://doi.org/10.1016/B978-0-12-816782-3.00007-3

Wells, E. M., Boden, M., Tseytlin, I., & Linkov, I. (2022). Modeling critical infrastructure resilience under compounding threats: A systematic literature review. *Progress in Disaster Science, 15*, 100244. https://doi.org/10.1016/j.pdisas.2022.100244

Xu, J., Jayakumar Nair, D., & Waller, S. T. (2025). Artificial intelligence in disaster management: Achievements, challenges, and prospects. *Natural Hazards, 121*(20), 23977–24033. https://doi.org/10.1007/s11069-025-07667-5

Yang, D. Y., & Frangopol, D. M. (2019). Life-cycle management of deteriorating civil infrastructure considering resilience to lifetime hazards: A general approach based on renewal-reward processes. *Reliability Engineering and System Safety, 183*, 197–212. https://doi.org/10.1016/j.ress.2018.11.016

Zhao, R., Yang, M., Long, D., Fan, X., Zhang, Z., Duan, Y., Zhang, Z., Ye, Y., & Chen, J. (2026). The evolution of transformative resilience research topics: A data-driven analysis. *Cities, 168*, 106425. https://doi.org/10.1016/j.cities.2025.106425

Zheng, Z., Zhong, Y., Wang, J., Ma, A., & Zhang, L. (2021). Building damage assessment for rapid disaster response with a deep object-based semantic change detection framework: From natural disasters to man-made disasters. *Remote Sensing of Environment, 265*, 112636. https://doi.org/10.1016/j.rse.2021.112636

Zhu, X. X., Tuia, D., Mou, L., Xia, G. S., Zhang, L., Xu, F., & Fraundorfer, F. (2017). Deep learning in remote sensing: A comprehensive review and list of resources. *IEEE Geoscience and Remote Sensing Magazine, 5*(4), 8–36. https://doi.org/10.1109/MGRS.2017.2762307

Zlateva, P., & Hadjitodorov, S. (2022). An approach for analysis of critical infrastructure vulnerability to climate hazards. *IOP Conference Series: Earth and Environmental Science, 1094*(1). https://doi.org/10.1088/1755-1315/1094/1/012004

Pawani, N.T., Jayanetti, J.K.D.D.T. and Ranasinghe, D.P.J.D., 2026. Applicability of Autoclaved Aerated Concrete (AAC) blocks compared to conventional bricks and blocks within the Sri Lankan context In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 205-219. DOI: https://doi.org/10.31705/WCS.2026.16. Available from: https://ciobwcs.com/papers/

# APPLICABILITY OF AUTOCLAVED AERATED CONCRETE (AAC) BLOCKS COMPARED TO CONVENTIONAL BRICKS AND BLOCKS WITHIN THE SRI LANKAN CONTEXT

**N.T. Pawani[1], J.K.D.D.T. Jayanetti[2], and D.P.J.D. Ranasinghe[3]**

## *ABSTRACT*

*Autoclaved Aerated Concrete (AAC) blocks have gained increasing attention as a lightweight, energy-efficient, and sustainable alternative to conventional masonry materials. However, despite the growing demand for faster and environmentally sustainable construction practices, AAC block utilisation within the Sri Lankan construction industry remains limited due to low awareness and uncertainty regarding its applicability. Therefore, this study aims to assess the suitability of AAC blocks compared with conventional bricks and concrete blocks in terms of quality and time efficiency within the Sri Lankan context. A mixed-method research approach was adopted through a systematic literature review, questionnaire survey, and semi-structured interviews. Quantitative data were collected from 92 construction professionals using simple random sampling and analysed using Statistical Package for the Social Sciences software, while qualitative data were gathered from ten industry experts selected through purposive sampling and analysed using content analysis. The findings revealed that only 47.8% of respondents were aware of AAC blocks, indicating a considerable lack of industry awareness. Nevertheless, AAC blocks were identified as superior in terms of lightweight properties, thermal insulation, reduced labour requirements, faster construction, and environmental sustainability. Compared with conventional bricks and blocks, AAC blocks significantly reduced construction time due to their larger size, fewer joints, and absence of curing requirements. The study concludes that AAC blocks represent a viable and sustainable alternative for the Sri Lankan construction industry, although greater industry awareness is required for wider adoption.*

***Keywords:*** *Autoclaved Aerated Concrete (AAC) Blocks; Quality; Sri Lankan Construction Industry; Time.*

[1] Lecturer, Civil Engineering and Construction, Skills College of Technology (SCOT) Campus, Sri Lanka, thakshilathishara@gmail.com
[2] Assistant Professor, Quantity Surveying, Sri Lanka Institute of Information Technology,, Sri Lanka, thamasha.j@sliit.lk
[3] Post Graduate Student, Construction Management, Central Queensland University, Australia, janaka.d96@gmail.com

# 1. INTRODUCTION

The construction industry is increasingly facing challenges related to environmental sustainability, resource consumption, rising material costs, and the demand for faster construction practices. Conventional masonry materials such as red clay bricks and concrete blocks continue to dominate the construction sector; however, these materials are associated with high energy consumption, environmental impacts, and extended construction durations. As a result, the industry has increasingly shifted its attention toward sustainable and lightweight alternative building materials capable of improving construction efficiency while minimising environmental impacts. AAC, known for its lightweight properties, has emerged as a prominent masonry material in the modern construction sector (Abhilasha et al., 2023). Recognised for its advantages in terms of time, quality, and cost parameters, AAC blocks have gained popularity in the market (Ghimire, 2022). With larger dimensions compared to traditional bricks, AAC blocks result in fewer joints, reducing the amount of mortar required and leading to significant savings in mortar usage (Nagavenkatasaikumar & Sathishchandra, 2017). The use of AAC blocks as a replacement for clay bricks has been found to result in faster construction and cost savings of up to 50% and 18% in single-family structures, respectively, making them a viable and cost-effective alternative (Bhandari et al., 2021). AAC blocks are also recognised as a contemporary Green material for construction in India, suitable for residential, industrial, and commercial buildings as a sustainable substitute for conventional red clay bricks (Sherin & Saurabh, 2018). Although AAC blocks have been widely recognised internationally for their lightweight properties, thermal insulation, construction efficiency, and environmental benefits, their adoption within the Sri Lankan construction industry remains limited. Existing studies mainly focus on the quality and time effectiveness of AAC blocks in international contexts, while limited research has examined their practical applicability within Sri Lanka. In addition, low industry awareness and uncertainty regarding implementation continue to restrict the wider adoption of AAC blocks in local construction projects. Therefore, this study aims to assess the suitability of AAC blocks compared with conventional bricks and blocks within the Sri Lankan context. In Sri Lanka, the construction industry encompasses a broad scope of intricate projects, thereby presenting numerous challenges (Salgadu et al., 2021). The integration of AAC blocks, tailored to contemporary technologies, within this industry can bring forth several advantages. One notable benefit is the preservation of environmental conditions. Moreover, society stands to gain from these strategies, as they facilitate a comprehensive understanding of the temporal and qualitative efficacy of AAC blocks, as well as their associated benefits (Mishra & Aithal, 2021). Both employers and contractors bear the consequences of employing AAC blocks, with significant outcomes such as reduced construction timelines, enhanced quality standards, prevention of project delays and cost overruns, among others (Usta & Zengin, 2021). The study aims to fulfil its research objectives by focusing on the following areas: evaluate the awareness and level of usage reduction of AAC blocks in the construction industry of Sri Lanka, analysis of the physical properties of AAC blocks and Conventional bricks and blocks affecting the quality, comparative analysis regarding time parameters of AAC blocks and Conventional bricks and blocks and finally, assess the suitability of AAC blocks in relation to time, and quality parameters. This study is confined to construction projects in the Sri Lankan sector, and AAC blocks, Solid Concrete, Hollow concrete blocks, and Red Clay bricks.

# 2. LITERATURE REVIEW

The growing demand for sustainable, lightweight, and time-efficient construction materials has increased global interest in alternative masonry technologies. Among these alternatives, AAC blocks have gained considerable attention due to their lightweight properties, thermal insulation performance, reduced environmental impact, and construction efficiency (Khandve, 2016). AAC blocks are increasingly recognised as a sustainable alternative to conventional masonry materials such as red clay bricks and concrete blocks in residential, commercial, and industrial construction projects (Sherin & Saurabh, 2018). Furthermore, AAC blocks contribute to faster construction and reduced material consumption due to their larger size and fewer mortar joints compared with traditional bricks (Bhandari et al., 2021). Therefore, understanding the characteristics and applicability of AAC blocks in comparison with traditional masonry materials is essential for improving modern construction practices.

## 2.1 AUTOCLAVED AERATED CONCRETE BLOCKS

### 2.1.1 Introduction to AAC Blocks

AAC is a lightweight masonry material that has gained increasing attention as a sustainable alternative to conventional walling materials. AAC is recognised as an environmentally friendly construction material due to its recyclable, reusable, non-toxic, and energy-efficient characteristics (Khandve, 2016). AAC blocks are considered an effective alternative to conventional clay bricks because of their lightweight properties and reduced structural dead load (Ghimire, 2022). Furthermore, AAC blocks improve construction efficiency through larger block dimensions, fewer mortar joints, and faster installation processes (Bhandari et al., 2021).

## 2.2 CONVENTIONAL BRICKS AND BLOCKS

### 2.2.1 Red Clay Bricks

Red clay bricks are among the most widely used masonry materials due to their durability, compressive strength, and availability (PR, 2019). Their long history of use has made them a common construction material in Sri Lanka (Vyshnavi et al., 2015). Red clay bricks are widely utilised in many countries because of their accessibility and established acceptance within the construction industry (Ghimire, 2022). However, compared with modern masonry materials such as AAC blocks, red clay bricks generally require greater labour input and longer construction durations (Mishra & Aithal, 2021).

### 2.2.2 Solid Concrete Blocks

Solid concrete blocks are manufactured using cement, aggregates, sand, and water and are recognised for their strength, durability, and fire resistance (Raj et al., 2020). These characteristics make them suitable for structural and non-structural construction applications [Swiss Resource Centre and Consultancies for Development (SKAT), 2006]. However, their relatively high weight can increase handling effort and labour requirements during construction (Shah et al., 2017).

### 2.2.3 Hollow Concrete Blocks

Hollow concrete blocks were introduced to reinforce concrete block masonry to attain high structural stability (Niazi et al., 2020). Sand, gravel, and cement are the most

common components of hollow or cavity-type blocks [Building Materials & Technology Promotion Council (BMTPC), 1990]. Hollow concrete has various benefits, including being bigger solid blocks and lighter than solid blocks; Wall construction is simple and rapid; steel bars and concrete can be used to fill the spaces, providing excellent seismic protection; the air gap provides good thermal insulation, Plumbing, and electrical installation are both possible in the cavities (SKAT, 2006).

## 2.3 LEVEL OF AWARENESS AND LEVEL OF USAGE REDUCTION OF AAC BLOCKS IN THE LOCAL CONTEXT

Burnt Clay Brick (BCB) is frequently used in the building sector. Because of its high strength, it is widely used (Chockalingam et al., 2021). Among the several precast concrete materials used in construction, solid concrete blocks are one of them (Raj et al., 2020). Hollow concrete bricks and blocks are more common today (BMTPC, 1990). This property makes AAC block a good wall-building material, but its acceptability by society also depends on economic and cultural factors. However, the market availability of materials and the non-commercial character of the AAC block are seen as the least relevant variables for utilisation (Mishra & Aithal, 2021). Few contractors are familiar with AAC, and professional masons must use thin-set mortar rather than standard cement-based mortar. Local government bodies such as the construction of buildings department, the design review department, and planning commissions are similarly 19 unfamiliar with AAC and must be educated on its capacity to meet local building requirements (Sherin & Saurabh, 2018). Although previous studies have identified awareness, technical familiarity, and market acceptance as important factors affecting AAC block adoption in international construction industries (Mishra & Aithal, 2021), limited research has specifically examined these issues within the Sri Lankan construction context. Furthermore, existing studies have mainly focused on the quality and technical performance of AAC blocks, while limited attention has been given to their practical applicability in relation to quality and time efficiency. Therefore, the present study contributes to the existing body of knowledge by evaluating the awareness, applicability, and practical suitability of AAC blocks among Sri Lankan construction professionals.

## 2.4 ANALYSIS OF THE PHYSICAL PROPERTIES OF AAC BLOCKS AND CONVENTIONAL BRICKS AND BLOCKS

Proper physical property consideration results in conservative and competent building design and servicing. AAC unit has many physical characteristics, including thermal expansion, shrinkage, thermal conductivity, sound absorption, density, moisture content, porosity, water absorption, permeability, capillarity, and initial absorption rate, among others (Raj, 2020). AAC blocks are a modern building material that weighs highly light compared to traditional brick (Jain et al., 2018). In filled wall construction, the base shear of AAC is 23.87% lower than that of solid concrete block and 22.53% lower than that of traditional red clay brick (Moktan et al., 2021). AAC blocks are more effective in insulating sound than traditional brick (Netula et al., 2017). According to recent research, AAC and wood-based construction materials may produce less $CO_2$ emissions than other building materials like concrete, brick, or steel (Gustavsson & Sathre, 2006). This study demonstrates that AAC blocks have considerably higher compressive strength than conventional clay bricks (Khandve, 2016). AAC blocks have a fire resistance capability of around seven hours, whereas clay bricks have a fire resistance capacity of roughly two hours (Sherin & Saurabh, 2018).

### 2.5 COMPARISON OF TIME PARAMETERS OF AAC BLOCKS AND CONVENTIONAL BRICKS AND BLOCKS

The use of AAC blocks rather than clay bricks may save construction time by 50% in single-family structures, respectively. As a result, AAC blocks are an appropriate and time-effective replacement for bricks. Similarly, the time necessary to do brickwork is three to four times more than the time required to complete AAC block construction (Mishra & Aithal, 2021).

*Table 1: Days for one cumulative of infill wall*

| Infill Wall Materials | Mason Gd.1 Days | | | Mason Gd.2 Days | | | Labour Days | | | Labour Cost | Cost Saving |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Days | Rate | Total | Days | Rate | Total | Days | Rate | Total | | |
| Red Clay Brick | 0.763 | 632.5 | 482.5 | 0.763 | 575 | 438.7 | 2.792 | 460 | 1078.2 | 1999.542 | 51% in AAC compared to the conventional brick |
| Solid Concrete Block | 0.763 | 632.5 | 482.5 | 0.763 | 575 | 438.7 | 2.792 | 460 | 1078.2 | 1999.542 | |
| AAC Block | 0.431 | 632.5 | 272.3 | 0.431 | 575 | 247.6 | 1.019 | 460 | 468.5 | 988.506 | |

Table 1 displays the quantity of work completed as expressed by the number of days needed by each worker to finish one cum of infill wall concerning the labour cost reduction (Moktan et al., 2021).

## 3. RESEARCH METHODOLOGY

This study adopted a mixed-method research design to comprehensively evaluate the applicability of AAC blocks within the Sri Lankan construction industry. The quantitative approach was used to assess the level of awareness and level of usage reduction of AAC block utilisation through questionnaire surveys conducted among construction professionals and the collected quantitative data were analysed using Correlation analysis. The qualitative approach was adopted to obtain expert perspectives regarding physical properties, time parameters, and the practical suitability of AAC blocks through semi-structured interviews while the collected qualitative responses were analysed using content analysis. The integration of both quantitative and qualitative methods enabled a broader understanding of the research problem by combining statistical analysis with expert insights. Authors used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) approach to systematically identify, screen, assess, and select relevant literature related to the applicability of AAC blocks and conventional masonry materials. Adopting PRISMA provides a transparent and structured procedure for conducting systematic literature reviews and ensures the inclusion of relevant studies

related to the research topic (Page et al., 2021). The PRISMA 2020 flow diagram adopted in this study is presented in Figure 1.

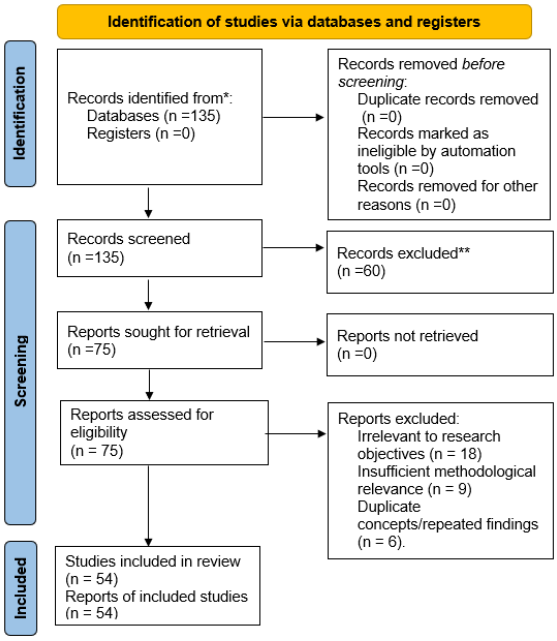



*Figure 1: PRISMA research process (Page et al., 2021)*

Through a systematic analysis following the PRISMA methodology, a comprehensive search using key terms such as AAC blocks, Conventional bricks, Conventional blocks, Construction Industry, applicability of AAC blocks within SL, applicability of Conventional bricks within SL, and applicability of Conventional blocks within SL yielded a total of 135 relevant articles. Initial screening was performed based on the abstracts of these articles, resulting in a subset of 75 articles. Subsequently, a critical analysis was conducted on this subset to further refine the selection. As a result, 42 articles were identified as directly pertinent to the study and were included for in-depth review. To augment the existing body of literature, additional references were sought from the selected 42 articles. A meticulous examination of these references led to the identification of 23 supplementary articles. Similar to the initial screening process, abstracts of these 23 articles were screened, followed by a comprehensive assessment, ultimately narrowing down the selection to twelve articles. In summary, a final corpus of 54 articles was meticulously chosen for the ultimate purpose of conducting a thorough review and analysis within the scope of this study. The selected literature was analysed to extract information related to the physical properties, thermal performance, fire resistance, compressive strength, environmental sustainability, construction time efficiency, and applicability of AAC blocks and conventional masonry materials. The extracted findings were used to support the comparative analysis conducted in this study and to develop the questionnaire survey and interview discussions. Furthermore, the literature findings were integrated with expert interview responses to evaluate the suitability of AAC blocks within the Sri Lankan construction industry. The quantitative analysis was used to evaluate the awareness and level of usage reduction of AAC blocks in the Sri Lankan construction industry. Quantitative data was collected through a questionnaire survey with two sections. The first section collects demographic information about the firm, responder, and projects, including details such as profession,

construction industry experience, position in the project, and areas of competence. The second section consists of closed-ended questions about the independent variables of the study, presented on a Likert scale. There were Likert scale questions such as Strongly Agree, Agree, Neutral, Disagree, and Strongly Disagree. The questions were developed based on a literature review of previous research. The questionnaire was prepared using google forms and distributed to construction industry professionals through emails and social media. An online-based questionnaire format was chosen to save time and increase the response rate. The qualitative analysis was used to fulfill the second, third and fourth objectives of the study. The semi-structured interviews were conducted, and it comprised two sections. The first section focuses on gathering basic information about the interviewee, such as their profession, experience in the construction industry, position in the project, and the company's areas of competence. The second section consists of open-ended questions that analyse the physical properties of AAC blocks and conventional bricks, as well as the impact on quality and a comparative analysis of time parameters, and suitability of AAC blocks. Conducting interviews with industry experts adds to the reliability of the data, as it is based on their expertise and current involvement in the field. The interviewees were selected using purposive sampling, and ten expert professionals, including project managers, architectures, quantity surveyor and engineers engaged in AAC blocks in Sri Lanka, were chosen for the interviews. The interviews were conducted through phone calls, zoom meetings, and face-to-face interactions. Recording the interviews was done to prevent data loss and save time during the discussion, particularly for online and phone conversations. Furthermore, the evaluation of physical properties and time-related comparisons was primarily based on expert interpretations and findings derived from the systematic literature review. Simple random sampling was adopted for the questionnaire survey to obtain quantitative responses from construction professionals regarding awareness and barriers affecting AAC block adoption within the Sri Lankan construction industry. The purposive sampling was employed for the semi-structured interviews to select experienced industry experts with practical knowledge of AAC blocks and conventional masonry materials. Construction professionals, including project managers, engineers, quantity surveyors, architects, and technical officers employed within construction organisations, were considered the target population for this study. The use of different sampling techniques enabled the collection of both broad quantitative data and in-depth qualitative insights relevant to the research objectives. The adopted mixed-method research design enabled the achievement of the research objectives through the integration of multiple data collection and analysis techniques. The systematic literature review was utilised to identify the physical properties, environmental benefits, time efficiency factors, and applicability characteristics of AAC blocks and conventional masonry materials. Questionnaire surveys and correlation analysis using Statistical Package for the Social Sciences (SPSS) were employed to evaluate the level of awareness, usage reduction, and barriers affecting AAC block adoption among construction professionals. Prior to conducting the statistical analysis, reliability testing was performed to evaluate the internal consistency of the questionnaire items using Cronbach's Alpha in SPSS software. The obtained Cronbach's Alpha value was 0.931 for 33 questionnaire items, exceeding the acceptable threshold of 0.70 and indicating a high level of reliability and internal consistency of the measurement scale. In addition, semi-structured interviews and content analysis were used to obtain expert insights regarding the practical suitability, construction efficiency, and implementation challenges associated with AAC blocks within the Sri Lankan construction industry. The combined

findings supported the overall evaluation of AAC block applicability and provided practical implications for improving awareness and future adoption within the local construction sector.

## 4. RESEARCH FINDINGS

This section evaluated the data collected through questionnaires, observations, semi-structured interviews, and secondary data. The questionnaire survey findings provided quantitative insights regarding the level of awareness, usage reduction, and barriers affecting AAC block adoption within the Sri Lankan construction industry. The semi-structured interviews conducted with industry experts generated qualitative insights related to the physical properties, time efficiency, practical applicability, and overall suitability of AAC blocks compared with conventional masonry materials. The integration of both respondent groups enabled the study to evaluate AAC block applicability from both statistical and practical industry perspectives.

*Table 2: Respondents results*

| Profession | No. of Respondents |
|---|---|
| Quantity Surveyors | 42 |
| Engineers | 34 |
| Architects | 8 |
| Project Managers | 6 |
| Technical officers | 2 |

The questionnaire survey was distributed among 110 construction professionals, but only 92 respondents received an 83.63% response rate (refer Table 2).

*Table 3: Respondents' Result based on Interviews*

| Profession | Code of the Respondents | Years of Experience |
|---|---|---|
| Project Manager | PM1 | 18 |
| Project Manager | PM2 | 05 |
| Engineer | CE1 | 20 |
| Engineer | CE2 | 14 |
| Engineer | CE3 | 13 |
| Architecture | AR1 | 15 |
| Architecture | AR2 | 04 |
| QS | QS1 | 15 |
| QS | QS2 | 05 |
| QS | QS3 | 05 |

Ten expert professionals currently engaged in the AAC block industry in Sri Lanka were selected to participate in semi-structured interviews to obtain their perspectives (refer Table 3).

## 4.1 EVALUATE THE AWARENESS OF USAGE REDUCTION OF AAC BLOCKS IN THE CONSTRUCTION INDUSTRY OF SRI LANKA

### 4.1.1 Level of Awareness

As mentioned, the questionnaire was distributed to construction industry professionals, of whom only 92 respondents were aware of AAC blocks, representing an awareness rate of 47.8%. This section included a question to check whether the respondent knows about the AAC blocks since it's no use to ask about the barriers if they do not know about the technology.

$$\frac{Number\ of\ completed\ responses}{Total\ number\ of\ responses} x\ 100 = Awareness \qquad (01)$$

= (44/92) * 100%

= <u>47.8%</u>

### 4.1.2 Level Of Usage Reduction of AAC Blocks in the Sri Lankan Construction Industry

Using SPSS statistical analysis software, the likert scale data collected from the questionnaire survey were evaluated. Analysis was done to determine the relationship between identified barriers and the level of usage reduction of AAC blocks in the Sri Lankan construction industry. Independent variables are Average of Attitudinal Barriers (AAB), Average of Knowledge Barriers (AKB), Average of Finance Barriers (AFB), Average of Technical Barriers (ATB), and the Dependent variable is AAP (Average Level of usage reduction of AAC blocks) (refer Figure 2).

| | | AAB | AKB | AFB | ATB | AAP |
|---|---|---|---|---|---|---|
| AAB | Pearson Correlation | 1 | .790** | .674** | .594** | .683** |
| | Sig. (2-tailed) | | <.001 | <.001 | <.001 | <.001 |
| | N | 44 | 44 | 44 | 44 | 44 |
| AKB | Pearson Correlation | .790** | 1 | .601** | .670** | .680** |
| | Sig. (2-tailed) | <.001 | | <.001 | <.001 | <.001 |
| | N | 44 | 44 | 44 | 44 | 44 |
| AFB | Pearson Correlation | .674** | .601** | 1 | .570** | .511** |
| | Sig. (2-tailed) | <.001 | <.001 | | <.001 | <.001 |
| | N | 44 | 44 | 44 | 44 | 44 |
| ATB | Pearson Correlation | .594** | .670** | .570** | 1 | .607** |
| | Sig. (2-tailed) | <.001 | <.001 | <.001 | | <.001 |
| | N | 44 | 44 | 44 | 44 | 44 |
| AAP | Pearson Correlation | .683** | .680** | .511** | .607** | 1 |
| | Sig. (2-tailed) | <.001 | <.001 | <.001 | <.001 | |
| | N | 44 | 44 | 44 | 44 | 44 |

**. Correlation is significant at the 0.01 level (2-tailed).

*Figure 2: Correlation Analysis*

Based on the data analysis, all the significant values for independent variables were less than 0.05, indicating that all independent variables have a relationship with the dependent variables.

## 4.2 ANALYSIS OF PHYSICAL PROPERTIES OF AAC BLOCKS AND CONVENTIONAL BRICKS AND BLOCKS AFFECTING THE QUALITY

Expert interviews were conducted with ten professionals, including project managers, engineers, architects, and quantity surveyors, each with 4-20 years of experience in the Sri Lankan construction industry. All participants agreed that the manufacturing process of AAC blocks requires precise dosing, mixing, pouring, and pre-curing. According to PM1 and CE1, this controlled process ensures higher quality and dimensional accuracy compared to traditional brick production. Every expert acknowledged that AAC blocks are lighter in weight, which reduces dead loads and facilitates faster construction. CE2 and QS1 noted that AAC blocks are approximately one-third the weight of conventional bricks, improving ease of handling and transportation. Most respondents agreed that AAC blocks are larger in size, allowing faster wall construction with fewer joints. Project managers (PM1, PM2) mentioned that this feature saves both time and labour costs, enhancing productivity. Experts further emphasised the high compressive strength and low thermal conductivity of AAC blocks. Engineers and architects confirmed that AAC offers adequate strength for low- to mid-rise structures while improving indoor comfort and energy efficiency. Environmental sustainability was another strongly supported factor. AR2 and QS3 highlighted that AAC blocks reduce raw material use and solid waste generation, aligning with sustainable construction practices. However, opinions were more varied regarding the initial setting time, curing process, and maintenance benefits. Only a few experts were aware that AAC blocks require minimal curing and lower water consumption, indicating limited field familiarity with these aspects. Architects and quantity surveyors identified sound insulation and smooth finishes as additional advantages, noting that AAC can reduce plastering needs and improve acoustic performance. In summary, experts expressed a strong positive perception of AAC blocks, particularly emphasising their lightweight nature, large size, thermal insulation, and environmental advantages. However, practical aspects such as curing, maintenance, and energy efficiency require further awareness and industry exposure to maximise AAC adoption in Sri Lankan construction projects.

## 4.3 COMPARATIVE ANALYSIS REGARDING TIME PARAMETERS OF AAC BLOCKS AND CONVENTIONAL BRICKS AND BLOCKS

### 4.3.1 Time Parameters Analysis

Time performance is a critical factor in construction projects, as the selection of appropriate building materials can significantly influence construction efficiency and project duration. The use of these elements saves both the owner and the contractor time and money on building expenditures. As a result, it allows the investor's contractor to construct structures faster and more precisely. In the manufacturing timeframe, expert interviewees PM1, CE1, CE2, CE3, AR2, QS1, and QS3 mentioned, "Typically cement/concrete blocks take about 28 days to release into the market after production. But AAC blocks can be released to the market within one day after manufacturing". According to the interviewees, the following factors were identified as the most time-effective factors. Such as, the weight of an AAC block is about three to four times less

than that of a traditional brick, as a result, AAC blocks require only fewer joints, and there is no curing requirement.

### 4.4 ASSESS THE SUITABILITY OF AAC BLOCKS IN RELATION TO TIME AND QUALITY PARAMETERS

The fourth objective of this research is to assess the suitability of AAC blocks with respect to time and quality parameters. This objective is addressed through the findings obtained from expert interviews. The time and quality aspects were analysed based on these expert responses. The results indicate that both time and quality are key factors when selecting building materials, and their importance varies according to client and contractor requirements. For instance, if a client prioritises completing a project quickly, materials that reduce construction time should be chosen. In the context of the Sri Lankan construction industry, commonly used materials include AAC blocks, red bricks, solid blocks, and hollow blocks. According to the study, when quality is the primary concern, AAC blocks are the most effective choice compared to the other options. Additionally, AAC blocks require less time for laying, making them both time-efficient and quality-effective**.** Based on the findings of objectives one through three, the ranking of building materials in terms of combined quality and time efficiency is as follows: AAC blocks as the highest, followed by hollow blocks**,** red bricks**,** and solid blocks.

## 5. DISCUSSION

This chapter has organized the collected data in a way that will aid in the achievement of the stated objectives of the current research, and it can be shown that the essence of the literature of this study exists when applied to the Sri Lankan construction industry. Overall, this chapter explains the relationship between the Applicability of AAC blocks and conventional bricks and blocks in the Sri Lankan context. From the first objective, determine the relationship between identified barriers and the degree of AAC blocks utilisation reduction in the Sri Lankan building sector. The findings revealed that only 47.8% of respondents were aware of AAC blocks, indicating a comparatively low level of awareness within the local construction industry. Limited technical familiarity and lack of professional exposure are significant barriers affecting AAC block adoption in developing construction sectors (Sherin & Saurabh, 2018). Awareness and social acceptance strongly influence the utilisation of AAC blocks (Mishra & Aithal, 2021). The present study further highlights that despite the global recognition of AAC technology, awareness and practical implementation within Sri Lanka remain comparatively limited. In the second objective, quality factors derived from expert interviewers were explored. As a result, AAC blocks provide advantages in terms of lightweight properties, thermal insulation, and construction speed, although their compressive strength is generally lower than that of conventional clay bricks and concrete blocks. This notion is well supported by scholars as well. The AAC unit has many physical characteristics, including thermal expansion, shrinkage, thermal conductivity, sound absorption, density, moisture content, porosity, water absorption, permeability, capillarity, and initial absorption rate, among others (Raj, 2020). AAC blocks are more effective in insulating sound than traditional brick (Netula et al., 2017). There are no environmental issues with the production of AAC blocks. AAC is a recognised eco-friendly building material that may be utilised for commercial, industrial, and residential construction since it is permeable, nontoxic, reusable, renewable, and recyclable (Khandve, 2016). AAC benefits when recycling,

sustainability, and energy are considered since it requires fewer natural resources (Usta & Zengin, 2021). Compared to clay bricks, AAC blocks perform thermally significantly better and insulate sound and fire better. Additionally, the AAC blocks' low thermal conductivity and strong thermal resistance, which result in reduced energy consumption, make them much more energy efficient than clay bricks in terms of thermal performance (Khalil, 2020). These findings are consistent with the present study, where industry professionals identified thermal insulation, lightweight properties, and environmental sustainability as major advantages of AAC blocks within Sri Lankan construction projects. Furthermore, the current study extends previous findings by emphasising the practical advantages of AAC blocks in improving labour efficiency and reducing deadloads in modern construction applications. Thirdly, determine the most time-effective material among AAC, Solid, Hollow, and red bricks from interviews. This notion is well supported by scholars as well. Similarly, the time necessary to do brickwork is three to four times more than the time required to complete AAC block construction (Mishra & Aithal, 2021). AAC blocks are identified as a time-efficient alternative due to reduced mortar joints, lightweight handling, and faster installation processes (Bhandari et al., 2021). Expert interviewees in the current study also emphasized that AAC blocks reduce construction duration due to their larger size and minimal curing requirements, thereby improving overall project efficiency within the Sri Lankan construction industry. The fourth objective examined the suitability of AAC blocks based on the findings from Objectives one to three derived from expert interviews. As a result, advantages such as lightweight properties, thermal insulation, and faster construction are offered by AAC blocks; however, their compressive strength is generally lower than that of conventional clay bricks and concrete blocks. Proving the opinions of expert interviewees, the applicability of AAC blocks based on dry density, compressive strength, the weight of the AAC block, water absorption, size variation, and fire-resistant qualities (Khanal et al., 2020). Currently, the utilisation of Autoclaved Aerated Concrete in high-rise structures is expanding daily (Vats, 2019). Direct costs will decrease by 20% (Khan, 2019). While previous international studies have primarily focused on the technical and economic advantages of AAC blocks, the present study contributes specifically by evaluating their applicability within the Sri Lankan construction industry. The findings demonstrate that AAC blocks have strong potential to support faster, higher-quality, and environmentally sustainable construction practices in Sri Lanka, although increased industry awareness and technical adaptation remain necessary for wider implementation.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The study was initiated to identify the Applicability of AAC blocks compared to conventional bricks and blocks within the Sri Lankan context. In the process, the data collection was carried out to cover the objectives through primary and secondary collection techniques. Both qualitative and quantitative data were gathered. As a result, this research employs both qualitative and quantitative methodologies. The study revealed that, for objective one, the correlation analysis was tested to identify the relationship between identified barriers and the level of usage reduction of AAC blocks in the Sri Lankan construction industry. The study demonstrated a clear link between independent and dependent variables. The data obtained from expert interviews were analysed using content analysis under Objective Two. For the third objective of the thesis, typical data collection methods were used other than those site visits, and observations were accompanied. The gathered data were subjected to content analysis. According to

the study, AAC blocks are more Time-effective than conventional bricks and blocks. In the final objective, the quality and time parameters were analysed based on the results obtained from objectives one to three and the expert interviews. According to the study, AAC blocks provide advantages in terms of lightweight properties, thermal insulation, and construction speed, although their compressive strength is generally lower than that of conventional clay bricks and concrete blocks. Considering the results, AAC blocks are the best when considering the quality factor. Since the size is big, plastering is unnecessary, the weight is low, and the time is less. It is easy for the labourers to handle the AAC block quickly, hence labour hours are reduced. Due to the economic crises in Sri Lanka, the correct blocks are AAC blocks because the amount of cement used for Solid and Hollow blocks is higher, and the cement prices are high. AAC block does not need to be plastered, so less cement is required compared to other blocks and bricks. Depending on the situation (time, and quality), the above findings can be used as a guide when considering the applicability of AAC blocks. This study was limited to evaluating the applicability of AAC blocks within selected Sri Lankan construction projects and primarily considered the perspectives of construction professionals involved in private-sector projects. The findings were mainly derived from questionnaire surveys, semi-structured interviews, and systematic literature review findings, if respondents possessed sufficient knowledge and experience related to AAC blocks and conventional masonry materials. Furthermore, the conference paper scope mainly focused on awareness, physical properties, time efficiency, and practical applicability aspects of AAC blocks. Future research may investigate solutions for barriers affecting AAC block adoption, evaluate the long-term sustainability and structural performance of AAC blocks, and develop comprehensive frameworks to assess AAC block suitability in relation to cost, time, and quality parameters within different construction contexts.

## 7. REFERENCES

Abhilasha, Kumar, R., Lakhani, R., Mishra, R. K., & Khan, S. (2023). Utilization of solid waste in the production of autoclaved aerated concrete and their effects on its physio-mechanical and microstructural properties: Alternative sources, characterization, and performance insights. *International Journal of Concrete Structures and Materials, 17*(1). 6. https://doi.org/10.1186/s40069-022-00569-x

Bhandari, M., Academy, M., & Aithal, S. (2021, January). Socio-economic suitability of AAC block in Nepal. *Solid State Technology, 64*(2), 575-595.https://doi.org/10.5281/zenodo.6538149

Building Materials & Technology Promotion Council, India (1990). *Techno economic feasibility report on concrete hollow & solid block*. Ministry of Housing & Urban Poverty Alleviation. https://www.bmtpc.org/DataFiles/CMS/file/02_Concrete%20Hollow%20&%20Solid%20Blo

Chockalingam, M. P., Palanisamy, N., Padmavathy, S. R., Mohan, E., Winsly, B. W., & Santhappan, J. S. (2021). Techno-economic feasibility study on the application of downdraft gasifiers in small-scale red clay bricks industries. *Applied Nanoscience*. *13*(2), 1155-1166 https://doi.org/10.1007/s13204-021-01942-0

Ghimire, S. (2022). Sustainability of autoclaved aerated concrete blocks over burnt clay brick. *International Journal of Engineering Applied Sciences and Technology, 6*(12), 293–298. https://doi.org/10.33564/IJEAST.2022.v06i12.048

Gustavsson, L., & Sathre, R. (2006). Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment, 41*(7), 940–951. https://doi.org/10.1016/j.buildenv.2005.04.008

Jain, U., Jain, M., & Mandaokar, S. (2018). Comparative study of AAC blocks and clay brick and costing. *International Journal of Research in Engineering, Science and Management, 1*(9), 539–543. Retrieved from https://www.ijresm.com/Vol_1_2018/Vol1_Iss9_September18/IJRESM_19_129.pdf

Khalil, E. A. S. (2020). *Impact of autoclaved aerated concrete (AAC) on modern constructions: A case study in the New Egyptian Administrative Capital* [Master's thesis, The American University in Cairo]. AUC Knowledge Fountain. https://fount.aucegypt.edu/etds/804

Khalil, E. A., & AbouZeid, M. N. (2020). Environmental impact of autoclaved aerated concrete in modern construction: A case study from the New Egyptian Administrative Capital. *International Journal of Civil and Environmental Engineering, 14*(1), 1–6. Retrieved from https://publications.waset.org/10010972/environmental-impact-of-autoclaved-aerated-concrete-in-modern-construction-a-case-study-from-the-new-egyptian-administrative-capital

Khanal, D., Mishra, A. K., & Ghimire, B. (2020). Technical suitability assessment of autoclaved aerated concrete block as alternative building wall construction material: A case of Nepal. *Saudi Journal of Civil Engineering, 4*(5), 55–67. https://doi.org/10.36348/sjce.2020.v04i05.002

Rathi, S. O., & Khandve, P. V. (2016). Cost effectiveness of using AAC blocks for building construction in residential buildings and public buildings. *International Journal of Research in Engineering and Technology, 5*(5), 517–520. https://doi.org/10.15623/ijret.2016.0505097

Salgadu, M. D., Devapriya, K. A., & Gowsiga, M.. (2021). Applicability of innovative building materials for wall structures to maximise the energy efficiency of buildings in Sri Lanka. In M. Thayaparan (Ed.) *Conference Proceedings-FARU* (pp. 23-31) FARU https://doi.org/10.31705/FARU.2020.2

Mishra, A. K., & Aithal, P. S. (2021). Socio-economic suitability of AAC block in Nepal. *Solid State Technology, 64*(2), 575–595. Retrieved from https://www.researchgate.net/profile/Anjay-Mishra/publication/348742861_Socio-Economic_Suitability_of_AAC_Block_in_Nepal/links/600ea28da6fdccdcb87aed7c/Socio-Economic-Suitability-of-AAC-Block-in-Nepal.pdf

Moktan, P. D., Dema, T., & Sonam Tenzin, U. D. (2021). Structural and cost comparative analysis of RC framed building by using various infill wall materials. *Gross National Happiness Journal of Construction Technology and Management, 2*, 157–168. Retrieved from https://www.researchgate.net/profile/Tshewang-Dorji-7/publication/356611896_3938_3986_4017_3939_3851_95_3937_3964_95_3908_3942_3851_95_3921_3906_3936_3851_95_3942_3984_4017_3954_95_3921_3851_95_3921_3924_3939_3851_95_3936_3931_3964_95_3928_3942_3851_95_3904_3984_4017_3954_95/links/61a4d67dc6494c310e78d988/3938-3986-4017-3939-3851-95-3937-3964-95-3908-3942-3851-95-3921-3906-3936-3851-95-3942-3984-4017-3954-95-3921-3851-95-3921-3924-3939-3851-95-3936-3931-3964-95-3928-3942-3851-95-3904-3984-4017-3954-95.pdf#page=168

Nagavenkatasaikumar, P., & Sathishchandra, D. (2017). Environmental conditions monitoring of AAC blocks usage of high rise buildings at Tadepalli, Andhra Pradesh. *International Journal of Civil Engineering and Technology, 8*(1), 189–198. Retrieved from http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=1

Netula, O., Singh, S. P., & Bhomia, E. R. (2017). Study and comparison of structures having different infill material (bricks, AAC blocks and hollow concrete blocks) using E-Tabs. *International Journal of Engineering Technology Science and Research, 4*(12), 403–411. Retrieved from https://www.irjet.net/archives/V7/i8/IRJET-V7I8155.pdf

Niazi, Z., Khanna, P., Gupta, S., & Sirohi, R. (2020). *Concrete block (CB): Production and construction guide*. Development Alternatives.

Fernando, P. R., Madushani, L. D., Praththana, M., & Nanayakkara, H. M., (2019). Synthesis and characterization of clay brick using waste groundnut shell ash. *Journal of Waste Resources and Recycling, 1*(1), 1–8. https://doi.org/10.15744/2766-5887.1.101

Raj, A., Borsaikia, A., & Dixit, U. (2020). Evaluation of mechanical properties of autoclaved aerated concrete (AAC) block and its masonry. *Journal of The Institution of Engineers (India): Series A, 101*, 315–325. https://doi.org/10.1007/s40030-020-00437-5

Sherin, K., & Saurabh, J. K. (2018). Review of autoclaved aerated concrete: Advantages and disadvantages. In *Proceedings of the National Conference on Advanced Structures, Materials and Methodology in Civil Engineering (ASMMCE–2018)* (pp. 35–39). https://www.researchgate.net/publication/329013600_An_Overview_of_Advantages_and_Disadvantages_of_Autoclaved_Aerated_Concrete

Swiss Resource Centre and Consultancies for Development (SKAT). (2006). *Concrete blocks*. Building Materials Leaflet. Retrieved June 24, 2026, from https://www.slideshare.net/slideshow/concrete-blocks-238111207/238111207#2

Sohrabi, C., Franchi, T., Mathew, G., Kerwan, A., Nicola, M., Griffin, M., Agha, M., & Agha, R. (2021). PRISMA 2020 statement: What's new and the importance of reporting guidelines. *International Journal of Surgery, 88*, 39–42. https://doi.org/10.1016/j.ijsu.2021.105918

Shah, H. U., Nadeem, M., Ur-Rehman, Q. F., & Ur-Rehman, E. W. (2017). Design and shape optimization of solid concrete blocks for masonry structures in northern areas of Pakistan. *International Journal of Scientific and Research Publications, 7*(9), 355–362. https://doi.org/10.13140/RG.2.2.27514.85446

Usta, P., & Zengin, B. (2021). The energy impact of building materials in residential buildings in Turkey. *Materials, 14*(11). 2793. https://doi.org/10.3390/ma14112793

Vats, F. (2019). Autoclaved aerated concrete: Versatile building material. *International Journal of Advance Research, Ideas and Innovations in Technology, 5*(3), 2092–2098. https://www.ijariit.com/manuscripts/v5i3/V5I3-2006.pdf

Gamage, I., Senaratne, S., Perera, S. and Jin, X., 2026. Appropriateness of commonly used methods for assessing the impacts of circular economy practices. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 220-234. DOI: https://doi.org/10.31705/WCS.2026.17. Available from: https://ciobwcs.com/papers/

# APPROPRIATENESS OF COMMONLY USED METHODS FOR ASSESSING THE IMPACTS OF CIRCULAR ECONOMY PRACTICES

**Iresha Gamage[1], Sepani Senaratne[2], Srinath Perera[3] and Xiaohua Jin[4]**

## *ABSTRACT*

*Circular economy (CE) is a trending concept in construction projects, which opposes the existing linear economy model of resource consumption. Transforming the construction industry towards a circular one requires shifting from traditional to more circular practices, while considering not only technical feasibility but also the impact that these practices have on the economy, society, and environment. There are various methods available for assessing and monitoring the economic, social and environmental (ESE) impacts of diverse CE practices in the construction context, like life cycle assessment. However, these methods are generic, thus not perfectly appropriate for assessing all categories of ESE impacts in an integrated manner. Furthermore, studies that discuss the appropriateness of these methods in CE impact assessment are deficient. Thus, this study aims to investigate the appropriateness of commonly used ESE impact assessment methods for assessing the impacts of CE practices in the construction context. An integrative review methodology was conducted to achieve the research aim. Commonly used impact assessment methods were studied in detail, considering their pros and cons. Cost-benefit analysis and life-cycle sustainability assessment using multi-criteria decision-making were proposed as the most appropriate methods for assessing the impacts of CE practices collectively. The findings of this research would assist professionals in deciding the appropriateness of the impact assessment methods based on the impact types considered for assessment.*

***Keywords:*** *Circular economy; Cost-benefit analysis; Impact assessment; Life cycle sustainability assessment; Multicriteria decision making.*

## 1. INTRODUCTION

The construction industry accounts for half of the global resource extraction and produces around 40 % of solid waste, along with up to 40 % of global carbon emissions (Abiodun et al., 2026). This is predominantly attributed to the linear economy model followed in the construction industry, known as ‘take, make, dispose’, which intensifies resource depletion and waste accumulation (Mani et al., 2025). Due to these negative impacts, the

[1] PhD student, School of Built Environment and Design, Western Sydney University, Australia, i.gamage@westernsydney.edu.au
[2] Associate Professor, School of Built Environment and Design, Western Sydney University, Australia, S.Senaratne@westernsydney.edu.au
[3] Professor, School of Built Environment and Design, Western Sydney University, Australia, Srinath.Perera@westernsydney.edu.au
[4] Professor, School of Built Environment and Design, Western Sydney University, Australia, Xiaohua.Jin@westernsydney.edu.au

global construction industry is facing growing pressure to move away from traditional linear models to more sustainable models (Rashidian et al., 2025).

The circular economy (CE) has emerged as a promising approach to tackle these challenges across many industries, including construction (Senaratne et al., 2024). Since the concept of CE is still a developing concept, there exists a lack of consensus on the CE definition, with numerous different definitions in the literature (Mani et al., 2025). The most pioneering definition among those is the definition by the Ellen MacArthur Foundation (EMF), which states the CE as an industrial system that is restorative or regenerative by intention and design (EMF, 2015). Senaratne et al. (2025) have come up with another definition recently, and consequently, the CE concept is defined as "an idea about an economic system that uses a systemic approach to restore or regenerate nature by intention and design, while contributing to sustainable development". According to Mani et al. (2025), CE in the construction context focuses on practices related to the disassembly, reuse, or recycling of embedded materials, components, and systems.

Successful implementation of CE in the construction industry results in many impacts on the economy, society and environment (Gamage et al., 2025). In particular, Wuni (2022) highlighted that a circular construction industry could result in reducing waste, increasing cost efficiency, minimising energy demand, increasing employment opportunities and creating new business opportunities. According to Goh et al. (2023), considerable reductions in capital and operational cost can be observed due to CE practices and Ghafourian et al. (2022) state that buildings that have adopted circular practices can benefit from lower maintenance costs. As highlighted in social impacts-related literature, adopting CE practices in construction projects can create significant positive impacts on safe and healthy living conditions (Vanhuyse et al., 2021). Environmentally, a study reported in EMF (2015) concludes that CE may decrease carbon emissions up to 83% by 2050.

Assessment plays a crucial role in determining whether the expected values are being achieved and what needs to be done to achieve them. The same phenomenon is applied for CE implementation as well (de Oliveira et al., 2021). A successful CE assessment should comprise both circular flow assessment and impact assessment. Circular flow assessment considers how efficient a particular CE practice is in achieving circularity, while impact assessment considers benefits or burdens created by the practice on economic, social and environmental aspects (de Oliveira et al., 2021). This study focuses predominantly on impact assessment and the methods available for impact assessment. Construction projects employ methods like life-cycle assessment (LCA), life-cycle costing (LCC) and social life cycle assessment (S-LCA) to assess the impacts of CE implementation (Mani et al., 2025). Even though there are diverse assessment methods available, there is a lack of a universally identified method to assess the impacts of implementing CE in the construction sector (Butković et al., 2023). None of the aforementioned assessment methods was specifically developed for CE impact assessment; thus, they frequently include general impact assessment criteria rather than CE-specific criteria (Ruiz et al., 2022). Furthermore, most of the existing methods are not capable of assessing all the impact types together, as they typically focus on one dimension, mostly environmental or economic (Corona et al., 2024; Ghisellini et al., 2018). In addition, existing literature highlights that decision-making based on CE impact assessment within the construction industry remains limited due to the fragmented nature of the assessment methods (Ruiz et al., 2022). Thus, it is required to critically evaluate

existing methods and see how those are capable of assessing ESE impacts of CE practices to generate an integrated result. In spite of different studies which have tried to define the exact use of each available assessment method, there is no study that compares all in one study and links them with the impacts specifically associated with CE implementation. Therefore, fulfilling the aforesaid research gap, this study aims to investigate the appropriateness of commonly used ESE impact assessment methods for assessing the impacts of CE practices in the construction context. As the final output, potential methods that can capture the ESE impacts of CE practices collectively would be proposed, which could support sound decision-making in construction projects.

The paper begins by reviewing the existing literature on environmental, social, and economic (ESE) impacts of CE practices. This is followed by a research methodology section that explains the approach adopted in the study. The findings section provides a detailed description of each identified impact assessment method. The discussion section then examines the appropriateness of these methods for CE impact assessment, highlighting their strengths and limitations and proposes potential methods that can capture the ESE impacts of CE practices collectively. Finally, the paper concludes with key insights and outlines directions for future research.

## 2. IMPACTS OF CE PRACTICES

A list of possible ESE impacts of adopting CE practices was identified, and these were categorised into several impact categories under the main economic, social and environmental pillars by referring to the available literature and the domain knowledge of the authors. The list of impacts and the impact categories are shown in Table 1.

A total of 18 impacts affecting the economy were identified under six (6) categories. Goh et al. (2023) revealed that CE practices may impact differently on different stakeholder groups economically, depending on the circumstances. Applying CE practices in the building lifecycle will impact the capital cost of a construction project, due to the change in the cost of materials and cost of labour and machinery (Ghisellini et al., 2018). Authors have frequently highlighted the cost savings that would be resulted due to the sustainable energy consumption during the operations (Goh et al., 2023). Conversely, there is a possibility of increased operational costs due to high-skilled manpower requirements in the operation stage to deal with circular aspects applied in the building (Ghafourian et al., 2022). Business opportunities would be available for stakeholders since companies will try numerous circular models in the industry. For instance, reusing creates business opportunities for companies which are interested in buying and selling used materials (Korhonen et al., 2018).

A total of 14 social impacts were identified from the literature and classified into six (6) categories considering their similarities as shown in Table 1. Some social impacts can either be beneficial or detrimental depending on the situation. As an example, Rizos et al. (2017) mentioned that CE practices would create a large number of job opportunities. Conversely, Luthin et al. (2023) argued that due to the necessity of special skills required for some CE practices, there would be a risk for a high turnover of low-skilled workers in industry, which would adversely affect employment percentages. As highlighted in the literature, adopting CE practices in construction projects would create significant positive impacts on safe and healthy living conditions (Vanhuyse et al., 2021).

*Table 1: Impacts of CE practices*

| Impact category | Impact |
|---|---|
| | ***Economic Impacts*** |
| Capital cost | Changes in the cost of labour and machinery (+/-)<br>Reduction of the cost of materials (+) |
| Operational cost | Changes in operational (running) costs (+/-)<br>Changes in maintenance costs (+/-)<br>Reduction of expenses related to environmental legislation and taxes (+)<br>Changes in waste management costs (+/-)<br>High rent premiums (-)<br>Reduction of emission control cost (+) |
| End-of-Life cost | High cost of dismantling (-)<br>High cost of recycling operations (-) |
| Market opportunities | Creating new business opportunities (+)<br>Improving brand reputation (+)<br>Higher competitive advantage and improved market share (+) |
| Revenue generation | Changes in revenue and profit from sales (+/-)<br>Impacting the expected return on investment and payback period (+/-) |
| Economic growth | Changes in GDP growth (+/-)<br>Changes in net exports (+/-)<br>Reduction of imports (+) |
| | ***Social Impacts*** |
| Employment | Growth in high-skilled employment (+)<br>Changes in low and medium-skilled employment (+/-)<br>Changes in healthy and safe working conditions (+/-) |
| Living standards | Improving the level of safe and healthy living conditions (+)<br>Changes in affordability (+/-) |
| Behavioural aspects | Changes in public relations and social networks (+/-)<br>Increase in community engagement in the industrial sector (+)<br>Changes in the behaviour of the people (+/-) |
| Education and Technology | Improvement in education and awareness (+)<br>Developments in innovation and technology (+) |
| Legal | Compliance with rights, regulations, and standards (+) |
| Stakeholder Responsibility & Satisfaction | Improving consumer responsibility (+)<br>Improving client satisfaction (+)<br>Improving suppliers' responsibility (+) |
| | ***Environmental Impacts*** |
| Environmental pollution | Impact on Greenhouse Gas (GHG) emissions (+/-)<br>Impact on eutrophication (marine and freshwater) (+/)<br>Reduction of acidification (+)<br>Impact on human toxicity and ecotoxicity (+/-)<br>Reduction of waste generation (+) |
| Consumption of resources | Reduction of virgin resource consumption (minerals and metals) (+)<br>Reduction of energy consumption (+)<br>Changes in water use (+/-)<br>Reduction of fossil fuel consumption (+) |
| Regeneration | Regeneration of nature (+)<br>Increased biodiversity (+) |

Affordability is another social criterion that reflects people's living standards and is affected either negatively or positively. Nevertheless, second-hand products enhance the affordability, but bio-based and degradable materials are not favoured towards it (Kayaçetin et al., 2023).

Eleven (11) environmental impacts were identified, and those were classified into three (3) impact categories. As stated in Rizos et al. (2017), a study conducted in the UK found that the carbon footprint of remanufactured products is at least 25% lower than that of new products, demonstrating the potential for significant reductions in large-scale greenhouse gas emissions. Waste generation in the construction industry can be minimised as a result of extended product lives through reuse, remanufacturing and refurbishment (Korhonen et al., 2018) resulting in a reduction in landfills, which provides more land for development and construction (John et al., 2023). Furthermore, CE will enhance biodiversity and contribute to the regeneration of nature. Using bio-based materials will help regenerate the soil and reduce chemical runoff in the soil once disposed of (John et al., 2023).

While some of the identified impacts are general and can be assessed using general impact assessment methodologies like LCA, some CE-specific impact categories, like market opportunities, economic growth, stakeholder responsibilities and regeneration, might require hybrid or new methodologies. This study intends to highlight that concern while comparing different impact assessment methodologies in the upcoming sections.

## 3. RESEARCH METHODOLOGY

Reviewing the existing literature is an essential exercise for any field to grow and develop. Literature reviews can either serve as the background for an empirical study or as an independent, standalone piece that provides a valuable contribution in its own right (Chigbu et al., 2023). Among the available types of reviews, an integrative review is a unique approach for synthesising existing knowledge to create a new piece of knowledge (Cronin & George, 2020). As mentioned by Snyder (2019), integrative reviews are suitable for both mature topics and emerging topics, and conceptual thinking skills from the researcher are required for the data analysis. This study aims to examine the suitability of commonly used impact assessment methods for CE impact assessment. As a novel contribution, it identifies and recommends the most appropriate methods for conducting CE impact assessments, thereby justifying the adoption of an integrative methodological approach for this study.

As the first step, relevant literature was identified through a systematic search of literature in both Scopus and Web of Science databases using the following keyword string.

(“Circular Economy” OR “Zero Waste Economy” OR “Cradle to Cradle”) AND “Construction Industry” OR “Built Environment” OR “Buildings”) AND “Impacts” AND (“Social” OR “Economic” OR “Environmental”) AND (“Assess*” OR “Evaluate” OR “Value” OR “Measure”) AND (“Indicators” OR “Tools” OR “Measures” OR “Frameworks” OR “Parameters”)

Initially, 327 articles were identified after removing duplicates and non-English articles. Only journal papers, conference papers, review papers, books and book chapters were considered to maintain the quality of literature. After the screening process, 105 studies were selected as relevant for the study. Impact assessment methods commonly used in the literature were identified from the articles. Since this systematic search was intended to identify commonly used impact assessment methodologies to assess their

appropriateness for CE impact assessment, a detailed content analysis of the selected articles was not conducted. Instead, a comparative analysis was conducted to examine the characteristics of impact assessment methods and how those capture economic, social and environmental dimensions of circular economy practices. Ultimately, the most appropriate methods for CE impact assessment were proposed, considering the findings of the comparative analysis.

# 4. RESEARCH FINDINGS

This section describes the commonly used impact assessment methods in the construction industry for assessing ESE impacts of CE practices, which were identified through the literature. As identified, many of these methods are with a life cycle approach, thus facilitating more rational assessment (Rigamonti & Mancini, 2021). Among the selected 105 articles, 86 articles have used LCA or modified LCA methods for environmental impact assessment, confirming that environmental as the highly researched impact category. Six (6) articles have used LCC for economic impact assessment, while three (3) studies have used SLCA for social impact assessment of CE. To fulfil the requirement of an integrated approach to assess the impacts on all three aspects together, the life cycle sustainability assessment (LCSA) was discussed in several review articles (Butković et al., 2023; Caldas et al., 2022; Larsen et al., 2022); however, no practical applications have been identified. The above-identified methods are discussed below.

## 4.1 LIFE CYCLE COSTING (LCC)

LCC is used to assess all costs that occur over the building's lifetime, including construction, operations, maintenance, and end-of-life related costs (Butković et al., 2023). In addition, LCC-based methods are mainly used for comparing the capital expenditure and profitability of investment options (Larsen et al., 2022). Three main variants to LCC can be noticed as Conventional LCC (C-LCC), Environmental LCC (E-LCC) and Societal LCC (S-LCC) (Kulakovskaya et al., 2023). Conventional LCC only addresses the financial costs, considering the investor's perspective (Hoogmartens et al., 2014). In E-LCC, monetary values of externalities are included in addition to the direct monetary flows of the particular product or service, while S-LCC mainly supports the government in decision-making and provides the monetary value of the social impacts that the product would have (Jansen et al., 2020). Waste disposal costs, environmental-related taxes are some costs considered under E-LCC, and costs associated with public health and human wellbeing are a few examples comes under S-LCC (Hoogmartens et al., 2014). LCC methodology considers different cost categories when assessing the economic impact of a particular project, and there are many modified versions available for the construction industry. As per the second edition of the ISO 15686-5 (International Standard Organisation [ISO], 2017), the cost categories of LCC for a construction project are construction cost, maintenance cost, operation cost and end-of-life cost.

## 4.2 SOCIAL LIFE CYCLE ASSESSMENT (S-LCA)

S-LCA is a methodology capable of assessing the social impacts of services, projects, and products, taking into consideration both definite and probable positive and negative impacts along the life cycle (Larsen et al., 2022). In contrast to economic or environmental impact assessments, social impact assessment requires the use of both qualitative and quantitative data (Kayaçetin et al., 2023). Therefore, S-LCA can be

performed as a quantitative, semi-quantitative or qualitative assessment. A stakeholder-based approach is employed by the S-LCA methodology, which involves taking into account potential impacts on different types of stakeholders. These potential social impacts are categorised under common impact categories, namely human rights, working conditions, cultural heritage, governance, and socio-economic implications (United Nations Environment Programme [UNEP], 2020).

### 4.3 LIFE CYCLE ASSESSMENT (LCA)

LCA is the most widely accepted and well-known tool for assessing the environmental impacts throughout the life cycle of a product (Butković et al., 2023), and it facilitates comparisons of environmental impacts among different products, processes and services (Iacovidou et al., 2017). As explained by Steen (2005), LCA was initiated to focus on energy and mass balances in material and waste streams, which was further developed as a framework to assess environmental impacts. It is based on quantitative evaluations, which show how the inputs and outputs of a product or system induce environmental impacts (Larsen et al., 2022). LCA has been applied in the construction sector for a long period; thus, included in several sustainability certification systems of buildings, for instance, BREEAM (Building Research Establishment Environmental Assessment Method), published by the Building Research Establishment (BRE - UK) and LEED (Leadership in Energy and Environmental Design), a green building rating system developed by the US Green Building Council (USGBC) (Larsen et al., 2022). ISO standard for LCA is widely used in many environmental impact assessments (Cottafava & Ritzen, 2021). According to ISO (1997), LCA assessment comprises four steps, namely, definition of goal and scope; inventory analysis; impact assessment; and interpretation of results. Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system, whereas impact assessment evaluates potential environmental impacts using the information gathered from inventory analysis (ISO, 1997).

### 4.4 LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA)

To fulfil the requirement of an integrated approach to assess the impacts on all three aspects, the LCSA was initiated (UNEP, 2020). It combines LCC, S-LCA and LCA into a single framework and provides a comprehensive assessment of sustainability at different occasions (Arulnathan et al., 2022). At present, there is no ISO standard published separately for LCSA.

## 5. DISCUSSION

There is no ideal methodology for assessing the ESE impacts of different CE practices in construction projects (Jansen et al., 2020). Thus, the impact assessment methods discussed in Section 4 are compared here in terms of their strengths and weaknesses to propose an appropriate ESE impact assessment methodology to assess all impacts collectively, depending on the circumstances.

A few of the general strengths that LCC possess are its simplicity, familiarity among the practitioners and availability of data (Kambanou & Sakao, 2020). Furthermore, the conventional LCC has been extended to capture not only direct financial costs but also environmental (ELCC) and social costs (SLCC) of the considered product or service (Hoogmartens et al., 2014). However, since LCC mainly uses market prices, which do

not capture environmental and social values, these variants are less competent in providing a full assessment of the environmental and social impacts of a product or service. In particular, economic impact categories like market opportunities and economic growth (in Table 1) are hardly captured through an LCC analysis. Furthermore, Hoogmartens et al. (2014) mentioned that ELCC does not provide a comprehensive environmental assessment like LCA. Thus, even though LCC can be used to assess ESE impacts of CE practices, it should be coupled with another assessment methodology (Kambanou & Sakao, 2020), which makes the entire process complex. Apart from that, Hoogmartens et al. (2014) figured out that LCC does not cover the full lifecycle of the project, but the economic lifecycle on some occasions, which can be considered a weakness of LCC. In addition, LCC focus on a product or specific service as its functional unit (Larsen et al., 2022); hence, it may not be suitable for assessing the ESE impacts of individual CE practices.

Several studies have identified SLCA as a way of assessing the social impacts of products or services (Tsalis et al., 2022). However, there are more weaknesses associated with S-LCA than strengths, since it is still a novel approach (Pollok et al., 2021; Venkatesh, 2019). As indicated by Luthin et al. (2023), S-LCA does not cover all the social impact categories of CE; thus, there is a need to add additional sub-categories which specifically address the social impacts of CE practices. ISO 14075:2024 is the international standard developed by ISO that formalises principles for S-LCA, which employs a more flexible approach and does not mandate a fixed list of impact categories to be assessed, as social impacts are context dependent. However, it specifically focuses on product S-LCA and is less appropriate for assessing the ESE impacts of CE practices. As stated by Petti et al. (2018), S-LCA follows the same methodology as in LCA, which makes S-LCA uncertain in assessing specifically the positive sides of social impacts. Apart from that, S-LCA includes different data sources and types, making it difficult to share, reuse or compare results ( Larsen et al., 2022; Pollok et al., 2021). There is no common unit for assessment in S-LCA, as both semi-quantitative and qualitative indicators are present (Petti et al., 2018). There are fewer provisions in S-LCA to provide a quantitative, impactful assessment, especially in the construction sector (Venkatesh, 2019). In a nutshell, it can be identified that S-LCA is a weak methodology in terms of its indicators, assessment methodology and unit of assessment.

In the CE context, LCA is a well-recognised quantification tool for the environmental impacts of different products (Lei et al., 2022). However, existing LCA indicators are not enough to cover all the CE-related environmental impact categories (Saade et al., 2022), which can be considered as a weakness of LCA. In particular, regeneration-related impacts (Table 1) are not covered in traditional LCA. Most of the time, LCA is considered a negative impact assessment (Bhambhani et al., 2022). LCA is a quantitative analysis of environmental impacts, thus providing an objective and influencing results through its analysis (Miah et al., 2017). However, different LCA indicators are assessed using different units of measurement; thus, less harmonisation in the result (Butković et al., 2023) can be observed. Another weak point of LCA's result is that it does not indicate how it aligns with monetary terms (Steen, 2005). Especially for an industry like construction, it is always a concern for the project stakeholders to understand how these environmental impacts have resulted in monetary values. Therefore, merely an LCA assessment of the environmental impacts of CE practices may not convince them to adopt CE practices in their projects. To do that, sometimes LCA is coupled with LCC when

assessing environmental impacts (Butković et al., 2023). Another weakness of LCA is that it applies in a product (project) context (Rigamonti & Mancini, 2021; Rønning & Brekke, 2014); thus, it may not be suitable for assessing the environmental impacts of CE practices individually.

Since LCSA is an integration of the above-discussed three methods, it could provide a holistic evaluation of the ESE impacts of CE practices (Bhambhani et al., 2022). The same strength of LCSA makes it weak in numerous ways. The aggregation of the results from the three assessments into a single frame is not clearly identified (Arulnathan et al., 2022). As mentioned by Iacovidou et al. (2017), while integrating three methods, there can be difficulties in defining system boundaries, as the three methods have different boundaries when carrying out the assessment (Larsen et al., 2022). Similarly, as identified in UNEP (2020), it is not easy to combine three methods since there can be overlaps when interpreting results. For instance, S-LCA covers the impact on human health, whereas LCA also cover it via its indicators. One of the major weaknesses of this method is heavy reliance on the nature of the assessment indicators. LCA indicators are quantitative and assess negative impacts on the environment. LCC indicators are both quantitative and qualitative, with a life cycle perspective and mostly consider the investor/client's point of view. S-LCA indicators are qualitative and consider the societal point of view (Bhambhani et al., 2022; Larsen et al., 2022). In addition, though LCSA provides an integrated assessment of all three sustainability pillars, Bhambhani et al. (2022) mention that it mainly focuses on damage assessment, not on benefit assessment.

Consequently, Table 2 summarises the main strengths and weaknesses of the commonly used impact assessment methods.

*Table 2: Key strengths and weaknesses of the commonly used impact assessment methods*

| Methodology | Strengths | Weaknesses |
|---|---|---|
| **LCA** | A quantitative analysis method which provides objective and influential results. | Uses different units of measurement, thus less harmonisation in the result. Majorly focus on negative impacts. |
| **LCC** | A simple, frequently used method that uses readily available data. | Less competent in providing a full assessment of environmental and social impacts. Only focus on costs. |
| **SLCA** | Uses a wide range of social indicators to evaluate the social impact | Requires different data types (qualitative, quantitative) and no common unit for assessment. |
| **LCSA** | An integrated method of LCA, LCC and SLCA, which provides a full assessment of ESE impacts | The process is complex as it integrates three different methods and has no common unit for assessment. |

## 6. PROPOSED METHODS FOR AN INTEGRATED IMPACT ASSESSMENT

All commonly used methods have considerable weaknesses and are not suitable for use individually for CE impact assessment. Thus, a new approach needs to be identified that assists in mitigating the weaknesses mentioned in the above methods. Accordingly, the proposed approach should be able to fulfil the following.

1) Assess ESE impacts using a single unit of measurement

2) Assess both positive and negative impacts
3) Assess all CE-specific impacts in addition to the general impacts
4) Generate an integrated impact value to compare different CE options in projects

To fulfil the aforesaid requirements, this study proposed two approaches: 1) Using a cost-benefit analysis; 2) using LCSA while integrating the results through multicriteria decision making (MCDM). How these methods are appropriate in fulfilling the above requirements is explained below.

## 6.1 COST-BENEFIT ANALYSIS (CBA)

CBA is an assessment methodology that is used in decision-making based on the estimated economic, social and environmental costs and benefits of a project (Butković et al., 2023). It is a more advanced and comprehensive methodology used in assessing ESE impacts (both positive and negative), where the above-mentioned methods can be used as a part of the assessment (New South Wales Government [NSWG], 2023). To assess the costs and benefits of a project, CBA uses monetary value as the standard unit of measurement (Office of Impact Analysis [OIA], 2023). Even though methods like LCA and LCC are mostly used with product-related assessments, CBA focuses either on products or processes, making it more suitable for assessing the ESE impacts of individual CE practices. The most important strength of CBA is the nature of the result. CBA assesses all the impacts using monetary terms, and the result would be in one unit of measurement (OIA, 2023) where it allows for an easy comparison among different options. Main weaknesses of CBA are the complexity of converting social and environmental impacts into monetary values and the requirement of a large amount of data (Iacovidou et al., 2017). Few authors have studied the possibility of CBA to analyse different CE options in construction projects with respect to financial, economic, social and environmental dimensions. Yuan et al. (2011) and Begum et al. (2006) have carried out CBA assessments for different construction and demolition waste management options. Wijayasundara et al. (2018) discussed the suitability of using recycled concrete aggregate to replace natural aggregate using a CBA analysis. However, compared to a method like LCA, a limited application of CBA can be observed as a method to assess the ESE impacts of CE practices in construction projects.

## 6.2 LCSA WITH MCDM

As identified earlier, in LCSA, it is necessary to integrate the assessment results obtained by methods such as LCA, LCC, and S-LCA. One of the most common ways used to integrate the results obtained from different tools/methods is multi-criteria decision making (MCDM) (Kalbar & Das, 2020). Given the inherent complexity of circular systems, many authors have chosen to evaluate these through a multi-criteria system (Sassanelli et al., 2019), and it is well recognised as a novel tool to measure CE practices (Dos Santos Goncalves & Campos, 2022). Even though there are many individual indicators to assess the impacts of CE practices, MCDM methods are capable of simultaneously analysing multiple dimensions and provide a broad assessment for CE implementation (Dos Santos Goncalves & Campos, 2022; Terra Dos Santos et al., 2023). In this approach, different criteria (LCSA indicators) can be selected and using the MCDM method, an integrated value can be obtained to compare the total ESE value addition that each CE practice would create. As examples, Hossaini et al. (2014) have

used LCSA, combined with MCDM, to develop a sustainability evaluation framework for mid-rise residential buildings, and Masseck et al. (2024) have used MCDM and the LCSA concept for assessing waste-based shading devices for public school building stock. The requirement of actual data is minimal in this approach; however, there can be issues with the subjectivity of the final output. Those can be minimised using fuzzy set theory in combination with MCDM methods.

Table 3 presents a conceptual matrix for identifying which methods can be used to assess the impact categories identified in Section 2, depending on project requirements and the availability of data. This conceptual matrix is based on the above discussion and the researcher's domain knowledge, which requires confirmation through a primary data collection.

*Table 3: Conceptual matrix for CE impact assessment methods and impact categories*

| Impact category | LCC | LCA | SLCA | LCSA+MCDM | CBA |
|---|---|---|---|---|---|
| Capital cost | x | | | x | x |
| Operational cost | x | | | x | x |
| End-of-Life cost | x | | | x | x |
| Market opportunities | | | | x | x |
| Revenue generation | | | | x | x |
| Economic growth | | | | x | x |
| Employment | | | x | x | x |
| Living standards | | | x | x | x |
| Behavioural aspects | | | x | x | x |
| Education and Technology | | | x | x | x |
| Legal | | | x | x | x |
| Stakeholder Responsibility & Satisfaction | | | | x | x |
| Environmental pollution | | x | | x | x |
| Consumption of resources | | x | | x | x |
| Regeneration | | | | x | x |

## 7. CONCLUSIONS

This study aimed to investigate the appropriateness of the commonly used ESE impact assessment methods for assessing the ESE impacts of CE practices in an integrated manner. According to the study, it was evident that each method has its own strengths and weaknesses. However, the CBA method and LCSA with MCDM have been proposed as potential methods to assess ESE impacts collectively and generate an integrated impact value. Although many studies have identified and used these methods in assessing ESE impacts of CE practices, they have not commented on the appropriateness of using them in the assessment. This study fulfilled the said gap through a comparative analysis of impact assessment methods. The findings conceptually mapped the impact assessment methods and types of impacts assessed, which aid in using assessment methods appropriately. Furthermore, proposed methods can be used to compare different CE practices in terms of ESE value creation, since they can consider CE-specific impacts and provide the total impact as a comparable value. Further research can be conducted to

validate the findings of this research and develop methods to assess the ESE impacts of CE practices, overcoming the weaknesses mentioned in the other methods.

## 8. REFERENCES

Abiodun, O., Abadi, M., Ejohwomu, O., & Manu, P. (2026). Transitioning to smart circular construction: A conceptual framework for circular economy implementation through Construction 4.0 technologies. *Environmental Impact Assessment Review*, *118*. https://doi.org/10.1016/j.eiar.2025.108260

Arulnathan, V., Heidari, M. D., Doyon, M., Li, E. P. H., & Pelletier, N. (2022). Economic indicators for life cycle sustainability assessment: Going beyond life cycle costing. *Sustainability*, *15*(1). https://doi.org/10.3390/su15010013

Begum, R. A., Siwar, C., Pereira, J. J., & Jaafar, A. H. (2006). A benefit–cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia. *Resources, Conservation and Recycling*, *48*(1), 86-98. https://doi.org/10.1016/j.resconrec.2006.01.004

Bhambhani, A., van der Hoek, J. P., & Kapelan, Z. (2022). Life cycle sustainability assessment framework for water sector resource recovery solutions: Strengths and weaknesses. *Resources, Conservation and Recycling*, *180*. https://doi.org/10.1016/j.resconrec.2021.106151

Butković, L. L., Mihić, M., & Sigmund, Z. (2023). Assessment methods for evaluating circular economy projects in construction: A review of available tools. *International Journal of Construction Management*, *23*(5), 877-886. https://doi.org/10.1080/15623599.2021.1942770

Caldas, L. R., Silva, M. V., Silva, V. P., Carvalho, M. T. M., & Filho, R. D. T. (2022). How different tools contribute to climate change mitigation in a circular building environment? - A systematic literature review. *Sustainability*,*14*(7). https://doi.org/10.3390/su14073759

Chigbu, U. E., Atiku, S. O., & Du Plessis, C. C. (2023). The science of literature reviews: Searching, identifying, selecting, and synthesising. *Publications*, *11*(1). https://doi.org/10.3390/publications11010002

Corona, B., Tunn, V. S., & van den Broek, K. L. (2024). Integrating consumer behaviour into the environmental assessment of circular packaging: A scoping review. *The International Journal of Life Cycle Assessment*, *29*(1), 80-98. https://doi.org/10.1007/s11367-023-02218-1

Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resources, Conservation and Recycling*, *164*. https://doi.org/10.1016/j.resconrec.2020.105120

Cronin, M. A., & George, E. (2020). The why and how of the integrative review. *Organizational Research Methods*, *26*(1), 168-192. https://doi.org/10.1177/1094428120935507

de Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. *Sustainable Production and Consumption*, *26*, 455-468. https://doi.org/10.1016/j.spc.2020.11.024

Dos Santos Goncalves, P. V., & Campos, L. M. S. (2022). A systemic review for measuring circular economy with multi-criteria methods. *Environmental Science and Pollution Research*, *29*(21), 31597-31611. https://doi.org/10.1007/s11356-022-18580-w

Ellen MacArthur Foundation. (2015). *Towards a circular economy - Business rationale for an accelerated transition.* https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition

Gamage, I., Senaratne, S., Perera, S., & Jin, X. (2025). Impacts of circular economy practices on the economy, society and environment: A Review in Construction context. *CIB Conferences*, *1*(1). https://doi.org/10.7771/3067-4883.1666

Ghafourian, M., Nika, C.-E., Mousavi, A., Mino, E., Al-Salehi, M., & Katsou, E. (2022). Economic impact assessment indicators of circular economy in a decentralised circular water system : Case of eco-touristic facility. *Science of the Total Environment*, *822*. https://doi.org/10.1016/j.scitotenv.2022.153602

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618-643. https://doi.org/10.1016/j.jclepro.2017.11.207

Goh, C. S., Su, F., & Rowlinson, S. (2023). Exploring economic impacts of sustainable construction projects on stakeholders: The role of integrated project delivery. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *15*(3). https://doi.org/10.1061/JLADAH.LADR-963

Hoogmartens, R., Van Passel, S., Van Acker, K., & Dubois, M. (2014). Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environmental Impact Assessment Review*, *48*, 27-33. https://doi.org/10.1016/j.eiar.2014.05.001

Hossaini, N., Reza, B., Akhtar, S., Sadiq, R., & Hewage, K. (2014). AHP based life cycle sustainability assessment (LCSA) framework: A case study of six storey wood frame and concrete frame buildings in Vancouver. *Journal of Environmental Planning and Management*, *58*(7), 1217-1241. https://doi.org/10.1080/09640568.2014.920704

Iacovidou, E., Millward-Hopkins, J., Busch, J., Purnell, P., Velis, C. A., Hahladakis, J. N., Zwirner, O., & Brown, A. (2017). A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. *Journal of Cleaner Production*, *168*, 1279-1288. http://doi.org/10.1016/j.jclepro.2017.09.002

International Organisation for Standardisation. (1997). *Environmental management - Life cycle assessment - Principles and framework* [Publication No.IS0 14040: 1997(E)].

International Organisation for Standardisation. (2017). *Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing* [Publication No. ISO 15686-5:2017(E)].

Jansen, B. W., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*. https://doi.org/10.1016/j.resconrec.2020.104857

John, I. B., Adekunle, S. A., & Aigbavboa, C. O. (2023). Adoption of circular economy by construction industry SMEs: Organisational growth transition study. *Sustainability*, *15*(7). https://doi.org/10.3390/su15075929

Kambanou, M. L., & Sakao, T. (2020). Using life cycle costing (LCC) to select circular measures: A discussion and practical approach. *Resources, Conservation and Recycling*, *155*. https://doi.org/10.1016/j.resconrec.2019.104650

Kayaçetin, N. C., Piccardo, C., & Versele, A. (2023). Social impact assessment of circular construction: Case of living lab ghent. *Sustainability*, *15*(1). https://doi.org/10.3390/su15010721

Kalbar, P. P., & Das, D. (2020). Advancing life cycle sustainability assessment using multiple criteria decision making. In J. Ren and S. Toniolo (Eds.), *life cycle sustainability assessment for decision-making* (pp. 205-224). https://doi.org/10.1016/b978-0-12-818355-7.00010-5

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The concept and its limitations. *Ecological Economics*, *143*, 37-46. https://doi.org//10.1016/j.ecolecon.2017.06.041

Kulakovskaya, A., Knoeri, C., Radke, F., & Blum, N. U. (2023). Measuring the economic impacts of a circular economy: An evaluation of indicators. *Circular Economy and Sustainability*, *3*(2), 657-692. https://doi.org/10.1007/s43615-022-00190-w

Larsen, V. G., Tollin, N., Sattrup, P. A., Birkved, M., & Holmboe, T. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering*, *50*. https://doi.org/10.1016/j.jobe.2022.104203

Lei, H., Yang, W., Wang, W., & Li, C.-Q. (2022). A new method for probabilistic circular economy assessment of buildings. *Journal of Building Engineering*, *57*. https://doi.org/10.1016/j.jobe.2022.104875

Luthin, A., Traverso, M., & Crawford, R. H. (2023). Assessing the social life cycle impacts of circular economy. *Journal of Cleaner Production*, *386*. https://doi.org/10.1016/j.jclepro.2022.135725

Mani, S., Hosseini, M. R., Karunsena, G., & Kocaturk, T. (2025). Inconsistencies revealed: A critical analysis of circular economy assessment methods for buildings. *Resources, Conservation and Recycling*, *218*. https://doi.org/10.1016/j.resconrec.2025.108203

Masseck, T., París-Viviana, O., Habibi, S., & Pons-Valladares, O. (2024). Integrated sustainability assessment of construction waste-based shading devices for the refurbishment of obsolete educational public building stock. *Journal of Building Engineering*, *87*. https://doi.org/10.1016/j.jobe.2024.109024

Miah, J. H., Koh, S. C. L., & Stone, D. (2017). A hybridised framework combining integrated methods for environmental life cycle assessment and life cycle costing. *Journal of Cleaner Production*, *168*, 846-866. https://doi.org/10.1016/j.jclepro.2017.08.187

New South Wales Government. (2023). *NSW government guide to Cost-benefit analysis* (Publication No. TPG23-08). NSW Treasury.

Office of Impact Analysis. (2023). *Cost-benefit analysis*. The Office of Impact Analysis, Department of Prime Minister and Cabinet, Australian Government.

Petti, L., Serreli, M., & Di Cesare, S. (2018). Systematic literature review in social life cycle assessment. *The International Journal of Life Cycle Assessment*, *23*, 422-431. https://doi.org/10.1007/s11367-016-1135-4

Pollok, L., Spierling, S., Endres, H.-J., & Grote, U. (2021). Social life cycle assessments: A review on past development, advances, and methodological challenges. *Sustainability*, *13*(18). https://doi.org/10.3390/su131810286

Rashidian, S., Hossain, S. K. T., Volz, K., & Teo, M. (2025). Enabling circularity in construction: A technology-phase alignment of construction 4.0 and circular economy principles. *Sustainable Production and Consumption*, *60*, 245-259. https://doi.org/10.1016/j.spc.2025.10.004

Rigamonti, L., & Mancini, E. (2021). Life cycle assessment and circularity indicators. *The International Journal of Life Cycle Assessment*, *26*(10), 1937-1942. https://doi.org/10.1007/s11367-021-01966-2

Rizos, V., Tuokko, K., & Behrens, A. (2017). *The Circular Economy: A review of definitions, processes and impacts* (Publication No. 2017/09). Centre for European Policy Studies.

Rønning, A., & Brekke, A. (2014). 4 - Life cycle assessment (LCA) of the building sector: strengths and weaknesses. In F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, & A. de Magalhães (Eds.), *Eco-efficient Construction and Building Materials* (pp. 63-83). Woodhead Publishing. https://doi.org/10.1533/9780857097729.1.63

Ruiz, L. A. L., Ramon, X. R., Mercedes, C. M. L., & Domingo, S. G. (2022). Multicriteria analysis of the environmental and economic performance of circularity strategies for concrete waste recycling in Spain. *Waste Management*, *144*, 387-400. https://doi.org/10.1016/j.wasman.2022.04.008

Saade, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., & Roux, C. (2022). Combining circular and LCA indicators for the early design of urban projects. *International Journal of Life Cycle Assessment*, *27*(1). 1-19. https://doi.org/10.1007/s11367-021-02007-8

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440-453. https://doi.org/10.1016/j.jclepro.2019.05.019

Senaratne, S., Gamage, I., Jayakodi, S., & Perera, S. (2025). A taxonomy of circular economy terminologies: insights from the construction industry. *Built Environment Project and Asset Management*, 1-20. https://doi.org/10.1108/BEPAM-01-2025-0008

Senaratne, S., Gamage, I., & Perera, S. (2024, September). The quantity surveyor's role towards a circular construction industry. *Built Environment Economist: Australia and New Zealand*, pp.32-36.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

Steen, B. (2005). Environmental costs and benefits in life cycle costing. *Management of Environmental Quality: An International Journal*, *16*(2), 107-118. https://doi.org/10.1108/14777830510583128

Terra Dos Santos, L. C., Giannetti, B. F., Agostinho, F., Liu, G., & Almeida, C. (2023). A multi-criteria approach to assess interconnections among the environmental, economic, and social dimensions of circular economy. *Journal of Environmental Management*, *342*. https://doi.org/10.1016/j.jenvman.2023.118317

Tsalis, T., Stefanakis, A. I., & Nikolaou, I. (2022). A framework to evaluate the social life cycle impact of products under the circular economy thinking. *Sustainability*, *14*(4). https://doi.org/10.3390/su14042196

United Nations Environment Programme. (2020). *Guidelines for social life cycle assessment of products and organisations 2020*. https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf

Vanhuyse, F., Fejzić, E., Ddiba, D., & Henrysson, M. (2021). The lack of social impact considerations in transitioning towards urban circular economies: a scoping review. *Sustainable Cities and Society*, *75*. 103394. https://doi.org/10.1016/j.scs.2021.103394

Venkatesh, G. (2019). Critique of selected peer-reviewed publications on applied social life cycle assessment: focus on cases from developing countries. *Clean Technologies and Environmental Policy*, *21*(2), 413-430. https://doi.org/10.1007/s10098-018-1644-x

Wijayasundara, M., Mendis, P., & Crawford, R. H. (2018). Integrated assessment of the use of recycled concrete aggregate replacing natural aggregate in structural concrete. *Journal of Cleaner Production*, *174*, 591-604. https://doi.org/10.1016/j.jclepro.2017.10.301

Wuni, I. Y. (2022). Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map. *Building and Environment*, *223*. https://doi.org/10.1016/j.buildenv.2022.109453

Yuan, H. P., Shen, L. Y., Hao, J. J. L., & Lu, W. S. (2011). A model for cost–benefit analysis of construction and demolition waste management throughout the waste chain. *Resources, Conservation and Recycling*, *55*(6), 604-612. https://doi.org/10.1016/j.resconrec.2010.06.004

Thathsara R. and Mallawaarachchi, H., 2026. AI-powered gesture recognition for occupational safety improvement in the Sri Lankan construction industry: A conceptual model. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 235-248. DOI: https://doi.org/10.31705/WCS.2026.18. Available from: https://ciobwcs.com/papers/

# AI-POWERED GESTURE RECOGNITION FOR OCCUPATIONAL SAFETY IMPROVEMENT IN THE SRI LANKAN CONSTRUCTION INDUSTRY: A CONCEPTUAL MODEL

**Rusin Thathsara[1] and Harshini Mallawaarachchi[2]**

## *ABSTRACT*

*It is generally accepted that the construction business is one of the most critical industries in which the safety is a paramount need. Even though the traditional safety management measures have been adopted, construction sites still record a high level of occupational accidents. Even though the Artificial Intelligence (AI)-powered gesture recognition has become an option in identifying the unsafe behaviours of workers and facilitating real-time safety interventions, yet it remains a less mature field. As the previous research lacks their focus on AI-based safety monitoring in the construction industry, this paper seeks to conceptualise an AI-powered gesture recognition model to enhance the occupational safety in the Sri Lankan construction sector. A non-systematic literature review was adopted under qualitative phenomenon, drawing on peer-reviewed journals, conference papers, and industry reports from databases including IEEE Xplore, ScienceDirect, Scopus, and Google Scholar, published from 2010 to 2026. The important technological elements, application fields, and implementation strategies of gesture recognition systems in the construction setting were first identified through thematic analysis. Based on these results, an AI-powered gesture recognition model for the Sri Lankan construction sites was conceptualised. The research indicates the possibilities of gesture recognition systems to achieve proactive safety management by real-time identification of dangerous behaviour, better communication, and automatic warnings The study does not involve empirical testing however, it develops a conceptual model based on literature synthesis. Lastly, the paper discusses on the practical issues that are related to the adoption of AI technology in Sri Lankan construction setting and a way forward for future research and practice directions.*

***Keywords:*** *Artificial Intelligence; Construction Industry; Gesture Recognition; Occupational Safety Improvement.*

## 1. INTRODUCTION

The construction industry can be recognised as one of the most unsafe occupational sectors worldwide due to the presence of heavy machinery, complex operations, and

[1] Undergraduate Student, Department of Building Economics, University of Moratuwa, Sri Lanka, rusinthathsaraofficial@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, harshinim@uom.lk

continuously changing work environments (Zhou et al., 2012; Li et al., 2015). Construction activities often encompass dynamic and temporary site conditions that upsurge the likelihood of accidents and injuries compared with many other industries. Globally, construction accidents remain a major concern since they often result in severe injuries, fatalities, project delays, and financial losses for construction organisations (López-Arquillos et al., 2012). Occupational safety management in construction has become a main requisite in national and international safety policies, procedures, where protective practices can be implemented to prevent injuries, accidents, and health risks among workers during construction operations (Lingard & Rowlinson, 2005). Therefore, improving occupational safety management has become a key priority for the construction industry. Research emphasises the fact that safety management using technological interventions is becoming a more crucial factor to minimise the risks and improve efficiency in operations within a construction setting (Qin et al., 2024).

Modern digital technologies, including Artificial Intelligence (AI), computer vision, and machine learning, have started to be used in the construction industry (in recent years) to enhance occupational safety. Safety monitoring strategies used in the past are mainly based on manual supervision, safety training and written safety procedures. Consequently, scholars have examined technology-based interventions that can be used to automatically detect violations of safety and risky behaviours. The use of AI-based systems, especially deep learning algorithms, has demonstrated promising outcomes in the detection of the use of safety equipment, the control of the activities of workers, and the recognition of the possible risks in the construction site (Islam et al., 2024). Further to the authors, the gesture recognition is one of the new technological methods in this field that is being used to allow computers to learn human gestures using machine learning algorithms and sensors. Gesture recognition technology can recognise movements of hands or body and convert it into commands or safety signs in real time. Hand gestures are widely used in construction settings as workers interact with crane operators, equipment drivers and other workers within the same group of people, especially in a noisy setting where they cannot easily communicate verbally. It has been shown that it is possible to use automated gesture recognition algorithms based on computer vision or wearable devices to identify worker gestures and recognise them to command the machine or monitor safety including heavy machinery operation, crane and heavy equipment signalling and fall hazard detection (Bangaru et al., 2020; Wang and Zhu, 2021; Wei et al., 2025). To illustrate, the frameworks of gesture recognition have been constructed to automatically decode construction worker hand signals and facilitate the human-machine interaction in construction activities (Wang et al., 2021).

Thus, there is still a gap in research in the application of AI-based gesture recognition systems to enhance occupational safety management in the Sri Lankan construction sector. Although gesture recognition frameworks have advanced significantly in global construction research since 2021, there remains a lack of implementation within the Sri Lankan construction industry. This gap is largely attributed to contextual constraints such as financial limitations, regulatory conditions, and site-level operational differences specific to Sri Lanka (Maduwage et al., 2025). The study positions its contribution as a conceptual model rather than an applied system. In addition, the limitations related to practical implementation are explicitly addressed in the discussion section to ensure transparency and contextual relevance. To this end, the current study aims to adopt the AI-based gesture recognition technology for occupational safety improvement in

construction, and this paper presents the development of an AI-based gesture recognition model to improve the occupational safety practices in the Sri Lankan construction industry. Accordingly, three objectives were formulated as; (1) review the modern technologies use for occupational safety improvement in construction emphasising AI-powered gesture recognition technology, (2) identify the different applications of AI-powered gesture recognition for occupational safety improvement, and (3) propose an AI-powered gesture recognition model to enhance the occupational safety in the Sri Lankan construction sector. While Objectives 1 and 2 focus on synthesising knowledge to establish contextual relevance, Objective 3 constitutes the primary contribution of this study by conceptualising an AI-powered gesture recognition model specifically for Sri Lankan construction industry.

# 2. LITERATURE REVIEW

## 2.1 OCCUPATIONAL SAFETY RISKS IN CONSTRUCTION

Construction business is universally known as one of the main drivers of the world economic growth, but it has a longstanding image of being among the most dangerous industries to human labour force. Most recent statistics show that the construction industry plays a significant role in the development of a country, with the contributing figures of about 13% to the Gross Domestic Product (GDP) in the world (Bilim, 2025). Nevertheless, a high number of incidents at the workplace regularly dampens this economic vitality, with the sector contributing to some 35 percent of all occupational deaths in the world (Kamalruzaman et al., 2026). Building sites are dynamic as they are associated with changing hazards that change depending on the project stage (Jayasundara & Eranga, 2025). Falls, struck by, caught-in/between, and electrocution still prevail in the field of safety across the world (Weerakoon, et al, 2025). Common risks caused by scaffolds and lifting equipment continue to be seen on any site despite any existing safety measures (Wei et al., 2025). The use of heavy machinery poses serious threats to the workers, which is a characteristic feature of high-rise buildings construction and results in long-term disability and loss of income. On the job, employees become exposed to awkward working postures and manual handling of materials, which causes musculoskeletal diseases including neck strains and back pains (Sarathkumar & Boopathi, 2026). As summarised in Table 1, the construction industry involves constant activity in high-force and high-exertion activities that around unpredictable areas.

*Table 1: Types of safety risks in construction and their health outcomes*

| Trade/Activity | Primary Ergonomic/Physical Risks | Health/Safety Outcome | Reference |
|---|---|---|---|
| Excavation | Vibration, awkward postures | Back injuries, lower body stress | Schneider and Susi, (2023) |
| Masonry | Heavy lifting, repetitive bending | Lower back stress, sprains | Schneider and Susi, (2023) |
| Steel Work | Squatting, kneeling | Musculoskeletal strain | Dhakal and Giri, (2024) |
| Finishing | Repetitive movements | Musculoskeletal pain | Sarathkumar and Boopathi, (2026) |

An example of this is structural steel work, which entails welding work that is usually performed in squatting or kneeling. In addition to physical trauma, construction employees work in stressful conditions that also lead to a very high probability of psychological trauma (Rahman et al., 2024). The situation can lead to accidents because the heavy machinery caused high noise levels, which can affect communication and situational awareness.

## 2.2 USE OF AI TECHNOLOGIES FOR OCCUPATIONAL SAFETY IMPROVEMENT IN CONSTRUCTION

Modern AI technologies incorporated in the construction sector have greatly enhanced occupational safety in that it allows to manage risks proactively, as well as to increase the competency of workers. The use of AI-based systems has demonstrated favourable outcomes in revealing the use of safety equipment, the control of the activities of workers, and the recognition of the possible risks in the construction site (Islam et al., 2024; Qin et al., 2024). Additionally, convolutional neural networks and object detection systems are examples of AI devices utilised in autonomously processing visual data that have been obtained with cameras or sensors, thus enhancing compliance with safety and lowering the risk of human error in safety supervision (Qin et al., 2024). The gesture recognition has been one of the new technological methods in this field that is being used to allow computers to learn human gestures using machine learning algorithms and sensors (Cui et al., 2025).

## 2.3 SYSTEM ARCHITECTURE OF AI-POWERED GESTURE RECOGNITION TECHNOLOGY

A gesture recognition system architecture based on AI, presented in Figure 1, is a hierarchical process that converts physical hand movements into a digital command. The general idea of this architecture is a data-acquisition module, pre-processing and feature-extraction module, deep learning-based recognition, and command execution are usually included in the pipeline between sensing and action (Cui et al., 2025).

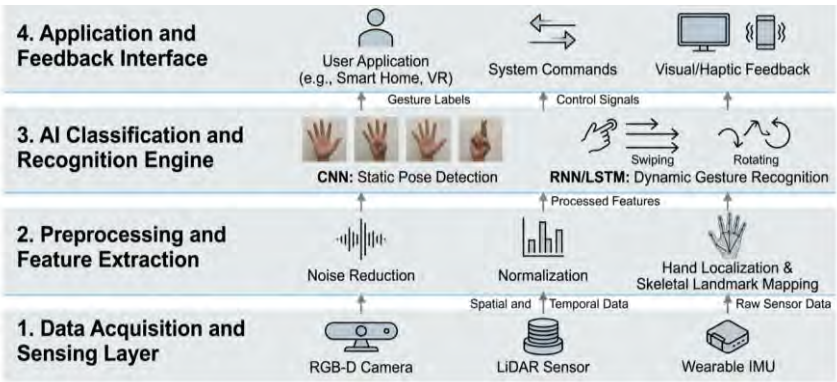



*Figure 1: AI-powered gesture recognition for human interaction - system architecture (Author constructed)*

The input and data acquisition module forms the base of the system and is charged with the duty of receiving raw gesture data of different sensors. The typical hardware will be RGB-D cameras and motion capture devices, which are able to address spatial and depth details that are important in precise hand tracking. As an example, the Leap Motion and the like depth cameras can measure the three-dimensional position of the hand joints,

which allows the precise detection of gestures. Inertial Measurement Units (IMUs) or radar sensors can also be employed to capture motion features in the environment in which camera data might be constrained. After this, the raw data is sent to the pre-processing and feature extraction module that pre-processes the data ready to be analysed by removing noise and identifying meaningful patterns. Image pre-process normally involves background subtraction, normalisation and segmentation to isolate the region of the hand. Spatial characteristics including the positions and movements of fingers are then removed. These features are usually learned by deep learning models; however, traditional methods can take engineered descriptors in feature selection followed by classification (Cui et al., 2025; Nogales & Benalcázar, 2023). The AI-based recognition unit consists of deep learning structures to recognize certain gestures. Convolutional neural networks (CNNs) are designed to learn spatial patterns, which are based on image data, and recurrent or hybrid networks also incorporate temporal information in the dynamic gesture sequences. Research shows that a CNNs-temporal network such as LSTM can be used to enhance the accuracy of dynamic gesture recognition in real time (Cui et al., 2025).

There is a command execution and interface module where the identified gestures are mapped to system actions. The gesture recognition output is connected to external devices or software through protocols and middleware including the Robot Operating System (ROS). Visual or auditory and haptic feedback on this module could also be used to show a successful gesture recognition to enhance the user interface and system stability in real time usage. Systems that are designed based on these principles have been implemented at consumer interfaces, and robotics as well as assistive technologies (Cui et al., 2025).

## 2.4 OCCUPATIONAL SAFETY IN SRI LANKAN CONSTRUCTION INDUSTRY

The Sri Lankan construction industry has been on a boom in the past decade, with the GDP reporting a large growth (Melagoda & Rowlinson, 2022). Over 600,000 people earn their livelihoods through the industry, which accounts to over 7% of the number of active workforce (Jayasundara & Eranga, 2025). Nonetheless, it has a dismal safety track record, which has caused 30% of all industrial accidents in the country (Weerakoon, et al, 2025). Overall applicability of sustainable practices to manage construction wood waste is very low in Sri Lanka because of the prevailing barriers. One of the significant obstacles that have been highlighted to hinder the application of sustainable management in local locations is financial constraints (Maduwage et al., 2025). It was found that health and safety training carried out on large-scale projects does not allow reaching the necessary level (Kumara, 2023).

To modify the attitude of workers, changes in the policy, legislation, and institutional framework were necessary to impose temperature checks and a one-meter social distance on all locations during the COVID-19 pandemic (Construction Industry Development Authority, [CIDA], 2024). These instructions require appointing special supervisors to control the following hygiene standards (CIDA, 2024). The cast in-situ and bored reinforced concrete piles have safety requirements that ensure that all the open boreholes should be covered to avoid accidents (CIDA, 2016). There is several key legislations and policies in Sri Lanka for occupational health and safety in construction. For example, the CIDA (2016) Guidelines introduce piling operations and site-specific safety measures, which is issued jointly by CIDA and ICTAD (CIDA, 2016). The Factories Ordinance (1942) also provides general occupational health, safety and welfare provisions. This

ordinance regulates the registration of factories including construction organisations, and daily removal of refuse to maintain workroom cleanliness (Factories Ordinance, 1942). However, the practical adaptation of the modern technology for safety improvements to the local industry context remains a challenge.

Although there are existing regulations in place regarding occupational health and safety within the Sri Lankan construction industry, the successful implementation of safety management practices is limited by some systemic barriers (Weerakoon, et al, 2025). The overall adoption of sustainable management practices in the sector is relatively low, primarily attributed to financial constraints which limit investment in upgrading technologies, training programmes and safety infrastructure (Maduwage et al., 2025). This is compounded by the lack of good skills development, with current health and safety training on large scale projects being found lacking in providing the competence of workers and supervisors (Kumara, 2023). Many construction firms have therefore continued to use traditional safety management practices which restricts their capacity to embrace innovative and technology-driven solutions for hazard identification, risk mitigation, and behavioural safety monitoring (Kumara, 2023; Weerakoon, et al, 2025). All these barriers together help to perpetuate unsafe work environments and slow the advancement of a more proactive and sustainable culture for safety within the industry (Maduwage et al., 2025; Weerakoon, et al, 2025).

Accordingly, the VOSviewer map in Figure 2 presents the main ideas behind the study. The VOSviewer visualisation revealed the clusters of the world safety technologies, and their low relationship with the local construction industry, which reflected the gap in research.

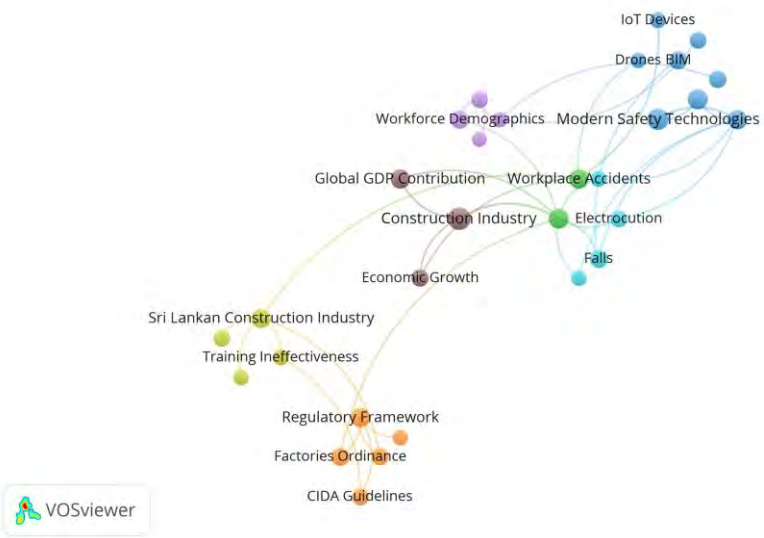



*Figure 2: Research gaps visualisation*

At the middle in the map are the construction industry and workplace accidents, which connect different research themes. In the top-right, a dark blue cluster characterises modern safety technologies, such as Building Information Modelling, Drones, and IoT devices (Manzoor et al., 2025). This indicates how digital tools can assist to manage the safety risks in real time. In contrast, the bottom-left yellow and orange cluster focuses on the safety risks in the Sri Lankan construction industry, where issues such as poor training

and old regulations dominate. The weak connection between these two clusters shows the research gap while the global industry uses advanced technology for safety. Sri Lanka still relies on basic rules and thus this study focuses on an AI-powered gesture recognition as a new opportunity to modernise safety monitoring locally.

## 3. RESEARCH METHODOLOGY

The research approach chosen in this study was qualitative research because it focused on studying the opportunities of gesture recognition based on AI to increase occupant safety in the Sri Lankan construction sector. The qualitative approach was adopted because it can be used to gain a deeper understanding of the research phenomenon (Yin, 2018) into the technological, organisational, and regulatory conditions that influence the implementation of AI-based safety interventions in construction.

The emerging and multidisciplinary nature of AI gesture recognition for construction safety, the narrow scope of directly relevant literature, and the requirement for a flexible and exploratory synthesis made a non-systematic literature review more appropriate than a protocol-driven systematic review (Yin, 2018). In addition, the literature search process followed the recommendations of Xiao and Watson (2019) who stated the necessity of systematic search procedures, transparency of inclusion and exclusion criteria and detailed consolidation of results when constructing conceptual contributions. Literature review is useful for summarising existing information, being able to pinpoint the holes in the research and creating conceptual models for new areas of study, according to Snyder (2019). A thematic analysis technique was used to identify, organise and interpret the common themes from literature reviewed. Themes were identified in an emergent way, rather than predetermined by a coding matrix, following the inductive coding process proposed by Braun and Clarke (2006). The search initially retrieved 124 publications. Following screening against the inclusion and exclusion criteria, 58 studies were retained for detailed review.

The keyword search string [(“gesture recognition” OR “activity recognition” OR “human activity recognition”) AND (“construction safety” OR “construction health and safety”) AND (“artificial intelligence” OR “AI” OR ‘’computer vision” OR “machine learning” AND (“Sri Lankan construction industry” OR “global construction industry” )] was used to conduct the queries on a variety of peer-reviewed journals, conference papers, and industry reports on the IEEE Xplore, ScienceDirect, Scopus and Google Scholar databases. The search included only English-language peer-reviewed sources that were published from 2010 to 2026. Only papers related to construction safety, AI-based gesture recognition, or activity recognition and Sri Lankan or global construction practices were selected from the initial pool of papers retrieved, while non-peer-reviewed papers, non-English papers and out of scope papers were excluded. Findings were synthesised emergently from the literature and analysed using the thematic analysis technique. The keyword co-occurrence analysis was used to analyse the relationships between the common research keywords. Three occurrences of the keywords were used as the minimum threshold to increase the reliability and clarity of the network visualisation. The VOSviewer software was chosen, as it is well-known and used for bibliometric mapping and offers a good tool for the visualization of thematic clusters, research relations, and emerging gaps in knowledge in multidisciplinary research fields. The resulting visualisation helped to pinpoint the lack of linkage between the global developments in

AI-enabled construction safety technologies and their application in the Sri Lankan construction industry, which aided in the development of the research gap of the study.

# 4. DATA ANALYSIS AND FINDINGS

## 4.1 APPLICATIONS OF AI-POWERED GESTURE RECOGNITION FOR OCCUPATIONAL SAFETY IMPROVEMENT

Gesture recognition using AI is becoming more commonly used in occupational safety systems to track worker movements, detect potentially unsafe behaviour and allow a safer approach to working with machinery and equipment in hazardous settings like construction and manufacturing industries. Such systems are usually based on computer vision and sensor-related technologies to track human body movements and convert them into digital signals that can activate safety warning systems or equipment control. Among the most popular technologies is the use of vision-based gesture recognition, which is based on an RGB camera, RGB-D camera, or infrared camera along with a neural network that detects the gestures of workers, their body position, and adherence to safety rules in real time (Zhou et al., 2023). Wearable sensing technologies are widespread, especially Inertial Measurement Units (IMUs) that combine accelerators, gyroscopes, and magnetometers to measure body motions including climbing, bending, or falling, hence AI models can classify the activities of workers and determine the possible dangers (Park et al., 2025). Moreover, through motion capture systems and optical tracking technologies, there are multicamera or markers which are used in rebuilding the 3D body movements to ensure accurate gesture recognition in dynamic work settings (Menache, 2010). Additional new creative technologies are the ElectroMyoGraphy (EMG) sensors, LiDAR, capacitive sensors, and smart gloves, which will be able to detect finer finger movements and enhance the interpretation of more complex gestures used to control a machine or communicate with a crane (Wei et al., 2025). Example applications of AI-powered gesture recognition for safety Improvements including related technologies and safety functions are summarised in Table 2.

*Table 2: Applications of AI-powered gesture recognition technology for safety*

| Applications in Occupational Safety | Technology Used | Safety Function | Key References |
|---|---|---|---|
| Worker posture and activity monitoring | Computer vision using RGB cameras and deep learning algorithms | Detects unsafe worker movements and monitors compliance with safety procedures | Zhou et al., 2023 |
| Contactless machinery operation | RGB-D cameras and vision-based gesture recognition systems | Enables workers to control equipment using predefined hand gestures, reducing physical interaction with hazardous machines | Rena and Kim, (2025) |
| Crane and heavy equipment signalling | AI-based hand signal recognition with video analytics | Automatically interprets standard crane hand signals and improves communication | Wei et al., (2025) |

| Applications in Occupational Safety | Technology Used | Safety Function | Key References |
|---|---|---|---|
| | | between operators and workers | |
| Worker falls and abnormal motion detection | Wearable sensors such as inertial measurement units (IMU), accelerometers, and gyroscopes | Identifies slips, falls, and unusual body movements that may indicate accidents or fatigue | Park et al., (2025) |
| Ergonomic and motion risk analysis | Optical motion capture and three-dimensional tracking systems | Evaluates body movement patterns to prevent musculoskeletal injuries in physically demanding tasks | Menache, (2010) |

Accordingly, based on the literature reviewed, an AI-based gesture recognition model is conceptualised expecting to close the distance between the safety technologies that are already available globally and their application to the Sri Lankan construction sites.

## 4.2 AI-POWERED GESTURE RECOGNITION FOR OCCUPATIONAL SAFETY IMPROVEMENT IN CONSTRUCTION INDUSTRY (PROPOSED MODEL)

Based on the reviewed key literature, the AI-powered gesture recognition model was conceptualised consisting of four stages; (1) Data acquisition, (2) AI processing, (3) Real-time action, and (4) Compliance management as shown in Figure 3.

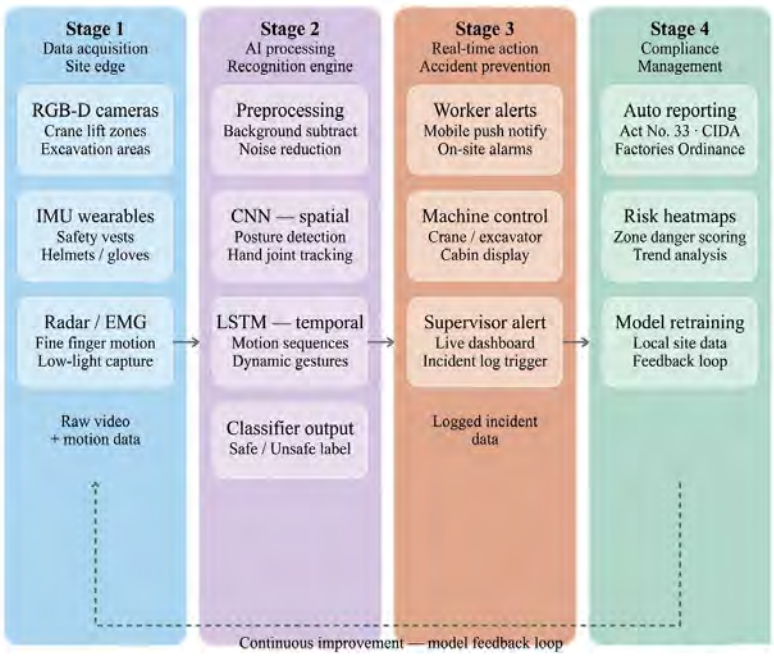



*Figure 1: AI-powered gesture recognition - proposed model*

Stage 1 is inspired by the sensor architectures proposed by Cui et al. (2025) and Wang and Zhu (2021). The CNN-LSTM recognition frameworks reported by Cui et al. (2025)

are used for Stage 2. Islam et al. (2024) identified the real-time intervention approaches in Stage 3. Stage 4 includes compliance requirements as per Factories Ordinance (1942), Construction Industry Development Act No. 33 of 2014 and CIDA guidelines. In the proposed model, Stage 1 is the sensory base, which captures physical movement and positional data based on RGB-D cameras mounted at the crane lifting points and excavation periphery, IMU wearables integrated in the safety vests and helmets, as well as auxiliary radar and EMG sensors which identify fine-grained finger movements during obstructed or low-light operations (Rena and Kim, 2025). This multimodal sensor fusion design guarantees that none of the failure points of any sensor in the system can cause the system to go blind to the unfolding hazard, which offers the rich and redundant data streams with which the downstream AI engine will operate with sufficient reliability in the unpredictable conditions of an active construction site. The raw data input here directly drives into the Stage 2, which is the AI recognition engine, then pre-processing routines, such as background subtraction, normalisation, and silhouette segmentation, purify the incoming streams and then input into the hybrid deep learning architecture. Each frame is fed to a Convolutional Neural Network (CNN) to obtain spatial posture and hand joint configuration information and the sequence of CNN outputs over time is fed to a Long Short-Term Memory network to obtain the temporal sequence of changing gestures: Is this an incidental arm movement or an intentional crane signaller stop gesture? The CNN-LSTM classifier together gives a binary safe or unsafe result, which is used as the trigger of all downstream intervention. When a dangerous gesture or posture is detected, Stage 3 instigates three parallel response lines in parallel without needing any intermediary action of a human such as is necessary in the traditional safety management based on supervision, which is the key difference between this system and the traditional safety management of the system which relies on supervision. Mobile push notifications and on-site audible alarms ensure that workers in the hazard zone are alerted immediately when a warning is needed and, in those situations, when a worker is not looking at the screen. At the same time, the system communicates directly with the control systems of the surrounding heavy equipment, sending stop or slow-down signals to crane and excavator operators cabs, and in some settings, automatically stopping the system before any physical contact may happen. A third channel also informs supervisors via a live dashboard, recording every incident in a time-stamped record of the type of gesture, location, and the workers and the machinery in operation that provides an audit trail directly to the compliance functions of Stage 4.

Stage 4 completes the loop of operation by transforming accumulated incidents data to automated compliance reports in line with the Construction Industry Development Act No. 33 of 2014 of Sri Lanka (Construction Industry Development Act, 2014), the Factories Ordinance of 1942 and the CIDA Guidelines. Heatmaps of risk zones created on the basis of aggregated location data allows visual identification of locations on a site that continually lead to unsafe behaviours, based on which redesign, supervision, or training intervention can be targeted, and a trend analysis allows the safety managers with the evidence base to understand whether the frequency of harmful incidents is decreasing with time.

Most importantly, the feedback loop between Stage 4 and Stage 1 is the constant improvement loop of the system, as the deployed model receives more and more labelled incident data, reflecting local hand signals, local site-specific postural patterns and local environmental conditions, this data is used to periodically induct the Stage 2 classifier,

gradually minimising the number of false positives that cause unnecessary perturbations to the system and false negatives that lets real hazards escape detection. It makes the system no longer a fixed deployment of technology, yet an adaptive safety infrastructure gradually becoming more effective as it spends time in. As the underlying AI concepts used on the proposed model were mostly derived from international research, the model was conceptualised to be adopted in the Sri Lankan construction industry by aligning its stages to reduce the occupational safety risks. However, additional empirical validation through industry expert feedback and real industry cases studies are required to further strengthen the applicability of the model within the Sri Lankan construction industry, which will be carried out as the next stage of the research.

## 5. DISCUSSION

While the proposed model is technically robust and contextually informed, the application in the Sri Lankan construction sector is associated with a very specific set of structural, financial, and institutional difficulties that should not be ignored in case the implementation process can be taken outside the realm of the conceptual phase. The barrier that is most readily visible is the financial constraint. As Maduwage et al. (2025) remark, financial constraints are one of the greatest inhibiters to the implementation of sustainable and technology-driven practice in Sri Lankan construction, and the capital investment to implement RGB-D camera networks, IMU wearables, and deep learning infrastructure in many of the active locations would be cost-prohibitive to the small and medium-sized contractors that form the bulk of the local industry. The human capital aspect is equally a big issue outside of the cost dimension. Even on large-scale projects in Sri Lanka, health and safety training has been identified lower than the required standard (Kumara, 2023). Further, it can be inferred that the current workforce and the supervisory cadres lack the necessary digital literacy and technical familiarity with an AI-driven safety system to operate, analyse, and maintain. The model of gesture recognition that is introduced here does not only require that the hardware itself works properly but also that the site supervisors can properly react to the dashboard alerts and that the workers learn to see the significance of monitoring their movements in the first place and that the maintenance personnel can competently act as trouble-shooters of the sensor malfunctions, which can hardly be assumed of the local community under the present conditions without significant and long-lasting financing of the training (Weerakoon, et al, 2025). It may be possible that workers will consider constant gestures tracking as a form of surveillance, not protection, and create resistance to adoption that may ruin the efficiency of the system in case the technical infrastructure is implemented successfully. The technical challenges to the performance of the system also arise due to the dynamic and volatile nature of construction sites, where work zones, sightlines, and personnel layouts vary on a daily basis, which means that the classifier trained on one set of conditions will show higher rates of false positive or false negative results when presented with a different set of conditions, especially at the beginning of deployment when the feedback retraining loop does not have enough local data to work with (Cui et al., 2025). The combination of these issues highlights the fact that the successful implementation of AI gesture recognition into the Sri Lankan construction is not merely an issue of technology acquisition but a structural change management issue that needs to be addressed on a coordinated basis in the financial, institutional, regulatory, and human capital sectors. However, since this study confirms a non-empirical contribution through a secondary data analysis and by conceptualising the AI-powered gesture recognition

model, the next stage will be focused on validating the proposed model in a real construction industry context for further strengthening and generalising the contribution of this research.

## 6. CONCLUSIONS AND A WAY FORWARD

This paper has presented a conceptual AI-driven gesture recognition model which is specifically targeted to enhance occupational safety in the Sri Lankan construction sector. Based on a substantial literature review, the study highlighted a great gap in the research and practice whereas the global construction industry has been increasingly embracing innovative digital safety tools and AI-based computer vision, in Sri Lanka yet it remains a less mature field. Hence, a four-stage model was suggested by the authors, including the multimodal site data acquisition, hybrid CNN-LSTM gesture detection, real-time multi-channel safety intervention, and compliance-consistent management reporting, with the feedback loop constituting the fourth stage, which can be viewed as a context-related response to this gap, incorporating the technical architecture of the offerings in the international literature and the regulatory framework in Sri Lanka.

To take a step into the future, several recommendations are suggested in both research and practice. Pilot deployments on larger scale infrastructure projects where budgets, technical oversight, and regulatory review are stronger, would supply the gestures datasets localised to the locals that would allow Stage 2 classifier to be intuitively retrained to the Sri Lankan context to overcome the data localisation issue that the existing conceptual model would fail to overcome by design alone. The next step of this research will be focused on the evolution of the qualitative and conceptual methodology chosen here into the empirical analysis, such as the quantitative field studies which will estimate the accuracy of gesture categorisation under the conditions of real Sri Lankan sites, the ergonomic research on the wearable sensor compatibility with the current personal protective equipment, and the cost-benefits studies that will be able to model the safety investment payback at various levels of deployment. Finally, the shift in occupational safety management in the construction industry of Sri Lanka between being reactive and proactive will need not only the technical systems outlined in this model, but also a more extensive cultural and institutional reorientation towards occupational safety as a measurable and technology-driven performance goal.

## 7. REFERENCES

Bangaru, S.S.B., Wang, C., Zhou, X., Jeon, H.W., & Li, Y. (2020). Gesture recognition-based smart training assistant system for construction worker earplug-wearing training. *Journal of Construction Engineering and Management, 146*(12). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001941

Bilim, A. (2025). Demographic analysis of occupational safety in the construction sector: Strategies and insights for risk reduction. Buildings, 15(4), 528. https://doi.org/10.3390/buildings15040528

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Construction Industry Development Authority [CIDA]. (2024). *Health and safety guidelines for Sri Lankan construction sites: COVID-19 protocols*. Construction Industry Development Authority, Ministry of Urban Development, Water Supply & Housing Facilities. https://www.scribd.com/document/463490570/CIDA-Guidelines-for-Construction-Sites

Construction Industry Development Authority [CIDA]. (2016). *Safety requirements for bored and cast in-situ reinforced concrete piles*. Construction Industry Development Authority, Ministry of Housing and Construction. https://www.scribd.com/document/432841735/cida

Cui, C., Sunar, M. S., & Su, G. E. (2025). Deep vision-based real-time hand gesture recognition: A review. *PeerJ Computer Science, 11*, e2921. https://peerj.com/articles/cs-2921/

Dhakal, D., & Giri, O. P. (2024). Identification of occupational hazard in high-rise building construction projects. *Asia-Pacific Journal of Management and Technology, 4* (3), 15-24. https://doi.org/10.46977/apjmt.2024V04I03.002

Factories Ordinance No. 45 of 1942, Chapter 4: Occupational Safety & Health and Payment of Workmetn's Compensation. (1942). https://employers.lk/wp-content/uploads/2021/03/1_Factories-Ordinance-No.-45-of-1942.pdf

Islam, M. S., Shaqib, S. M., Ramit, S. S., Khushbu, S. A., Sattar, A., & Noori, S. R. H. (2024). *A deep learning approach to detect complete safety equipment for construction workers based on YOLOv7*. arXiv preprint arXiv:2406.07707. https://arxiv.org/abs/2406.07707

Jayasundara, S. S., & Eranga, B. A. I. (2025). IoT-based real-time monitoring systems in Sri Lankan high-rise construction. In K.G.A.S. Waidyasekara, H.S. Jayasena, P.L.I. Wimalaratne, & G.A. Tennakoon, (Eds.), *Proceedings of the 13th world construction symposium* (pp. 934–947). https://doi.org/10.31705/WCS.2025.70

Kamalruzaman, M.S., Mohd, N.I., Maaz, Z. N., & Bandi, S. (2026). A review of safety knowledge sharing in the construction industry (2021–2025). *International Advanced Research Journal in Science, Engineering and Technology*, 10(1), 1–15. https://doi.org/10.47772/IJRISS.2026.10100372

Kumara, K. R. P. (2023). Investigation of health and safety training requirements in Sri Lanka [Master's thesis, University of Moratuwa]. Digital Library, University of Moratuwa, Sri Lanka. http://dl.lib.uom.lk/handle/123/22688

Li, H., Lu, M., Hsu, S., Gray, M., & Huang, T. (2015). Proactive behavior-based safety management for construction safety improvement. *Safety Science, 75*, 107–117. https://doi.org/10.1016/j.ssci.2015.01.013

Lingard, H., & Rowlinson, S. (2005). *Occupational health and safety in construction project management*. Spon Press, Taylor & Francis Group. https://api.taylorfrancis.com/content/books/mono/download?identifierName=doi&identifierValue=10.4324/9780203507919&type=googlepdf

López-Arquillos, A., Rubio-Romero, J. C., & Gibb, A. (2012). Analysis of construction accidents in Spain, 2003–2008. *Journal of Safety Research, 43*(5–6), 381–388. https://doi.org/10.1016/j.jsr.2012.07.005

Manzoor, B., Charef, R., Antwi-Afari, M. F., Alotaibi, K. S., & Harirchian, E. (2025). Revolutionizing construction safety: Unveiling the digital potential of Building Information Modeling (BIM). *Buildings, 15*(5), 828. https://doi.org/10.3390/buildings15050828

Maduwage, R. S., Ramachandra, T., Indikatiya, I. H. P. R., & Karunasinghe, N. S. (2025). Managing barriers affecting to implement sustainable construction wood waste management in Sri Lanka. In, *Proceedings of the international conference on facilities management futures (FMF) 2025: Safety-enabled and sustainable facilities* (pp. 213–221). Facilities Management Research Unit (FaMRU). https://doi.org/10.31705/ICFMF2025.

Melagoda, D. G., & Rowlinson, S. (2022). The institutional framework of construction safety management: A case study of Sri Lanka. *IOP Conference Series: Earth and Environmental Science, 1101*(4), 042038. https://doi.org/10.1088/1755-1315/1101/4/042038

Menache, A. (2010). *Understanding motion capture for computer animation and video games*. Morgan Kaufmann.

Nogales, R. E., & Benalcázar, M. E. (2023). Analysis and evaluation of feature selection and feature extraction methods. *International Journal of Computational Intelligence Systems*, *16*, 153. https://doi.org/10.1007/s44196-023-00319-1

Park, S., Youm, M., & Kim, J. (2025). IMU sensor-based worker behavior recognition and construction of a cyber–physical system environment. *Sensors, 25*(2), 442. https://doi.org/10.3390/s25020442

Construction Industry Development Act, No. 33 of 2014. https://www.srilankalaw.lk/YearWisePdf/2014/CONSTRUCTION_INDUSTRY_DEVELOPMENT_ACT,_No._33_OF_2014.pdf

Qin, R., Cui, P., & Muhsin, J. (2024). Research progress of automation ergonomic risk assessment in building construction: Visual analysis and review. *Buildings, 14*(12), 3789. https://doi.org/10.3390/buildings14123789

Rahman, M. F. W., Partiwi, S. G., & Widyaningrum, R. (2024). Psychosocial factors issues in construction workers: A systematic review and future research directions. *International Journal of Safety and Security Engineering*, 14(1), 171–183. https://doi.org/10.18280/ijsse.140117

Rena, Z., & Kim, J. I. (2025). The role of AI in on-site construction robotics: A state-of-the-art review using the sense–think–act framework. *Buildings, 15*(13), 2374. https://doi.org/10.3390/buildings15132374

Sarathkumar, R., & Boopathi, R. (2026). An analysis of agnomical hazard/risks in construction industry. (2026). An analysis of ergonomical hazards/risks in construction industry. International Advanced Research Journal in Science, Engineering and Technology, 13(1), 332-337. https://doi.org/10.17148/IARJSET.2026.13119

Schneider, S. & Susi, P. (2023). Ergonomics in the construction industry: A review of potential hazards in new construction. American Industrial Hygiene Association Journal, 55(7), 335-649. https://stacks.cdc.gov/view/cdc/204634

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Wang, X., & Zhu, Z. (2021). Wearable sensor-based hand gesture recognition of construction workers. In *Proceedings of the 38th international symposium on automation and robotics in construction*. International Association for Automation and Robotics in Construction (IAARC). https://doi.org/10.22260/ISARC2021/0068

Wang, X & Zhu, Z. (2021). Vision-based framework for automatic interpretation of construction workers' hand gestures. *Automation in Construction, 127*, 103872. https://doi.org/10.1016/j.autcon.2021.103872

Weerakoon, A., Thorpe, D., Heravi, A. & Chakraborty, S. (2025). Assessing the key construction safety challenges in Sri Lanka. Safety, 11(1), 2. https://doi.org/10.3390/safety11010002

Wei, Z., Ali, G. M., & Li, X. (2025). Dynamic hand-signal recognition and prediction framework for crane operations using deep learning. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 42, pp. 89-96). IAARC Publications. https://doi.org/10.22260/isarc2025/0013

Yin, R. K. (2018). *Case study research and applications* (Vol. 6). Thousand Oaks, CA: Sage.

Zhou, H., Wang, D., Yu, Y., & Zhang, Z. (2023). Research progress of human – Computer interaction technology based on gesture recognition. *Electronics, 12*(13), 2805. https://doi.org/10.3390/electronics12132805

Zhou, W., Whyte, J., & Sacks, R. (2012). Construction safety and digital design: A review. *Automation in Construction, 22*, 102–111. https://doi.org/10.1016/j.autcon.2011.07.005

Kosala, G.K.G.S. and Nayanathara, R.P.T., 2026. Assessing BIM knowledge among construction professionals in Sri Lanka: Challenges and opportunities. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 249-262. DOI: https://doi.org/10.31705/WCS.2026.19. Available from: https://ciobwcs.com/papers/

# ASSESSING BIM KNOWLEDGE AMONG CONSTRUCTION PROFESSIONALS IN SRI LANKA: CHALLENGES AND OPPORTUNITIES

**G.K.G.S. Kosala[1] and R.P.T. Nayanathara[2]**

## *ABSTRACT*

*Building Information Modelling (BIM) is increasingly changing the way construction projects are designed, managed, and delivered around the world. However, BIM implementation in the Sri Lankan construction industry remains limited, and the level of professional awareness is still developing. This study aimed to assess BIM awareness among construction professionals in Sri Lanka and identify strategies for increasing BIM awareness among professionals. A comprehensive literature review was carried out, followed by a structured questionnaire survey distributed among construction professionals from different disciplines in Sri Lanka. The collected data were analyzed using the Relative Importance Index (RII) method to identify the significance of responses. The findings revealed that although many professionals are aware of BIM concepts, only a limited number have received formal training or applied BIM in their professional practice. BIM usage was mainly limited to 3D modelling, with limited use of advanced BIM applications. The most significant barriers identified were the high cost of BIM training and certification, limited BIM training programs, and the shortage of experienced BIM trainers in Sri Lanka. The main strategies identified included introducing more BIM courses in university curricula, increasing professional training opportunities, and encouraging companies to provide workplace-based BIM training to improve BIM awareness and adoption. Addressing these barriers and implementing the identified strategies can help to promote BIM adoption in the Sri Lankan construction industry.*

***Keywords:*** *Awareness; Barriers; BIM; Strategies; Sri Lanka.*

## 1. INTRODUCTION

Building information modeling, also known as BIM, is one of the most promising new developments in the Architecture, Engineering, Construction and Operation (AECO) sector (Charef et al., 2019). BIM has been shown to increase efficiency, lower costs, and improve collaboration in the construction industry (Kineber et al., 2023). Siriwardhana et al. (2018) state that BIM is a game-changing paradigm that enhances the efficiency and effectiveness of the AECO industry, enabling the delivery of cost-effective, high-quality

[1] Postgraduate, Department of Engineering and Construction, International College of Business and Technology, Sri Lanka, sachinthanikosalagkg@gmail.com
[2] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, nayanathararpt.24@uom.lk

products while significantly benefiting AECO sectors worldwide. Rogers et al. (2015) show that the adoption of BIM has transformed the construction sector. They highlight that some of the many benefits associated with employing BIM for construction projects include increased profit with reduced expenses and on-time project completion. The literature currently in publication claims that there are several BIM dimensions, from 2D to 10D, with an emphasis on various elements like sustainability, maintenance, and costs (Kaushalya et al., 2024). BIM has many advantages for the building sector. It improves disciplinary coordination, which lowers mistakes and rework (Azhar, 2011). While clash detection tools find conflicts before construction starts, BIM's 3D visualization capabilities help stakeholders understand project designs (Sacks et al., 2018). Mahdi and Ali (2019) show that the BIM technique can effectively address construction issues in the Iraqi AEC industry by reducing material waste and risks. According to them this approach improves project performance, increases customer value, and benefits the national economy by lowering material waste and increasing overall value. Accurate quantity take-offs and cost estimation enhance cost control, and 4D and 5D simulations facilitate improved financial forecasting and project planning (Abanda et al., 2018). Despite these advantages, the Sri Lankan construction sector lacks understanding and implementation of BIM, with many professionals unaware of its potential benefits (Kaushalya et al., 2024). As a result, it limits the ability of industry to adopt new technologies and compete globally.

The aim of this study is to assess BIM awareness among construction professionals in Sri Lanka and identify strategies to enhance BIM awareness within the industry. Although BIM adoption and implementation have been widely studied around the world, there has been limited research into BIM awareness among Sri Lankan construction professionals. Existing research in Sri Lanka has primarily focused on the technical aspects of BIM and its application or benefits in specific projects, rather than assessing the overall level of industry awareness, preparedness, and related challenges. Therefore, a clear understanding of how construction professionals perceive BIM and the barriers affecting its wider awareness and adoption is still lacking. This study seeks to close this gap by assessing the current level of BIM awareness among Sri Lankan construction professionals, identifying barriers to BIM awareness, and proposing appropriate strategies for improving BIM knowledge and adoption in the Sri Lankan construction industry.

# 2. LITERATURE REVIEW

## 2.1 BIM AWARENESS AND ADOPTION IN THE CONSTRUCTION INDUSTRY

BIM is one of the most significant technological advancements in the Architecture, Engineering, and Construction (AEC) industry. The National BIM Standard-United States defines BIM as "the digital representation of the physical and functional characteristics of a facility" (Patel, 2022). BIM is both a software application and a collaborative process that allows project stakeholders to create, manage, and exchange project information throughout the course of a construction project. According to Eastman et al. (2008), BIM is a highly promising development in the construction industry because it enables the creation of precise digital models containing geometric, technical, procurement, and construction-related information. The growing global adoption of BIM demonstrates that its benefits are becoming more widely recognized in

the construction industry. BIM can help with project coordination, design conflicts, stakeholder communication, rework, and decision-making during project execution. Because of these benefits, building owners, contractors, consultants, and government agencies have increasingly encouraged the use of BIM in construction projects. According to Eastman et al. (2008), BIM contributes to higher project quality, shorter project durations, and better cost control, making it an effective solution for addressing inefficiencies in traditional construction practices.

Several countries have already recognized the transformative potential of BIM and incorporated it into national construction practices and policies. Babatunde et al. (2020) state that many countries around the world acknowledge the ability of BIM to modernize and improve the performance of the construction industry. However, the level of BIM adoption varies significantly across countries, depending on technological infrastructure, industry readiness, government support, and professional awareness. Developed countries such as the United Kingdom, the United States, Germany, France, and Sweden have achieved relatively high levels of BIM implementation as a result of strong policy support and industry investment. In 2014, France launched a national BIM initiative to support the development of 500,000 housing units using digital construction technologies, allocating more than €20 million to the digital transformation of the construction industry (Shah, 2025). Similarly, McGraw Hill Construction (2014) recognized the United States as a global leader in BIM implementation. According to their findings, BIM adoption in North America increased from 28% to 71% between 2007 and 2012. Similar adoption trends were observed in the United Kingdom, where architects and contractors implemented BIM at rates of 70% and 74%, respectively. These statistics show an increasing reliance on BIM technologies in developed construction industries.

Charef et al. (2019) investigated BIM adoption in 28 European Union countries and discovered that BIM implementation policies differ significantly across Europe. Their findings revealed that 25% of European countries had already mandated BIM implementation, with another 25% planning to do so in the near future. However, several countries lacked clear implementation plans and national BIM strategies. This demonstrates that, even within developed regions, BIM implementation varies according to industry conditions and government priorities. Although BIM adoption has increased rapidly in developed countries, implementation in developing countries remains limited. Ismail et al. (2017) noted that, while developed countries have gradually integrated BIM into construction practices, many developing Asian countries continue to have low levels of BIM implementation.

## 2.2 BIM ADOPTION IN THE SRI LANKAN CONSTRUCTION INDUSTRY

Despite growing global interest in BIM technologies, the Sri Lankan construction industry is still in the early stages of adopting them. The Sri Lankan construction industry continues to rely heavily on traditional construction techniques and project management methods. However, as construction projects become more complex and there is a greater demand for efficient project delivery, more advanced digital solutions such as BIM become necessary. According to Epasinghe et al. (2018), interoperability issues, insufficient awareness, and low levels of industry readiness continue to limit BIM adoption in Sri Lanka. According to their findings, many construction organizations continue to struggle with integrating BIM into existing workflows and project management practices. Nonetheless, the researchers emphasized that BIM has the

potential to improve collaboration, communication, and information sharing among project stakeholders across the entire project lifecycle.

Recent studies conducted in Sri Lanka have highlighted the potential benefits of BIM implementation in local construction projects and consulting practices. According to Samaraweera et al. (2025), BIM improves project visualization, collaboration, coordination, and project management efficiency, as well as the competitiveness of construction consultancy firms. Similarly, Rathnasiri and Jayasena (2022) stated that Green BIM can promote sustainable construction practices in Sri Lankan construction by optimizing building performance, increasing energy efficiency, and improving facilities management. The importance of digital transformation within the Sri Lankan construction sector has become increasingly significant in recent years. According to Fathima et al. (2024), the construction sector contributes significantly to GDP growth, job creation, and infrastructure expansion in Sri Lanka. However, the researchers discovered several industry-related issues, such as outdated design approaches, reliance on traditional technologies, and ineffective stakeholder communication during critical project stages. These limitations emphasize the importance of using digital technologies like BIM to improve overall project performance and industry productivity. Although awareness of the benefits of BIM has gradually increased among Sri Lankan professionals, Kaushalya et al. (2024) found that BIM implementation in the country remains relatively slow. The study suggests that, while industry professionals recognize the benefits of BIM technologies, practical adoption remains limited due to technical, organizational, and financial challenges.

## 2.3 BARRIERS TO BIM AWARENESS AND ADOPTION

Several studies have identified various barriers to BIM awareness and adoption in the construction industry. According to Zaia et al. (2023), the most significant barriers to BIM implementation are a lack of BIM specialists, insufficient knowledge, and reliance on traditional contracting methods. These barriers are especially common in developing countries, where digital transformation of the construction industry is still slow. Ismail et al. (2017) noted that factors such as low awareness, insufficient technical knowledge, high implementation costs, a lack of training opportunities, and insufficient technological infrastructure keep hindering BIM adoption in many developing Asian countries. Aibinu and Venkatesh (2014) identified resistance to change and a lack of awareness about the benefits of BIM as major barriers to its implementation in Nigeria.

In the Sri Lankan context, Epasinghe et al. (2018) identified interoperability issues, insufficient technical knowledge, and low industry readiness as major barriers to BIM implementation. Many organizations continue to struggle with integrating BIM technologies into their existing systems and project workflow. Furthermore, the scarcity of skilled BIM professionals presents challenges for organizations attempting to implement BIM in construction projects. According to Kaushalya et al. (2024), resistance to innovation, a lack of standardized BIM guidelines, insufficient training opportunities, financial limitations, and organizational challenges continue to be significant barriers to widespread BIM adoption in the construction sector of Sri Lanka. The lack of clear national BIM standards and implementation frameworks has slowed the shift from traditional construction practices to digital construction methods. Another significant barrier to BIM adoption is a lack of awareness about the long-term benefits of BIM implementation. Al-Kazee et al. (2025) stated that insufficient industry knowledge and

resistance to changing traditional working practices continue to hinder BIM adoption in many developing countries. As a result, construction professionals may be hesitant to invest in BIM technologies because of concerns about implementation costs, training requirements, and return on investment.

### 2.4 STRATEGIES TO ENHANCE BIM AWARENESS

Several researchers have proposed various strategies to increase BIM awareness and adoption in the construction industry. One of the most commonly recommended strategies is to provide BIM-related education and training opportunities for students and industry professionals. Kaushalya et al. (2024) emphasized that universities, professional institutions, and training organizations play an important role in improving BIM knowledge and technical competencies among current and future construction workers. Kaushalya et al. (2024) proposed several additional strategies to support BIM implementation in Sri Lanka, including increasing government support for BIM adoption, negotiating financial support for software and hardware investments, and offering free trials of BIM software. The researchers also emphasized the importance of holding in-person orientation and technical support sessions to help organizations with BIM software installation and implementation processes. Furthermore, improving industry collaboration and awareness initiatives can have a significant impact on BIM adoption. According to Samaraweera et al. (2025), improving client awareness, promoting digital transformation, and increasing organizational readiness can all help to facilitate BIM integration within consulting firms. Awareness campaigns, industry conferences, and knowledge-sharing platforms can help professionals understand the long-term benefits of BIM implementation. Such initiatives can reduce implementation challenges and encourage construction firms to more effectively integrate BIM technologies into their operations.

## 3. METHODOLOGY

This study used a quantitative research approach to assess BIM awareness among Sri Lankan construction professionals. According to Denscombe (2010), quantitative research allows researchers to identify patterns and relationships between variables by analyzing data from a large sample. This approach was deemed appropriate for the current study because it allowed for the systematic and consistent collection and analysis of data. A structured questionnaire survey was used as the primary data collection method. The questionnaire was selected because it is an effective tool for gathering a wide range of opinions and experiences from respondents within a standardized format. The questionnaire had four major sections: demographic information, BIM awareness and adoption, barriers to BIM awareness, and strategies for increasing BIM awareness. The barriers and strategies included in the questionnaire were identified after a thorough review of previous BIM-related studies conducted both globally and in Sri Lanka. To obtain measurable and comparable responses, the questionnaire primarily used multiple-choice and Likert scale questions.

The questionnaire was distributed online via Google Forms to ensure greater accessibility and convenience for respondents from various geographical areas of Sri Lanka. The questionnaire was distributed via LinkedIn and email communication to increase response rates and obtain responses from professionals representing various disciplines in the construction industry. The target population of the study consisted of Sri Lankan

construction professionals involved in the planning, design, construction, and management stages of construction projects where BIM tools and processes are considered relevant. The respondents included architects, civil engineers, quantity surveyors, project managers, MEP engineers, and academic staff engaged in the Sri Lankan construction industry. Participants from various educational backgrounds, including diplomas, Higher National Diplomas (HNDs), undergraduate and postgraduate degrees, were considered eligible for the study if they were involved in construction-related professional or academic activities.

The inclusion criteria of the study consisted of professionals engaged in the Sri Lankan construction industry or construction-related academic field and willing to participate in the questionnaire survey. Individuals who did not participate in construction-related professional or academic activities were excluded from the study. The non-probability convenience sampling technique was used to recruit participants due to the accessibility and availability of respondents through professional networks and online communication platforms. The sample size for the study was determined using Cochran's formula to ensure an adequate number of responses for reliable data analysis.

$$n_0 = (Z^2 \times p \times q) / e^2 \qquad (01)$$

Where $n_0$ is the sample size for an infinite population, Z is based on the confidence level and considered to be 95%, so Z-score = 1.96, p is the estimated proportion (assumed to be 0.5), and e is the margin of error, which is taken to be 0.1.

$$n_0 = (1.96^2 \times 0.5 \times 0.5) / 0.1^2 = 96.04$$

As a result, the minimum sample size is approximately 96 respondents. This sample size was chosen to ensure that the collected data was statistically significant and representative of the construction professional population in Sri Lanka.

# 4. FINDINGS AND DISCUSSION

A total of 392 invitations were sent, and 98 responses were received, for a response rate of approximately 25%. A total of 98 valid replies were collected and analyzed. The survey results are presented as descriptive statistics for demographic responses and BIM awareness responses.

## 4.1 DEMOGRAPHIC RESPONSES

Among the valid responses, quantity surveyors were the largest professional category among respondents, accounting for 70.4% of the total. Civil engineers (14.3%) were the second most represented group, followed by academic staff (8.2%), project managers (3.1%), architects (1.0%), and MEP engineers (1.0%). Furthermore, individuals classified as "Others" (2.0%) included professionals such as interior designers, demonstrating that BIM is relevant outside typical construction positions. Table 1 shows the participant's experience in the construction industry. The majority of respondents had less than 5 years of experience (64.29%). This was followed by those with 5-10 years of experience (25.51%). These two categories together account for the majority of the sample, confirming that the data represents the perspectives of early- to mid-career professionals. A smaller proportion of the sample reported having 10 years or more of experience (10.20%), which provides value by incorporating more seasoned opinions.

*Table 1: Years of experience among professionals*

| Years of Experience | Percentages |
|---|---|
| Less than 5 years | 64.29% |
| 5-10 years | 25.51% |
| 10 years and above | 10.20% |

## 4.2 BIM AWARENESS AND ADOPTION IN SRI LANKA

Table 2 shows the respondents' self-reported familiarity with BIM. The majority of participants stated that they apply BIM on a limited basis (45.9%), implying that while awareness exists, full integration into daily processes is still developing. The second largest group had heard of BIM but had never used it (34.7%), indicating that there is a significant group of people who are conceptually aware of BIM but lack hands-on experience. A smaller but significant proportion of respondents reported using BIM on a regular basis (18.4%), showing a rising user base with practical expertise. Only 1% of respondents said they had never heard of BIM, indicating that BIM awareness is practically universal among surveyed professionals.

*Table 2: Level of BIM familiarity*

| Level of BIM Familiarity | Percentages |
|---|---|
| Never heard of BIM | 1.0% |
| Have heard of it but never applied it | 34.7% |
| Apply it on limited basis | 45.9% |
| Apply it regularly | 18.4% |

Table 3 demonstrates that the majority of participants (41.84%) had not received formal BIM training but expressed an interest in doing so. This indicates a strong desire to learn and improve, which might be harnessed through targeted training activities. The second-largest group had attended training but were not certified (30.61%), followed by those who were formally certified (25.51%), indicating a growing number of professionally recognized BIM practitioners. Only 2.04% reported no interest in BIM training, indicating little resistance to upskilling in this area.

*Table 3: Training and certification in BIM*

| Formal BIM Training | Percentages |
|---|---|
| No, not interested in BIM training | 2.04% |
| No, but interesting in training | 41.84% |
| Yes, attended BIM training but not certified | 30.61% |
| Yes, certified BIM | 25.51% |

As indicated in Table 4, the majority of respondents (45.9%) stated that they had no prior experience with BIM. Those with less than 1 year of experience were the second largest group (27.6%), followed by those with 1-5 years of experience (23.5%). Only 3.1% had 6-10 years of expertise, indicating that experienced BIM users remain rare in the country. This research underscores the need of having more hands-on experience with BIM procedures, tools, and workflows.

*Table 4: Years of experience in BIM usage*

| Years of BIM Experience | Percentages |
|---|---|
| No experience | 45.9% |
| Less than 1 year | 27.6% |
| 1-5 years | 23.5% |
| 6-10 years | 3.1% |

As shown in Table 5, spreadsheets (e.g., MS Excel) are still the most popular approach for quantity takeoff (52.0%). This demonstrates a strong preference for familiar tools and processes that are simple to use and well understood. The second most popular option was specialist measurement software like CostX or Cubicost (38.8%), which provides a more automated and efficient approach, particularly in BIM-integrated environments. A smaller percentage still uses traditional/manual methods, accounting for only 9.2%, demonstrating a gradual drop in manual activities.

*Table 5: Preferred method for quantity takeoff*

| Approach to Quantity Takeoff | Percentages |
|---|---|
| Traditional/ manual approach (pen and paper) | 9.2% |
| Spreadsheets for calculations | 52.0% |
| Specialist measurement software (e.g., CostX, Cubicost) | 38.8% |

When questioned about the most advanced level of BIM practice, 3D modeling was the most popular (41.8%), as illustrated in Table 6. This is consistent with global trends, where 3D visualization is often the first step into BIM workflows. The second most practiced level was 2D drafting (36.7%), indicating a continued dependence on traditional CAD technologies. 5D BIM (cost estimation) ranked third (15.3%), followed by 4D BIM (time/scheduling) (4.1%). Only a few respondents had worked with 6D BIM or above (2.0%), which includes sustainability and facility management. This pattern demonstrates that, while BIM is present, it is primarily used in early-stage applications rather than advanced, integrated levels.

*Table 6: Maximum BIM level practiced*

| Highest BIM Level Achieved | Percentages |
|---|---|
| 2D CAD for documentation without BIM integration | 36.7% |
| Creating 3D models without additional BIM dimension | 41.8% |
| 4D BIM (time/ scheduling) | 4.1% |
| 5D BIM (cost estimation) | 15.3% |
| 6D BIM or higher | 2.0% |

## 4.3 BARRIERS TO BIM AWARENESS

Identifying and understanding the primary barriers to increasing awareness and acceptance of BIM is critical for developing effective strategies. In this study, respondents were asked to rate a series of potential barriers on a 5-point Likert scale ranging from Strongly Disagree to Strongly Agree. The factors were rated on a five-point Likert scale, with a weight of 1 for "strongly disagree," 2 for "disagree," 3 for "neutral," 4 for "agree," and 5 for "strongly agree". Table 7 lists the most common barriers to BIM awareness and

acceptance. The Relative Important Index (RII) is calculated using the formula in equation (2) to determine relative relevance of each barrier.

$$RII = \frac{\sum W}{AN} \qquad (02)$$

Where W represents the weight given to each factor by the respondents, A is the highest weight on the Likert scale, and N is the total number of respondents. The RII value ranges from 0 to 1. A higher value indicates that the factor is more important than a lower value. The calculated RII values were then used to sort the factors from most to least significant.

*Table 7: Barriers to increasing awareness and acceptance of BIM*

| **Barriers** | **Frequency** | | | | | **Overall** | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | RII | Rank |
| High cost of BIM training and certification. | 20 | 44 | 20 | 9 | 5 | 0.733 | 1 |
| Limited BIM training programs. | 5 | 6 | 19 | 56 | 12 | 0.731 | 2 |
| Shortage of experienced BIM trainers in Sri Lanka. | 5 | 14 | 14 | 44 | 21 | 0.727 | 3 |
| Employers do not support or sponsor BIM training. | 2 | 11 | 28 | 45 | 12 | 0.71 | 4 |
| Universities provide little support for BIM education. | 2 | 24 | 19 | 41 | 12 | 0.676 | 5 |
| Lack of BIM research. | 6 | 19 | 25 | 38 | 10 | 0.655 | 6 |
| Lack of trust in new technology. | 4 | 31 | 28 | 23 | 12 | 0.616 | 7 |
| BIM is perceived as a difficult tool to learn. | 10 | 28 | 24 | 28 | 8 | 0.592 | 8 |

The RII findings identified the high cost of BIM training and certification as the most significant barrier. This suggests that budgetary constraints remain a significant barrier, particularly for individuals and smaller companies with limited training budgets. The limited availability of BIM training programs came in second, indicating a vacuum in the local education and professional development scene. While interest in BIM grows, a lack of structured and accessible training choices makes it difficult for professionals to improve their skills. The shortage of experienced BIM trainers in Sri Lanka was identified as the third-highest barrier, further intensifying the training challenge. Without a sufficient number of experienced instructors, even existing training programs may fall short in terms of quality or practical applicability. The lack of employer support or sponsorship for BIM training, ranked fourth, indicates that many businesses have yet to grasp the long-term worth of BIM investment, leaving the individual to bear the whole weight of professional growth.

Additionally, the limited integration of BIM in university curricula, placed fifth, indicates that many graduates enter the workforce without adequate exposure to BIM concepts or tools. This educational gap lays a fragile basis for industrial adoption. The lack of BIM-related research, which placed sixth, contributes to the poor progress by providing limited evidence-based insights and locally relevant case studies, lowering both awareness and confidence in BIM technology. While cultural factors also play a role, lack of trust in new technologies was ranked seventh, indicating that a portion of the industry remains hesitant to adopt BIM due to unfamiliarity or fear of change. Interestingly, the belief that BIM is a difficult tool to learn was the lowest-ranked barrier. This implies that, while some may

be frightened by its complexity, the majority of respondents do not see technical difficulties as the key obstacle; rather, they are constrained by external factors such as access, cost, and institutional support.

## 4.4 STRATEGIES TO ENHANCE BIM AWARENESS

Using a 5-point Likert scale, respondents were given with several strategies to investigate successful methods for increasing BIM awareness in Sri Lanka. The responses were analyzed using the Relative Importance Index (RII) method to identify the most strongly recommended approaches.

*Table 8: Strategies to increasing awareness and acceptance of BIM*

| Strategies | Frequency | | | | | Overall | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | RII | Rank |
| More universities should offer BIM courses. | 4 | 1 | 11 | 49 | 33 | 0.816 | 1 |
| More professional BIM training programs are needed. | 3 | 3 | 8 | 53 | 31 | 0.816 | 1 |
| Companies should provide in-house BIM training. | 4 | 1 | 10 | 52 | 31 | 0.814 | 3 |
| More affordable BIM software access for students and trainees. | 3 | 6 | 11 | 40 | 38 | 0.812 | 4 |
| Clients should be educated on BIM benefits. | 2 | 3 | 13 | 52 | 28 | 0.806 | 5 |
| Government should introduce policies to promote BIM. | 3 | 5 | 10 | 52 | 28 | 0.798 | 6 |

The analysis indicated that two strategies were similarly ranked at the top: expanding BIM courses in universities and providing more professional BIM training programs. This significant preference demonstrates that education remains the cornerstone for increasing BIM awareness. Respondents believe that exposure to BIM principles should begin at the academic level, with universities playing an important role in educating graduates for a BIM-integrated sector. Simultaneously, there is an urgent need for structured, accessible, and continuous professional development courses to upskill those already engaged in the construction industry. The strategy of providing in-house BIM training came in third. This finding highlights the importance of organizational responsibility in promoting continuous learning. Many professionals may be willing to embrace BIM if their employers play an active role in training and equipping them with the necessary skills.

Providing more affordable access to BIM software for students and trainees came in fourth, indicating that the high cost of BIM software remains a barrier to both learning and practical application. Respondents agreed that software accessibility is critical, particularly for young professionals and students who would otherwise be excluded due to financial constraints. Interestingly, the recommendation to educate clients on the benefits of BIM was ranked fifth. While clients are important decision-makers in construction projects, the lower ranking may indicate that respondents prioritize internal capacity-building over external awareness efforts. Nonetheless, client understanding and demand for BIM can be a powerful motivator for its widespread adoption throughout the industry. Finally, the suggestion that the government should introduce policies to promote BIM received the lowest rank. While this does not mean that policy intervention is

unimportant, it may indicate a lack of urgency or trust in government action. Alternatively, respondents may believe that change should be driven by educational institutions and industry stakeholders before government intervention is effective.

In conclusion, the results show that education, training, and accessibility are the most effective strategies for raising BIM awareness. Academic curricula, expanded professional training, and improved access to tools can significantly improve the industry's readiness to adopt BIM. Organizational and institutional efforts must collaborate to create a supportive environment for BIM learning and practice.

### 4.5 PREFERRED METHOD FOR LEARNING BIM

*Table 8: Preferred method for learning*

| Preferred Method for Learning | Percentages |
|---|---|
| Formal university education | 17.3% |
| Online courses and self- learning | 28.6% |
| Workplace training and workshops | 49.0% |
| Conference and industry events | 3.1% |
| Other | 2.0% |

Participants were asked about their preferred ways to learn about BIM. The majority opted for workplace training and workshops (49.0%), indicating that professionals value learning through real-world experience and hands-on sessions. This was followed by online courses and self-learning (28.6 %), indicating that many people prefer flexible, self-paced learning methods. Formal university education (17.3%) followed, emphasizing the continued importance of academic involvement. Conferences and industry events (3.1%) were less popular, and only a few people chose other methods (2.0%). These responses clearly demonstrate that most professionals prefer practical, accessible learning methods that can be applied directly to their workplaces. It also implies that BIM education should be more prevalent in academic and professional settings.

## 5. DISCUSSION

The findings of this study indicate that BIM awareness among Sri Lankan construction professionals is gradually increasing, although practical implementation remains limited. This finding is consistent with previous research, which found that BIM adoption in Sri Lanka is still in its early stages due to limited industry readiness, insufficient technical knowledge, and organizational challenges (Epasinghe et al., 2018; Kaushalya et al., 2024). While many professionals are aware of BIM concepts and benefits, the use of BIM in projects remains relatively low. The findings further indicate a difference between BIM familiarity and practical BIM experience among respondents. While many participants reported being familiar with BIM or having used it on a limited basis, a significant proportion stated that they had no prior BIM experience. This could indicate that BIM awareness among construction professionals is frequently based on theoretical understanding or limited exposure rather than ongoing practical application. The findings also show that awareness alone does not always lead to regular BIM implementation in construction practice. The study also found that BIM usage is primarily limited to 3D modeling, with limited use of advanced BIM dimensions such as 5D and 6D. Similar findings were found by Ismail et al. (2017), who stated that BIM implementation in

developing countries is frequently hampered by a lack of training opportunities, technical expertise, and high implementation costs.

According to the RII analysis, the most significant barriers to BIM awareness and adoption are the high cost of BIM training and certification, as well as the limited availability of BIM training programs. These findings support previous research conducted both globally and in Sri Lanka, which found that financial constraints and a lack of educational support remain major barriers to BIM implementation (Kaushalya et al., 2024; Zaia et al., 2023). However, respondents did not strongly agree that BIM is difficult to learn or that a lack of trust in technology is a significant barrier, indicating that professionals are generally willing to adopt BIM technologies. The findings also showed that respondents highly ranked the strategy of introducing more BIM-related courses through universities, while workplace training and online self-learning were identified as the most preferred learning methods. This may suggest that respondents recognize the importance of universities in building a strong foundation of BIM knowledge for future professionals, while working professionals may prefer more flexible and practical learning methods that can be directly applied within the industry. Therefore, both academic education and practical industry-based training appear to be important for improving BIM awareness and implementation in Sri Lanka.

## 6. CONCLUSIONS AND RECOMMENDATIONS

This study assessed BIM awareness among construction professionals in Sri Lanka and identified the major barriers and strategies related to BIM adoption. The findings revealed that, while BIM awareness among Sri Lankan professionals is gradually increasing, practical implementation in the industry is still limited. Most professionals possess only basic BIM knowledge, and BIM usage is mainly restricted to 3D modelling applications. The study further identified that the high cost of BIM training and certification and the limited availability of training programs are the major barriers affecting BIM awareness and implementation. At the same time, respondents emphasized the importance of expanding BIM education and practical training opportunities through universities, professional institutions, and workplace training programs. Based on these findings, universities and professional organizations should expand BIM-related courses and provide more accessible practical training. Greater institutional and industry support is also required to promote wider BIM adoption in the Sri Lankan construction industry. Future research can focus on BIM implementation in specific sectors, such as infrastructure, MEP, and residential construction projects.

## 7. REFERENCES

Abanda, F. H., Mzyece, D., Oti, A. H., & Manjia, M. B. (2018). A study of the potential of cloud/mobile BIM for the management of construction projects. *Applied System Innovation, 1*(2), 9. https://doi.org/10.3390/asi1020009

Aibinu, A., & Venkatesh, S. (2014). Status of BIM adoption and the BIM experience of cost consultants in Australia. *Journal of Professional Issues in Engineering Education and Practice*, *140*(3), 04013021. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000193

Al-Kazee, M. F., Mahdavinejad, M., Ramhamdani, R. & Sallam, I. M. (2025). An investigation of barriers to adopting building information modeling (BIM) in the AEC industry of developing countries: A critical review. *Civil and Environmental Engineering, 21*(2), 1005-1014. https://doi.org/10.2478/cee-2025-0076

Azhar, S. (2011). Building Information Modelling (BIM): Trends, benefits, risks and challenges for the AEC industry. *Leadership and Management in Engineering, 11(3),* 241-252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Babatunde, S. O., Udeaja, C., & Adekunle, A. O. (2020). Barriers to BIM implementation and ways forward to improve its adoption in the Nigerian AEC firms. *International Journal of Building Pathology and* Adaptation, 39(1), 48-71. https://doi.org/10.1108/ijbpa-05-2019-0047

Charef, R., Emmitt, S., Alaka, H., & Fouchal, F. (2019). Building Information Modelling adoption in the European Union: An overview. *Journal of Building Engineering, 25,* 100777. https://doi.org/10.1016/j.jobe.2019.100777

Denscombe, M. (2010). *The good research guide: For small-scale social research projects* (4th ed.). Open University Press.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Epasinghe, E. A. K., Jayasena, H. S., Kolugala, L. M. B. N., & Wijewickrama, M. K. C. S. (2018). Open BIM adoption in Sri Lankan construction industry. *Proceedings of the FOSS4G Asia 2018 Conference* (pp. 1-13). University of Moratuwa. https://www.geoinfo-lab.org/foss4g-asia_2018/FOSS4GAsia_Publication_2018/Full%20Papers/Full%20paper_ID_44.pdf

Fathima, F., Jayasinghe, S., Prasadika, J., & Wijerathna, S. (2024). Drivers of actual usage of building information modelling tools by civil engineering professionals in construction industry of Sri Lanka. *Proceeding of the 2024 International Research Conference on Smart Computing and Systems Engineering (SCSE) (pp.* 1-7). IEEE. https://doi.org/10.1109/SCSE61872.2024.10550677

Ismail, N. A. A., Chiozzi, M., & Drogemuller, R. (2017). An overview of BIM uptake in Asian developing countries. *Proceeding of the 3rd International Conference on Construction and Building Engineering (ICONBUILD)* (pp.1-7). American Institute of Physics. https://doi.org/10.1063/1.5011596

Kaushalya, K. W. A. H. H., Thayaparan, M., Weerasinghe, L. N. K., & Attfield, A. (2024). Rogers' diffusion of innovation theory to enhance BIM implementation in the construction industry of Sri Lanka. *Intelligent Buildings International, 16*(4), 182-198. https://doi.org/10.1080/17508975.2024.2430217

Kineber, A. F., Othman, I., Famakin, I. O., Oke, A. E., Hamed, M. M., & Olayemi, T. M. (2023). Challenges to the implementation of building information modeling (BIM) for sustainable construction projects. *Applied Sciences, 13*(6), 3426. https://doi.org/10.3390/app13063426

Mahdi, M. M. & Ali, N. S. (2019). Reducing waste of construction materials in civil engineering projects in Iraq. *Zanco Journal of Pure and Applied Sciences, 31*(3). https://pdfs.semanticscholar.org/9bf8/740f9f1cc71c3377573a1f29582a9988095f.pdf

McGraw Hill Construction. (2014). *The business value of BIM for owners* (SmartMarket Report). McGraw Hill Construction, New York. https://damassets.autodesk.net/content/dam/autodesk/www/solutions/building-information-modeling/bim-value/Business_Value_of_BIM_for_Owners_SMR_(2014).pdf

Patel, A. (2022, September 30). *What is BIM (Building Information Modeling)? Uses & benefits.* United-BIM. https://www.united-bim.com/building-information-modeling/

Rathnasiri, P., & Jayasena, H. S. (2022). Green building information modelling technology adoption for existing buildings in Sri Lanka: Facilities management perspective. *Intelligent Buildings International, 14*(1), 23-44. https://doi.org/10.1080/17508975.2019.1632782

Rogers, J., Chong, H.Y., Preece, C., Lim, C. C., & Jayasena, H. S. (2015). *BIM development and trends in developing countries: Case studies*. Bentham Science Publishers. https://doi.org/10.2174/97816810801781150101

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers. John Wiley & Sons.

Samaraweera, R. L., Abeynayake, D. N., & Sivanraj, S. (2025). Integrating BIM into business models of consultancy firms: Barriers and enablers. *Proceedings of the 13th World Construction Symposium* (pp. 881-894). Ceylon Institute of Builders https://doi.org/10.31705/WCS.2025.66

Shah, N. (2025, November 25). *Leading countries with BIM adoption*. United-BIM. https://www.united-bim.com/leading-countries-with-bim-adoption/

Siriwardhana, M. S., Jayasena, H. S., Wijewickrama, M. K. C. S., & Kolugala, L. M. B. N. (2018). Suitable government initiative strategy for BIM implementation in Sri Lanka. Proceeding of t*he 7th World Construction Symposium 2018: (pp.* 519-526). Ceylon Institute of Builders. http://docs.suranga.net/publications/2018_Gov_Strategy4BIM_SL.pdf

Zaia, Y. Y., Adam, S. M. & Abdulrahman, F. H. (2023) Investigating BIM level in Iraqi construction industry, *Ain Shams Engineering Journal*, 14(3), 101881. https://doi.org/10.1016/j.asej.2022.101881

Thamodhya, G.H.D., Chandanie, H. and Subhasingha, H.D., 2026. Assessment of material wastage and material reconciliation practices in Sri Lankan road construction projects. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 263-277. DOI: https://doi.org/10.31705/WCS.2026.20. Available from: https://ciobwcs.com/papers/

# ASSESSMENT OF MATERIAL WASTAGE AND MATERIAL RECONCILIATION PRACTICES IN SRI LANKAN ROAD CONSTRUCTION PROJECTS

**G.H.D. Thamodhya[1], H. Chandanie[2] and H.D. Subhasingha[3]**

## *ABSTRACT*

*Road construction projects involve extensive use of materials such as asphalt, aggregates, and concrete, making them highly susceptible to material wastage and associated cost implications. Effective material reconciliation is therefore essential for monitoring material consumption, minimising wastage, and improving cost control. However, despite its importance, the application of structured material reconciliation practices in road construction projects in Sri Lanka remains limited and largely unstandardised. This study aims to identify wastage sensitive materials and examine the prevailing material reconciliation practices adopted in road construction projects in Sri Lanka. A quantitative research approach was adopted, where data were collected through a questionnaire survey administered among 54 road construction industry professionals using a heterogeneous purposive sampling technique. The collected data were analysed using descriptive statistical analysis with the support of IBM SPSS software, employing statistical parameters including mean and standard deviation. The findings revealed that asphalt is perceived as the most cost significant material in road construction projects. In contrast, aggregate and gravel were identified as the materials most susceptible to wastage due to factors such as transportation losses, handling issues, and storage challenges. The study further identified that material reconciliation in the Sri Lankan road construction sector is predominantly carried out through traditional manual practices. The adoption of advanced technological solutions and digital monitoring tools remains relatively limited. The study highlights the need for establishing standardised material reconciliation procedures and integrating digital technologies to enhance material monitoring, reduce wastage, and strengthen cost control in road construction projects.*

***Keywords:*** *Material Reconciliation; Material Waste; Road Construction Projects; Sri Lanka; Wastage Sensitive Materials.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, thamodhyaghd.21@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, subhasinghahd.20@uom.lk

# 1. INTRODUCTION

Road construction projects depend heavily on large volumes of few materials, making them highly susceptible to material wastage throughout the project lifecycle (Aftab et al., 2025). As a result, road projects generate substantial amounts of construction waste, making material wastage a critical challenge for the industry (Waty et al., 2018). This issue is particularly significant as excessive material waste contributes to cost overruns, resource inefficiencies, and adverse environmental impacts (Kothalawala et al., 2025). This necessitates the need for a proper mechanism to monitor the material wastage, since in road projects planned scopes, budgets, and meeting schedules are located in different geographic regions presenting significant challenges (Rachid et al., 2019). Material reconciliation is widely recognised as an effective mechanism for monitoring material consumption, identifying discrepancies between estimated and actual usage, and controlling wastage through proper documentation and accountability (Priyaruwan et al., 2020). Although material reconciliation and proper documentation are recognised as effective strategies to manage wastage, its actual application in road construction projects remains limited (Priyaruwan et al., 2020). Despite the importance, Sri Lanka lacks a structured framework to regulate construction waste in road projects which leads to uncoordinated and ineffective practices (Nishanthi & Ratnayake, 2025). The absence of proper material reconciliation system has been identified as the major reason for the excessive material wastage in construction sites in Sri Lanka (Kothalawala et al., 2025). According to Rameezdeen et al. (2004), ineffective waste measurement methods, insufficient record-keeping, and the inability to accurately capture waste generated through rework have hindered effective material control and reconciliation processes. Existing studies primarily focus on waste generation rates and disposal methods, with limited attention given to quantifying the associated cost implications specifically in road construction (Jayapadma et al., 2025). However, the absence of a standardised, structured approach to material reconciliation has led to frequent discrepancies between estimated and actual material usage in Sri Lanka (Rameezdeen et al., 2004). Consequently, a significant research gap exists regarding the implementation of material reconciliation in Sri Lankan road construction projects, particularly in identifying wastage-sensitive materials that require prioritised monitoring and establishing effective reconciliation approaches that can be integrated into the project lifecycle (Senarathna & Perera, 2021).Therefore this study aims to identify wastage sensitive materials and examine prevailing material reconciliation practices in road construction projects in Sri Lanka through below mention objectives. i.e. Critically review the significance of material reconciliation in road construction projects, with particular emphasis on wastage sensitive materials, and identify the current material reconciliation practices in the Sri Lankan road construction industry.

# 2. LITERATURE REVIEW

Given the scale of road construction work, a substantial amount of construction waste is generated during operations throughout the project lifecycle (Paranavithana et al., 2024). Road construction projects usually extend over wide geographical areas and are particularly susceptible to high threat due to unpredictable underground conditions (El-Sayegh & Mansour, 2015; Mishmish & El-Sayegh, 2018). Consequently, storage arrangements are often inadequate due to the limited availability of storage space in road projects (Aftab et al., 2025). However, uncertainties in road length and lack of specific

material intensity data may lead to significant discrepancies in stock estimations which complicate resource allocation and increase risk of material waste (Grossegger et al., 2024). Ogbu and Adindu (2019) stated that road construction projects often lead to cost overruns, with the majority being due to material wastages. Accordingly, the impact of waste materials on projects encompasses cost, time, productivity, and sustainability (Nagapan et al., 2012). Hence, critical understanding of the underlying causes of material waste within the road construction industry is essential for improving efficiency, reducing environmental impact, and lowering project costs (Paranavithana et al., 2024).

## 2.1 WASTAGE SENSITIVE MATERIALS IN ROAD CONSTRUCTION

Focused studies on Aggregate Base Course (ABC) wastage in Sri Lankan Road projects indicate that material waste is primarily caused by inappropriate storage, improper utilisation, transportation damage, and inadequate documentation (Priyaruwan et al., 2020). Similarly, a study conducted in Qatar identified 26 generic causes of waste in infrastructure projects and through structural equation modelling, systematically categorised into five clusters i.e. (i) design, (ii) logistics, (iii) procurement, (iv) execution, and (v) others thereby highlighting the multifaceted ways of material wastage within the construction process (Aftab et al., 2025). Furthermore, poor material management practices, such as inaccurate procurement and suboptimal onsite storage practices, lead to excess inventory and increased material waste, emphasising the need for proper planning, supply, logistics, and transport (Yıldız et al., 2024). Thus, material management is important to minimise material waste in road construction (Priyaruwan et al., 2020).

Moreover, road construction projects face distinct material management challenges due to complex supply chains and the management of locally procured materials including large volumes of asphalt, aggregates, and reinforcement steel (Awaad et al., 2024). Material costs significantly influence the overall expenditure of a construction project while wastage reduces profit margins particularly in road construction where even minor reductions in material waste can result in substantial financial savings (Aftab et al., 2025). Aftab et al. (2025) further reported that key materials in road construction include subgrade, subbase, base, and asphaltic layers for pavements, along with concrete and steel for culvert and bridge structures.

*Table 1: Wastage sensitive materials in road construction*

| Key material | Wastage Factors | Cost Significance | References |
|---|---|---|---|
| Aggregate | Loss during loading, transport, spillage and difficult recovery on site | Major cost component due to high consumption volumes and direct influence on overall pavement cost | [1], [2], [6], [8], [16], [17], [18], [19], [20], [21], [22] |
| Concrete | Over ordering and mixing errors, quick hardening limits reuse | High-cost burdens because unused or rejected quantities result in direct financial loss with limited recovery value | [3], [4], [5], [8], [9], [10], [11], [12], [15], [16], [18] |

| Key material | Wastage Factors | Cost Significance | References |
|---|---|---|---|
| Asphalt | Improper timing, placement, or compaction during surfacing operations | Highly cost significant as errors or inefficiencies often necessitate expensive rework or premature resurfacing throughout the pavement life cycle | [6], [7], [10], [13] |
| Sand | Lost due to wind, water displacement and spillage | Low priced yet extensive and repetitive usage requirements across multiple layers | [1], [13], [14], [21], [22] |
| Steel | Off-cuts, design changes, inaccurate bar bending schedules, theft and corrosion | High-cost significance duet to high value and wastage directly increases structural cost, limited reuse after cutting and bending | [2], [3], [10], [12], [21] |
| Gravel | Overestimation and unmanaged stockpiling cause waste | Moderate cost significance, mainly due to repurchasing needs and added transport cost | [13], [14] |
| Cement | Moisture exposure and poor storage lead to wastage | Moderate cost significance since any damaged cement becomes unusable, resulting in total material loss | [11], [12], [21] |
| Tarmac | Degrades if not promptly applied, process errors cause rework | Very High significance for sealing, surfacing degraded material requires full replacement | [11], [12], [22] |
| Granular Materials | Waste in site clearance, transport losses, and poor compaction | Moderate cost significance, as poor compaction affects pavement | [10], [13] |

[1] (Patil & Pataskar, 2013); [2] (Busari et al., 2019); [3] (Mazhar et al., 2023); [4] (Fanijo et al., 2023); [5] (Ray et al., 2021); [6] (Havanagi et al., 2012); [7] (Rahman et al., 2020); [8] (Waty et al., 2018); [9] (Ahmed et al., 2025); [10] (Grossegger et al., 2024); [11] (Swinburne et al., 2010); [12] (Aftab et al., 2025); [13] (Rajendran & Gambatese, 2007); [14] (Krausmann et al., 2017); [15] (Ouslimane et al., 2025); [16] (Yuriz et al., 2020); [17] (Thakur et al., 2022); [18] (Assadi, 2022); [19] (Priyaruwan et al., 2020); [20] (Perera & Shandraseharan, 2023); [21] (Munkombwe & Chibomba, 2025); [22] (Paranavithana et al., 2024)

As evidenced by Table 1, concrete and aggregate emerge as the most extensively investigated materials in the existing literature, reflecting their widespread investigation across most of the reviewed studies. Consequently, these materials can be identified as the most wastage sensitive, yet careful consumption is adequate due to its high-cost significance. Additionally, sand, gravel, cement, tarmac, steel, and granular materials were found to be moderately susceptible to wastage, underscoring the substantial research

emphasis placed on these materials due to their extensive utilisation in road construction and their significant implications for project cost, quality, and sustainability.

## 2.2 MATERIAL RECONCILIATION AND ITS BENEFITS

Material reconciliation is a key technique in material waste management which aims to eliminate discrepancies between the amount of material procured and the quantity specified in Bills of Quantities (BOQ) (Ajayi et al., 2017). Senarathna and Perera (2021) further state that preparation of material reconciliation report compares the difference between store records and actual material requirement. Thus, the wastage can be considered as proportionate to the actual work done (Mishra & Aithal, 2022). Effective material reconciliation ensures accurate tracking of usage, minimises waste, and enhances cost control, aligning with sustainable construction practices (Ahmad et al., 2025). Road construction projects are regarded as high risk because of the constant cost escalation, which is mainly due to the wastage of materials (Kothalawala et al., 2025). It is imperative for contractors to have a precise understanding of the materials required for each activity to compare against the actual material consumption (Manewa et al., 2007). In addition, comprehensive documentation and record keeping managed by quantity surveyors, are primarily essential to ensure accuracy and transparency in the process of material reconciliation (Ekanayake et al., 2025).

The precise determination of road layer service time and careful tracking of material movements, especially in the context of demolition activities when on site recycling is often unrecorded and essential to reduce discrepancies between estimated and reported waste generation (Grossegger et al., 2024). Similarly, Priyaruwan et al. (2020) revealed implementing effective material management practices lead to secure resources, control departmental expenditures, ensure reliable supplies, and maintain accurate records, including material reconciliation. Periodic updating of the material reconciliation reports is a key determinant of cost control through the detection of excesses or shortages (Ogbu & Adindu, 2019). Moreover, material reconciliation is preferred over work studies as it overcomes challenges such as inaccurate waste measurement during construction (Rameezdeen et al., 2004). Accordingly, the absence of proper material reconciliation system has been identified as a major contributor to material wastage in Sri Lankan road construction projects highlighting the need to adopt into appropriate waste minimisation approaches (Priyaruwan et al., 2020).

## 2.3 CURRENT MATERIAL RECONCILIATION PRACTICES AND TECHNIQUES IN SRI LANKA

Effective project delivery requires actions such as accurate material estimation, effective scheduling, regular monitoring, risk management, inventory management, and the adoption of technology enabled tracking and monitoring systems (Gunawardana & Bandaranayake, 2024). Material reconciliation was conducted by examining the difference between the store records and actual requirement of the material according to the items in the BOQ (Perera & Amarathunga, 2018; Rameezdeen et al., 2004). Material reconciliation reports are prepared to achieve timely and cost targets (Waduwawala et al., 2019). The Table 2 presents the current material reconciliation practices, tools used and the supporting management approaches within the Sri Lankan construction industry.

*Table 2: Current material reconciliation practices in construction projects in Sri Lanka*

| Category | Element | References |
|---|---|---|
| Material Reconciliation Practices | Comparison of Theoretical vs. Actual Quantities | [1], [2], [3], [10], [11], [16], [17], [18], [20] |
| | Physical Stocktaking and Audits | [2], [12], [18] |
| | Detailed Documentation | [2], [3], [21] |
| | Reconciliation Reports | [3], [10], [11], [15], [19] |
| Supporting Management Approaches | Lean construction practices | [3], [13], [14] |
| | Circular Economy principles | [5], [6], [7], [9] |
| Supporting Tools and Technologies | Spreadsheets and Basic Databases | [8] |
| | Construction ERP Systems | [4], [12], [21] |
| | Building Information Modeling (BIM) | [3], [12] |

[1] (Rameezdeen et al., 2004); [2] (Priyaruwan et al., 2020); [3] (Kothalawala et al., 2025); [4] (Hewavitharana et al., 2025); [5] (Victar & Waidyasekara, 2024); [6] (Bimsara et al., 2024); [7] (Wanaguru et al., 2022); [8] (Pararajasingam et al., 2024); [9] (Victar & Waidyasekara, 2025); [10] (Manewa et al., 2007); [11] (Seneviratne et al., 2015); [12] (Jayapadma et al., 2025); [13] (Pandithawatta et al., 2019); [14] (Senevirathne & Wimalasena, 2025); [15] (Waduwawala et al., 2019); [16] (Abeyrathne et al., 2022); [17] (Paranavithana et al., 2024); [18] (Karunasena et al., 2023); [19] (Swaranjali, 2017); [20] (Perera & Amarathunga, 2018); [21] (Gowthaman et al., 2025)

According to Table 2, the comparison of theoretical and actual material quantities is the most widely adopted material reconciliation practice in construction projects. Traditional manual and paper-based methods continue to dominate material reconciliation activities in the Sri Lankan road construction sector (Priyaruwan et al., 2020). In addition to these direct practices, lean construction approaches such as the 5S concept support material reconciliation by improving material organisation, monitoring, and control (Senevirathne & Wimalasena, 2025; Thilakarathna & De Silva, 2014). Similarly, Circular Economy principles contribute to reconciliation objectives through waste reduction and resource efficiency (Victar & Waidyasekara, 2024). Furthermore, technologies such as spreadsheets, databases, ERP systems, and BIM facilitate material reconciliation by improving data management, stock control, and reporting capabilities. Therefore, while management approaches and technologies support effective material reconciliation, they are distinct from the reconciliation practices themselves.

## 2.4 DRAWBACKS IN CURRENT MATERIAL RECONCILIATION PRACTICES

Notable limitations can be identified in existing material reconciliation practices which leads to ineffective material management (Eze et al., 2020). Thus, material reconciliation practices remain inconsistent, informal, and inadequately documented within developing construction sectors such as Sri Lanka (Pararajasingam et al., 2024). However, further drawbacks such as lack of standardisation, inadequate knowledge of staff, improper recording and return of materials can be observed in current material reconciliation practices in Sri Lanka (Priyaruwan et al., 2020). Material management systems are conducted manually, with stock accumulation or depletion determined by input output balances although quantifying flows and stocks remain challenging due to data

uncertainties and limited availability (Rameezdeen et al., 2004). Traditional methods are often encountered with incomplete documents and delays in documentation (Pathiranage & Halwatura, 2010). The absence of records on criminal wastage, and the difficulty of capturing waste from rectification work, though its tedious nature often restricts quantification to the most used materials in Sri Lankan projects (Rameezdeen et al., 2004). Moreover, inefficient material monitoring and lack of real time tracking systems have been reported as a significant issue in Sri Lankan construction industry (Ekanayaka & Eranga, 2025).

# 3. RESEARCH METHODOLOGY

Quantitative research approach was adopted in this study since it statistically analyses the data. Initially, a literature review was conducted to identify the wastage sensitive materials and material reconciliation practices from existing studies. Questionnaire survey offers data which can be interpreted and analysed (Cohen et al., 2017). Therefore, the perspective of material reconciliation practices was collected from industry practitioners. The heterogeneous purposive sampling technique was used for quantitative approaches to select a representative sample from the population as it assisted in selecting a sample that is relevant to a range of experiences, perspectives, and characteristics (Tongco, 2007). The questionnaire survey was administered to approximately 80 construction industry professionals to collect data, as it is sufficient to get a moderate response rate of 60-70%. The questionnaire consisted of three main sections. The first section is used to collect demographic information of the respondents, and second and third sections are used to gather insights of wastage sensitive materials and material reconciliation practices in road construction projects in local context. In addition, questionnaire surveys were circulated via email, LinkedIn and WhatsApp to encourage participation of industry practitioners. IBM SPSS software was employed as the primary analytical tool to facilitate the statistical evaluation of the survey data utilising descriptive statistical analysis. The analysis was further elaborated through the application of key statistical parameters including Mean, Standard Deviation, and Variance, derived from ratings of the respondents (Yin et al., 2022).

# 4. RESEARCH FINDINGS

This section presents the result and findings obtained from the questionnaire survey conducted among industry professionals with reference to wastage sensitive materials and prevailing material reconciliation practices.

## 4.1 RESPONDENT'S DEMOGRAPHIC INFORMATION

Most respondents represented main contracting organisations. However, participants from consultancy firms, subcontractor organisations, and government institutions were further included to ensure comprehensive coverage of all relevant stakeholder groups within the construction industry. The professional roles of the selected respondents are further illustrated in Figure 2. Quantity Surveyors constituted most of the respondents, whilst the remaining participants comprised Project Managers, Site Engineers, Material and Storekeepers, Technical Officers, Contract Administrators, and Deputy Project Managers.

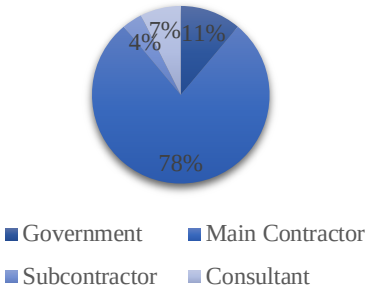



*Figure1: Type of organisation*

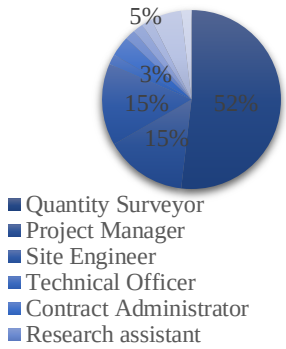



*Figure 2: Respondent's role*

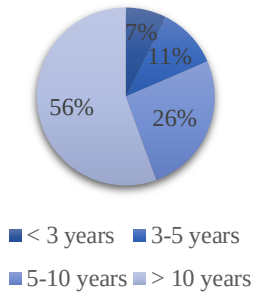



*Figure 3: Years of experience*

The distribution of respondents according to their level of industry experience is presented in Figure 3. In terms of industry experience, the largest proportion of respondents possessed more than ten years of professional experience, followed by those with experience ranging between five and ten years affirming that most survey participants had substantial industry exposure. Moreover, based on the demographic study of the analysis, the average years of experience and minimum qualifications reflected an adequate amount of experience and expertise, which subsequently guarantees the ability of the respondents to properly understand and answer the questionnaire.

## 4.2 Assessment of Wastage Sensitivity and Cost Significance of Materials in Road Construction Projects

### 4.2.1 Cost Significant Materials in Road Construction Projects

The respondents were provided with a 5-point Likert scale to assess the level of cost significance of each identified material. The materials subject to evaluation were derived from the literature synthesis.

*Table 3: Statistical parameters of cost significant materials from descriptive analysis*

| Key material | Mean | Std. Deviation |
|---|---|---|
| Asphalt | 4.5000 | 0.86330 |
| Aggregate | 4.1296 | 1.02876 |
| Concrete | 3.9815 | 1.07266 |
| Granular Materials | 3.7593 | 1.04494 |
| Cement | 3.7407 | 1.06727 |
| Gravel | 3.7222 | 1.20403 |
| Steel | 3.6667 | 1.19748 |
| Tarmac | 3.5000 | 1.29949 |
| Sand | 3.3889 | 1.10602 |

The standard deviation values range between 0.863 and 1.299, indicating a moderate level of variability in perceptions of respondents regarding the cost significance of materials used in road construction projects. Subsequently, cost significance of each material was ranked according to the calculated mean value. The result revealed that asphalt recorded the highest mean score, indicating the highest cost significance among listed materials marking higher than 4.20 Mean value.

### 4.2.2 Wastage Sensitive Materials in Road Construction Projects

Several road construction materials were provided to respondents to evaluate considering the possibility of wastage of given materials using 5-point Likert scale. The scale ranged from 1 (Very low possibility) to 5 (Very high possibility) reflecting the perceived degree of wastage possibility attributed to each material. The collected data were subjected to descriptive statistical analysis.

*Table 4: Statistical parameters of wastage sensitive materials from descriptive analysis*

| Key material | Mean | Std. Deviation |
|---|---|---|
| Aggregate | 3.7407 | 1.26170 |
| Gravel | 3.6852 | 1.24118 |
| Granular Materials | 3.3889 | 1.21960 |
| Sand | 3.1296 | 1.25962 |
| Concrete | 2.9074 | 1.24792 |
| Cement | 2.8704 | 1.16629 |
| Asphalt | 2.8333 | 1.16149 |
| Steel | 2.8333 | 1.20924 |
| Tarmac | 2.6111 | 1.13962 |

As per the given table, aggregate recorded the highest perceived possibility of wastage marking 3.74 Mean, followed by gravel reflecting 3.68 Mean value. In contrast tarmac recorded the lowest possibility of wastage marking 2.61 Mean value. The standard deviation ranging from 1.13 to 1.26 reflects the moderate variability in perceptions of respondents regarding the wastage potentiality of the determined materials considering the practical complexities in construction projects. The identified materials were systematically ranked considering the Mean value to facilitate a comprehensive interpretation of the result.

## 4.3 MATERIAL RECONCILIATION PRACTICES IN ROAD CONSTRUCTION PROJECTS

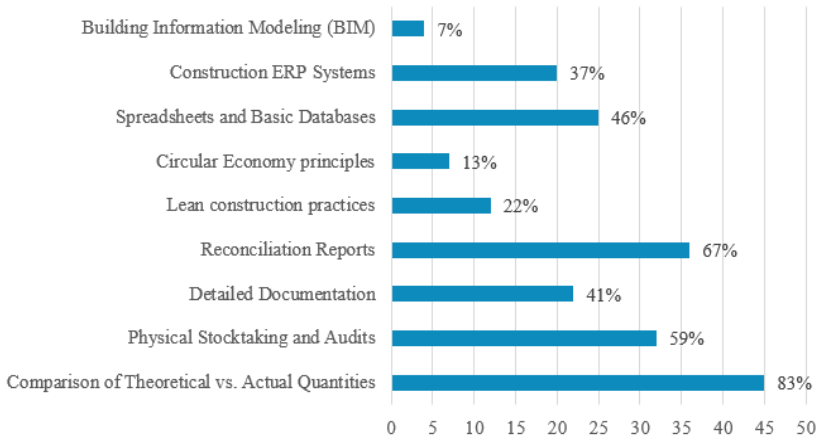



*Figure 4: Current material reconciliation practices identified*

The findings revealed that the comparison of theoretical quantities against actual quantities utilised was the most widely practised material reconciliation method, as reported by 83% of the survey respondents. Accordingly, 67% of respondents have stated

that preparation of reconciliation reports is widely applied in road construction projects followed by 59% of respondents have mentioned that physical stocktaking and audits are widely used. Moreover, spreadsheet-based material reconciliation and use of databases have been identified as moderately used in road construction projects as mentioned by 46% of respondents while construction ERP system was used in few road construction projects as mentioned by 37% of respondents. Practices such as lean construction practices (22%), and circular economy principles (13%), are less frequently used in road construction projects. Notably, Building Information Modelling (BIM) recorded the lowest adoption rate of merely 7%, suggesting that this technology remains largely unsuitable and inapplicable within the current material reconciliation practices of road construction projects in Sri Lanka.

### 4.4 INPUT DOCUMENTS USED IN MATERIAL RECONCILIATION

The respondents were requested to mention the input documents that predominantly utilised to conduct material reconciliation in road construction projects through an open-ended question. The responses received were systematically compiled and presented in a frequency table to facilitate a more accurate and structured analysis of the collected data. The empirical findings demonstrate a pronounced reliance on procurement and site records including material issue note, goods received note, and stock records emerging as primary input documents. As illustrated in the radar chart these documents represents the highest frequency of usage as input documents to conduct material reconciliation indicating that prevailing industry practices remain heavily rely on manual paper-based approaches.

*Figure 5: Input documents used in road construction projects*

## 5. DISCUSSION

The findings present wastage sensitive materials and the current material reconciliation practices within road construction projects in Sri Lanka. Thus, the analysis revealed that asphalt emerged as the most cost significant material, and it presents a mean value that exceeds threshold value and shows the presence of strong impact of asphalt on the total costs of the projects (Rajendran & Gambatese, 2007). The significance of the other materials like aggregate and ready-mix concrete was further found to be relatively high. Aggregate and gravel were identified as the materials most susceptible to wastage, a finding attributable to the considerable losses incurred during transportation, spillage

during handling, and the inability to recover such materials once lost on site (Priyaruwan et al., 2020). These results correlate with previous studies that have found aggregates as high waste prone materials in road construction works due to the substantial quantities involved in road construction projects (Waty et al., 2018). Furthermore, the findings suggest that material reconciliation is predominantly conducted through traditional methods such as comparison of theoretical quantities with actual quantities, preparation of reconciliation reports, and physical stocktaking (Kothalawala et al., 2025). However, the adoption of advanced practices, including ERP systems, lean construction techniques, and circular economy practices remains relatively limited. This implies that material reconciliation processes are largely manual and decentralised highlighting the necessity for enhanced standardisation and greater integration of digital technologies to improve material monitoring and waste control.

## 6. CONCLUSIONS

This study investigated road construction materials and prevailing material reconciliation practices within the context of road construction projects in Sri Lanka. Based on the descriptive statistical analysis asphalt was established as the most cost significant material whereas the aggregate and gravel demonstrated the highest possibility of wastage due to losses incurred during handling, transportation and storage. The findings further revealed that material reconciliation practices within the Sri Lankan road construction industry are majorly based on the traditional manual method including theoretical and actual quantity comparisons, reconciliation reporting and physical verification of stock. Even though these techniques offer a simple approach to tracking the material utilisation, the implementation of advanced technological solutions, including ERP systems, and other digital monitoring tools, remains considerably limited within the industry. Thus, the research underscores critical importance of establishing standardised material reconciliation procedures and advocating for the integration of modern digital technologies to enhance material tracking, minimise wastage, and strengthen cost control mechanisms in road construction projects in Sri Lanka. This study is limited to the context of road construction projects in Sri Lanka. Therefore, the applicability of the findings is constrained within similar project environments. Future studies can be extended the scope to other infrastructure sectors and explore advanced approaches of conducting material reconciliation in global construction sector and adoptability and suitability of the identified approaches to further enhance material management practices within the construction industry.

## 7. REFERENCES

Abeyrathne, S., Jayasooriya, S., & Withanage, K. (2022). Impact of material management on cost overruns in construction projects in Sri Lanka. In *General Sir John Kotelawala Defence University – 15th International Research Conference*. General Sir John Kotelawala Defence University. http://ir.kdu.ac.lk/handle/345/6079

Aftab, U., Jaleel, F., Aslam, M., & Tipu, J. A. K. (2025). Exploring the critical waste factors affecting highway construction projects in Pakistan. *PLOS One*, *20*(5), e0323841. https://doi.org/10.1371/JOURNAL.PONE.0323841

Ahmad, D. M., Gáspár, L., Shaheen, H. M., Al-Shihabi, T. A., Maya, R. A., & Pinto, F. S. (2025). Improving material tracking for sustainable construction: A Standard Operating procedure (SOP) framework for resource efficiency. *Buildings*, *15*(11), 1941. https://doi.org/10.3390/buildings15111941

Ahmed, W., Lu, G., Ng, S. T., & Liu, G. (2025). Innovative valorization of solid waste materials for production of sustainable low-carbon pavement: A systematic review and scientometric analysis. *Case Studies in Construction Materials*, *22*, e04541. https://doi.org/10.1016/J.CSCM.2025.E04541

Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Alaka, H. A., & Owolabi, H. A. (2017). Optimising material procurement for construction waste minimization: An exploration of success factors. *Sustainable Materials and Technologies*, 11, 38–46. https://doi.org/10.1016/j.susmat.2017.01.001

Assadi, A. (2022). The benefits of using recycled crushed aggregates in infrastructure projects study report. In EXP Services Inc. https://www.ossga.com/multimedia/2022-12-06-140628-15051/exp-benefits_of_using_recycled_crushed_aggregates.pdf

Awaad, S., Mansour, D. M., Mahdi, I., & Abdelrasheed, I. (2024). Impact of material supply chain on the productivity optimization for the construction of roads projects. Scientific Reports, 14, 3294. https://doi.org/10.1038/s41598-024-53660-6

Bimsara, K.D.M., Abenayake, D.N., Lingasabesan, V. and Shanika, V.G., 2024. Adopting circular economy practices in major building materials and elements to minimise waste in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). Proceedings of the 12th World Construction Symposium, 9-10 August 2024, Sri Lanka. pp. 105-118. https://doi.org/10.31705/WCS.2024.9

Busari, A., Adeyanju, E., Loto, T., & Ademola, D. (2019). Recycled aggregate in pavement Construction: Review of literatures. *Journal of Physics Conference Series*, *1378*(2), 022026. https://doi.org/10.1088/1742-6596/1378/2/022026

Cohen, L., Manion, L., & Morrison, K. (2017). Questionnaires. *Research Methods in Education*, 471–505. https://doi.org/10.4324/9781315456539-24

Ekanayaka, E. M. K. K., & Eranga, B. A. I. (2025). Enhancing labour productivity in the Sri Lankan construction industry through computer vision. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), Proceedings of the 13th World Construction Symposium (pp. 635–648). https://doi.org/10.31705/WCS.2025.48.

Ekanayake, G. B. E. M. A. S., Disaratna, P. A. P. V. D. S., Ilangakoon, I. W. M. A. D., & Perera, B. A. K. S. (2025). Adequacy of document management systems for post contract quantity surveying roles: A qualitative delphi study. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *17*(4), 04525043. https://doi.org/10.1061/JLADAH.LADR-1243

El-Sayegh, S. M., & Mansour, M. H. (2015). Risk assessment and allocation in highway construction projects in the UAE. *Journal of Management in Engineering*, *31*(6), 04015004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000365

Eze, C. E., Awodele, I. A., Adegboyega, A. A., Onyeagam, O. P., & Guto, J. A. (2020). Assessment of the triggers of inefficient materials management practices by construction SMEs in Nigeria. *International Journal of Real Estate Studies*, *14*(1), 38–56. https://doi.org/10.11113/INTREST.V14N1.134

Fanijo, E. O., Kolawole, J. T., Babafemi, A. J., & Liu, J. (2023). A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability. *Cleaner Materials*, *9*, 100199. https://doi.org/10.1016/J.CLEMA.2023.100199

Gowthaman, M., Gamage, I., & Karunaratne, T. (2025). Framework for managing deficiencies and inefficiencies in quantity surveying-related software implementation. *Construction Economics and Building*, *25*(2), 192–214. https://doi.org/10.5130/AJCEB.V25I2.9191

Grossegger, D., MacAskill, K., & Al-Tabbaa, A. (2024). A critical review of road network material stocks and flows: Current progress and what we can learn from it. *Resources Conservation and Recycling*, *205*, 107584. https://doi.org/10.1016/j.resconrec.2024.107584

Gunawardana, M. D. D., & Bandaranayake, D. (2024). Technological infrastructure for remote construction works in Western province of Sri Lanka. *Journal of Research Technology and Engineering*, *5*(4), 93–102. https://www.jrte.org/wp-content/uploads/2024/10/Technological-Infrastructure-for-Remote-Construction-Works-in-Western-Province-of-Sri-Lanka.pdf

Havanagi, V. G., Sinha, A. K., Arora, V. K., & Mathur, S. (2012). Waste materials for construction of road embankment and pavement layers. International Journal of Environmental Engineering Res, 1(2), 51-59.

Hewavitharana, S., Perera, A., Perera, S., Perera, P., & Nanayakkara, S. (2025). Framework for systematic adoption of ERP systems in the Sri Lankan construction industry. *Built Environment Project and Asset Management*, *15*(3), 629–646. https://doi.org/10.1108/BEPAM-12-2023-0226

Jayapadma, M., Wijekoon, K., & Deheragoda, H. (2025). Impact of material waste management on construction cost of projects in the Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), Proceedings of the 13th World Construction Symposium (pp. 841–852). https://doi.org/10.31705/WCS.2025.63.

Karunasena, G., Fernando, G., Ashokkumar, D., & Liu, C. (2023). Influence of labour experience in the generation of construction material waste in the Sri Lankan construction industry. Sustainability, 15(6), 5406. https://doi.org/10.3390/su15065406

Kothalawala, N. T. B., Malkanthi, S. N., & Dharmaratne, P. D. (2025). Material wastage on cost overrun in construction projects: An impact study carried out in Sri Lanka. *Journal of Advances in Engineering and Technology*, *3*(2), 65–77. https://doi.org/10.54389/OUTQ9902

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences*, *114*(8), 1880–1885. https://doi.org/10.1073/PNAS.1613773114

Manewa, R., Rameezdeen, R., Amaratunga, D., & Ginige, K. (2007). Towards The sustainable construction through minimising site waste in Sri Lanka. *University of Salford Institutional Repository (University of Salford)*, 319–326. http://usir.salford.ac.uk/id/eprint/9851/1/138_Manewa_RMAS_et_al_TOWARDS_THE_SUSTAINABLE_CONSTRUCTION_THROUGH_MINIMISING_SITE_WASTE_IN_SRI_LANKA_IPRC_2007.pdf

Mazhar, M. A., Alam, P., Ahmed, S., Khan, M. S., & Adam, F. A. (2023). Sustainable usage of demolished concrete waste as a sub-base material in road pavement. *Frontiers in Sustainability*, *4*, 1060878. https://doi.org/10.3389/FRSUS.2023.1060878/

Mishmish, M., & El-Sayegh, S. M. (2018). Causes of claims in road construction projects in the UAE. *International Journal of Construction Management*, *18*(1), 26–33. https://doi.org/10.1080/15623599.2016.1230959

Mishra, A. K., & Aithal, P. S. (2022). Assessing the magnitude of waste material using lean construction. *International Journal of Case Studies in Business, IT, and Education*, *6*(1), 578–589. https://doi.org/10.47992/IJCSBE.2581.6942.0180

Munkombwe, B., & Chibomba, K. (2025). Examining material management in project performance: A case study of road constructions projects in Solwezi. *International Journal of Advanced Multidisciplinary Research and Studies*, *5*(2), 1344–1355. https://doi.org/10.62225/2583049X.2025.5.2.3985

Nagapan, S., Rahman, I. A., & Asmi, A. (2012). Factors contributing to physical and non-physical waste generation in construction industry. *International Journal of Advances in Applied Sciences (IJAAS)*, *1*(1), 1–10.

Nishanthi, K., & Ratnayake, R. M. K. (2025). Harmonizing road development with natural resource management for Sri Lanka's sustainability. In *Young Scientists Forum (YSF) Thematic Publication-2025 Publisher: NASTEC, Sri Lanka* (pp. 255–274). https://www.researchgate.net/publication/389624361_Harmonizing_Road_Development_with_Natural_Resource_Management_for_Sri_Lanka's_Sustainability

Ogbu, C. P., & Adindu, C. C. (2019). Direct risk factors and cost performance of road projects in developing countries: Contractors' perspective. *Journal of Engineering Design and Technology*, *18*(2), 326–342. https://doi.org/10.1108/jedt-05-2019-0121

Ouslimane, N., Bensalah, J., Barebita, H., Ebntouhami, M., Younous, Y. A., Okla, M. K., Ibenmoussa, S., Dimane, F., & Belfaquir, M. (2025). Development and performance evaluation of alternative road construction material using clay and recycled concrete debris. *Scientific Reports*, *15*(1). https://doi.org/10.1038/S41598-025-89708-4

Pandithawatta, T. P. W. S. I., Zainudeen, N., & Perera, C. S. R. (2019). An integrated approach of Lean-Green construction: Sri Lankan perspective. *Built Environment Project and Asset Management*, *10*(2), 200–214. https://doi.org/10.1108/BEPAM-12-2018-0153

Paranavithana, G. N., Samarakoon, S. M. K., & Chathurika, R. H. J. (2024). Analysis of road construction waste generation in developing economies: A focus on surfacing and sub-base construction projects in Sri Lanka. *Journal of Cleaner Production*, *457*, 142465. https://doi.org/10.1016/J.JCLEPRO.2024.142465

Pararajasingam, R., Waidyasekara, A. S., & Victar, H. C. (2024). Exploring causes of ineffective material management and impact on successful project deliverables in civil engineering construction projects in Sri Lanka. *Construction Innovation*, *26*(1), 22–43. https://doi.org/10.1108/ci-11-2023-0281

Pathiranage, Y. L., & Halwatura, R. U. (2010). Factors influencing the duration of road construction projects in Sri Lanka. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *43*(4), 17. https://doi.org/10.4038/ENGINEER.V43I4.6997

Patil, A., & Pataskar, S. (2013). Analyzing material management techniques on construction project. International Journal of Engineering and Innovative Technology (IJEI, 3(4), 96–100. https://www.researchgate.net/profile/Ashwini-Patil-17/publication/354931892_Analyzing_material_management_techniques_on_construction_project/links/6154acee2b34872782013112/Analyzing-material-management-techniques-on-construction-project.pdf

Perera, B. L. S. H., & Amarathunga, A. R. K. (2018). Reducing the concrete waste while optimizing the cost, time & quality in Sri Lankan construction industry. In *11th International research conference General Sir John Kotelawala defence university*. General Sir John Kotelawala Defence University. https://ir.kdu.ac.lk/bitstream/handle/345/2464/Untitled%2814%29.pdf?sequence=1&isAllowed=y

Perera, B. A. K. S., & Shandraseharan, A. (2023). A framework for aggregate base course waste control in road construction projects. *International Journal of Construction Management*, *23*(6), 1009–1020. https://doi.org/10.1080/15623599.2021.1948187

Priyaruwan, E., Shandraseharan, A., & Perera, B. (2020). Management of aggregate base course wastage in road construction projects. *FARU Journal*, *7*, 40–47. https://doi.org/10.4038/faruj.v7i0.29

Rachid, Z., Toufik, B., & Mohammed, B. (2019). Causes of schedule delays in construction projects in Algeria. *International Journal of Construction Management*, *19*(5), 371–381. https://doi.org/10.1080/15623599.2018.1435234

Rahman, M. T., Mohajerani, A., & Giustozzi, F. (2020). Recycling of waste materials for asphalt concrete and bitumen: A review. *Materials*, *13*(7), 1495. https://doi.org/10.3390/MA13071495

Rajendran, S., & Gambatese, J. A. (2007). Solid waste generation in asphalt and reinforced concrete roadway life cycles. *Journal of Infrastructure Systems*, *13*(2), 88–96. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:2(88)

Rameezdeen, R. D. A., Kulatunga, U., & Amaratunga, D. (2004). Quantification of construction material waste in Sri Lankan sites. In *Proceedings of the International Built and Human Environment Research Week 2004*. The University of Salford. http://www.irbnet.de/daten/iconda/CIB14730.pdf

Ray, A., Nanda, R. P., & Roy, P. (2021). Use of C&D Waste in Road Construction: A critical review. *IOP Conference Series Materials Science and Engineering*, *1116*(1), 012159. https://doi.org/10.1088/1757-899x/1116/1/012159

Senarathna, D. R., & Perera, B. L. S. H. (2021). Managing concrete wastes by implementing contemporary construction practices in Sri Lanka. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 9th World Construction Symposium* (pp. 413–421). https://doi.org/10.31705/WCS.2021.36.

Senevirathne, H. M. K. A., & Wimalasena, B. A. D. S. (2025). Implementation of lean principles in building construction industry, Sri Lanka. *Advances in Technology*, *5*(01). https://doi.org/10.31357/AIT.V5I01.8404

Seneviratne, K., Rameezdeen, R., & Amaratunga, D. (2015). Contractor capacity and waste generation: An empirical investigation. *Journal of Construction in Developing Countries*, *20*(2), 25–36.

Swaranjali, K. (2017). Material management for construction site with using ERP. *International Journal of Innovative Science and Research Technology*, *2*(5). www.ijisrt.com573

Swinburne, J., Udeaja, C., & Tait, N. (2010). Measuring material wastage on construction sites: A case study of local authority highway projects. *Built and Natural Environment Research*

*Papers*. https://researchportal.northumbria.ac.uk/en/publications/measuring-material-wastage-on-construction-sites-a-case-study-of-

Thakur, C., Sharma, N., & Kanoungo, A. (2022). Utilization of construction and demolition waste in flexible pavements. *International Journal of Mechanical Engineering*, *7*(5), 325–332. https://www.researchgate.net/publication/360859885_Utilization_of_Construction_and_Demolition_Waste_in_Flexible_Pavements

Thilakarathna, N., & De Silva, M. L. (2014). Significance of minimizing non-value adding activities in construction processes using lean techniques. In *1st International conference of the CIB Middle East & North Africa Research Network CIB-MENA*. University of Moratuwa. http://dl.lib.mrt.ac.lk/handle/123/14151

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications*, *5*, 147–158. https://doi.org/10.17348/era.5.0.147-158

Victar, H. C., & Waidyasekara, A. S. (2025). Optimising construction waste management in Sri Lanka through Circular economy strategies: A focus on construction and renovation and use and operate stages. *Engineering, Construction and Architectural Management*, *32*(7), 4275–4309. https://doi.org/10.1108/ECAM-06-2023-0608

Victar, H. C., & Waidyasekara, K. G. A. S. (2024). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management & Research*, *42*(11), 953–976. https://doi.org/10.1177/0734242X231206988

Waduwawala, H. B., Perera, K. K., & Samaraweera, A. (2019). *Creating a sustainable lean culture in the construction organisations of developing countries: the case of Sri Lanka in CIDA journal 2019 December*.

Wanaguru, K., Mallawaarachchi, H., & Vijerathne, D. (2022). Circular economy (CE) based material selection: development of a CE-based '10R' evaluation framework for building construction projects in Sri Lanka. *World Construction Symposium*, 208–219. https://doi.org/10.31705/WCS.2022.18

Waty, M., Alisjahbana, S. W., Gondokusumo, O., Sulistio, H., Hasyim, C., Setiawan, M. I., Harmanto, D., & Ahmar, A. S. (2018). Modeling of waste material costs on road construction projects. *International Journal of Engineering and Technology*, *7*(2), 474–477. https://doi.org/10.14419/ijet.v7i2.11250

Yıldız, S., Güneş, S., & Kıvrak, S. (2024). Examining the impact of material management practices on project performance in the construction industry. *Buildings*, *14*(7), 2076. https://doi.org/10.3390/buildings14072076

Yin, K., Cao, Y., Zhou, S., & Lv, X. (2022). Research on optimization of index system design and its inspection method: data quality diagnosis, index classification and stratification. *Marine Economics and Management*, *5*(2), 105–146. https://doi.org/10.1108/maem-05-2022-0005

Yuriz, Y., Ismail, T. N. H. T., & Hassan, N. N. M. (2020). An overview of waste materials for sustainable road construction. *International Journal of Sustainable Construction Engineering and Technology*, *11*(1), 215–229. https://doi.org/10.30880/IJSCET.2020.11.01.021

Wijayawardhana, G.C.K., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Barriers to smart procurement implementation in the Sri Lankan construction sector: An empirical investigation. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 278-291. DOI: https://doi.org/10.31705/WCS.2026.21. Available from: https://ciobwcs.com/papers/

# BARRIERS TO SMART PROCUREMENT IMPLEMENTATION IN THE SRI LANKAN CONSTRUCTION SECTOR: AN EMPIRICAL INVESTIGATION

**G.C.K. Wijayawardhana[1], K. Thiruchelvam[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Smart procurement has the potential to improve decision-making, efficiency, and transparency in the procurement process using digital technologies like blockchain, artificial intelligence, and building information modelling. Despite the benefits of smart procurement techniques, their adoption remains low due to various barriers. This study investigates the barriers to smart procurement implementation in construction industry in Sri Lanka. A mixed-method research approach was used, beginning with a literature review to identify key barriers stated in global context, followed by a questionnaire survey of 30 industry experts with a significant procurement experience to assess their significance. The Relative Importance Index (RII) method was used to evaluate and rank the significance of identified barriers, while qualitative responses were analysed using thematic analysis to understand the perceived level of smart procurement adoption in the industry and to support the statistical findings. The results show that the most critical barrier is high implementation costs, which are followed by limited management support, data integrity concerns, legal and regulatory challenges, and cybersecurity risks. The qualitative analysis also reveals that small and medium-sized businesses in Sri Lanka still use traditional procurement methods, while smart procurement adoption is still restricted and mostly concentrated within large scale organizations. These findings provide policymakers and industry stakeholders with clear evidence on priority barriers, enabling the implementation of targeted strategies to address each barrier and promote the adoption of smart procurement in Sri Lanka's construction sector.*

***Keywords:*** *Barriers; Construction Industry; Smart Procurement; Sri Lanka.*

## 1. INTRODUCTION

In the construction industry, a project's success depends not only on meeting the time, cost, and quality but also on delivering an outcome that satisfies the client's expectation (Naoum & Egbu, 2015). Construction procurement remains largely traditional and slow to adapt to digitalization and causes inefficiencies in construction procurement and supply chains, leading to inflated project costs (Hamma-adama & Ahmad, 2021). To address

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, wijayawardhanagck.21@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

these challenges and to improve communication, to encourage transparency, as well as to enable improved integration among key stakeholders such as clients, consultants, contractors, and suppliers, smart procurement methods can be utilized (Masoom et al., 2025). Smart procurement can be defined as implementing digital technologies like artificial intelligence (AI), blockchain, e-procurement platforms, and integrated supply chain systems in procurement process to facilitate real-time cost monitoring, automated tendering, risk prediction, and data-driven contract management and it transforms procurement from a mere transactional process into a strategic role that supports social and environmental responsibility as well as economic resilience (Akande et al., 2025). Although there are many benefits of smart procurement such as higher transparency, efficiency, increased accountability, and cost effectiveness, their adoption remains low due to various barriers (Mbao et al., 2025).

There are several existing studies that discuss digital technology adoption in Sri Lankan construction industry such as those conducted by, Fernando et al. (2025), Gamage et al. (2025), and Nitharsan and Francis (2022). However, these authors discuss the use of individual technologies such as Building Information Modelling (BIM), e-tendering, digital twin etc. and there is a lack of studies that investigate smart procurement as a whole concept. Furthermore, there is a lack of studies investigating the perceptions of construction industry practitioners regarding the current level of smart procurement adoption in the construction industry in Sri Lanka. Although several studies such as Bandara et al. (2024) and Yaparathne et al. (2025) have discussed the barriers to digitalization in the Sri Lankan construction industry in general, they have not specifically examined how these barriers relate to smart procurement. Understanding these barriers can facilitate the effective implementation of smart procurement approaches within the construction sector. Therefore, the need for a proper investigation into the barriers to smart procurement implementation in Sri Lanka is required. The aim of this study is to examine the adoption of smart procurement in Sri Lanka's construction industry while evaluating the barriers influencing its effective implementation. To achieve the aim, the following objectives were formulated.

1. To review the barriers to the adoption of smart procurement in construction industry.
2. To assess the perceived significance of the identified barriers for the Sri Lankan construction industry.
3. To assess the perceived level of smart procurement adoption in Sri Lanka's construction industry.

# 2. LITERATURE REVIEW

## 2.1 WHAT IS SMART PROCUREMENT?

Procurement can be defined as the systematic process of identifying project needs, sourcing suppliers, evaluating bids, and acquiring goods, services, or works through tendering or competitive bidding (Bandara et al., 2024). On the other hand, smart procurement is the process of integrating new technologies like blockchain, smart contracts, and the Internet of Things (IoT) into construction supply chain procurement procedures to improve their efficacy and efficiency (Yevu et al., 2021b).

Since the traditional procurement system follows a linear and sequential process, it is considered as one of the slowest methods for project delivery (Okereke et al., 2022). Most current procurement stakeholders are aware that technology can be used to increase

performance, efficiency, and transparency of the procurement process (Uduwage et al., 2023). However, the introduction of digital procurement systems which were intended to replace traditional paper-based procurement and enhance project procurement processes, has experienced a slow rate of adoption (Yevu & Yu, 2019).

## 2.2 BARRIERS TO SMART PROCUREMENT

Despite that advanced digital technologies offer considerable potential to improve overall productivity of construction industry, numerous barriers continue to limit their effective adoption and widespread implementation within the industry (Perera et al., 2023a). Ojo-Fafore and Laryea (2024), defines barriers to the digitalization of procurement as the factors that hinder the smooth implementation of digital technologies in the procurement of goods and services within construction processes.

Barriers faced by developed countries and developing countries are different since the technological, infrastructural, organizational, financial, and cultural environments in which they operate affect how strongly each barrier group limits the use of digitalized systems (Yevu et al., 2022). In developed countries, the use of digital technology is rapidly expanding within industry while in developing countries, the opposite trend is observed, as various barriers continue to hinder the adoption and progress of these new technological concepts (Ojo-Fafore & Laryea, 2024). According to Yevu et al. (2022), in developed economies, the barriers to digital adoption are largely associated with technology usability, system integrations, and security issues, as compared to the developed economies where infrastructure constraints, limited finances, skill gaps and weak organizational support are more critical factors.

The barriers selected for this study were those most frequently reported across previous studies on digital procurement adoption in both developed and developing countries and they were subsequently classified according to the dimensions under which they were originally discussed in the literature, namely technological barriers, legal barriers, organizational barriers and financial barriers as presented in Table 1.

*Table 1: Barriers to smart procurement implementation*

| Category | Code | Barrier | Source |
|---|---|---|---|
| **Technological Barriers** | B1 | Cybersecurity concerns | [1], [2], [3], [4] |
| | B2 | Data integrity concerns | [2], [5] |
| **Legal Barriers** | B3 | Legal and regulatory challenges | [2], [4], [6] |
| **Organizational Barriers** | B4 | Limited management support | [3], [4], [5], [7] |
| **Financial Barriers** | B5 | High implementation costs | [2], [3], [4], [5], [6] |

1 - Yevu et al. (2021b); 2 - Ibem and Laryea (2015); 3 - Precious et al. (2025); 4 - Ali et al. (2025); 5 - Bruzzi et al. (2019); 6 - Mbao et al. (2025); 7 - Lee and Shaharud-Din (2022)

### 2.2.1 Technological Barriers

Technological factors include the usability, compatibility, and interoperability of information technology systems within organizations and the quality, reliability, and ease of use of these technologies are crucial in influencing the adoption of digital procurement systems. A strong Information Communication Technology (ICT) infrastructure facilitates the adoption of ICT-driven innovations, including smart procurement technologies (Gascó et al., 2018). Furthermore, Ali et al. (2025) confirms this idea by

stating that poor internet connectivity, in developing countries, further hinders the adoption. Additionally, Yevu et al. (2021a) states barriers such as inadequate Information Technology infrastructure and technical capability, limited system integration and interoperability, and risks associated with technology immaturity and compatibility fall within this category.

### 2.2.2 Legal Barriers

Lack of proper legal framework can be a major barrier, that poses challenges to the adoption of digital procurement (Mbao et al., 2025). Since procurement activities are legally governed, the lack of clear laws and regulations supporting the use of smart procurement systems discourages construction stakeholders from adopting these technologies (Yevu et al., 2021a).

### 2.2.3 Organizational Barriers

Barriers which arise from organizational structures, cultures, and processes that create resistance or difficulties in integrating e-procurement technologies into existing workflows are called organizational barriers (Yevu et al., 2021a). Support from management is a fundamental concept in organizational leadership which reflects the collective mindset, beliefs, and strategic direction of an organization and it includes the values, assumptions, and perspectives that shape decision making at the highest level of the organization (Issah et al., 2024). Furthermore, Adebayo and David (2016) also identify management support as a crucial factor for the successful implementation of smart procurement techniques.

### 2.2.4 Financial Barriers

The high implementation costs of digital technologies hinder widespread adoption, causing many construction firms to hesitate to invest in new technologies due to economic uncertainty and the absence of immediate returns, despite potential long-term efficiency gains (Pittri et al., 2025). Tanoli (2025) identifies financial obstacles such as insufficient design fees to support digital initiatives, the cost of digital tools and setup, limited budgets for training or competitive salaries, and the financial burden of transitioning to new systems as challenges for the digitalization process.

## 2.3 CURRENT SRI LANKAN CONTEXT RELATED TO ADOPTION OF SMART PROCUREMENT

Being a developing country, the digitalization of construction industry in Sri Lanka, is limited by the unwillingness to adopt new technologies, causing the productivity to be lower than in industries where technology is adopted at a faster pace (Bandara et al., 2024). In Sri Lanka, the most common procurement delivery methods used are traditional method, design and build, Build-Own-Operate-Transfer (BOOT), Build-Own-Transfer (BOT) and Public Private Partnership (PPP) (Siriwardhana et al., 2018). Yevu et al. (2021b) identifies several digital technologies that can be implemented in the procurement delivery process such as BIM, Blockchain, and IoT. Even though several digital technologies are currently used in construction industry, survey findings show that their adoption in Sri Lanka is lower than in other countries, with BIM emerging as the most widely implemented technology (Perera et al., 2023b). Still, BIM adoption in Sri Lanka is still in its early stages and is mainly confined to large-scale infrastructure projects and foreign stakeholders (Wijesinghe et al., 2024). Although blockchain

adoption is increasing globally in the construction industry, its implementation in Sri Lanka remains limited (Bandara et al., 2025). Indunil et al. (2025) states that the adoption of Digital Twin (DT) technology in Sri Lanka remains limited compared to more technologically advanced countries.

According to Epasinghe et al. (2018) and Gamage et al. (2025), the construction sector in Sri Lanka has low levels of IT maturity, where there is heavy dependence on basic software and traditional systems, and this leads to low adoption of digital technologies. Additionally, regulatory barriers, insufficient technical capabilities, and limited government support for digital innovation further constrain the digitalization of the industry (Gamage et al., 2025). High rates of errors, regular conflicts, and low output and productivity also hinder the digitalization process and to overcome these challenges, a shift to more innovative procurement strategies is needed (Hettiaarachchige et al., 2022).

The existing studies on digital technology adoption in the Sri Lankan construction industry, such as those by Fernando et al. (2025), Gamage et al. (2025), Indunil et al. (2025), Nitharsan and Francis (2022), and Perera et al. (2023b) only focus on individual technologies such as BIM, e-tendering, and digital twins etc, and these studies do not explore the concept of smart procurement and barriers for adopting smart procurement.

## 3. RESEARCH METHODOLOGY

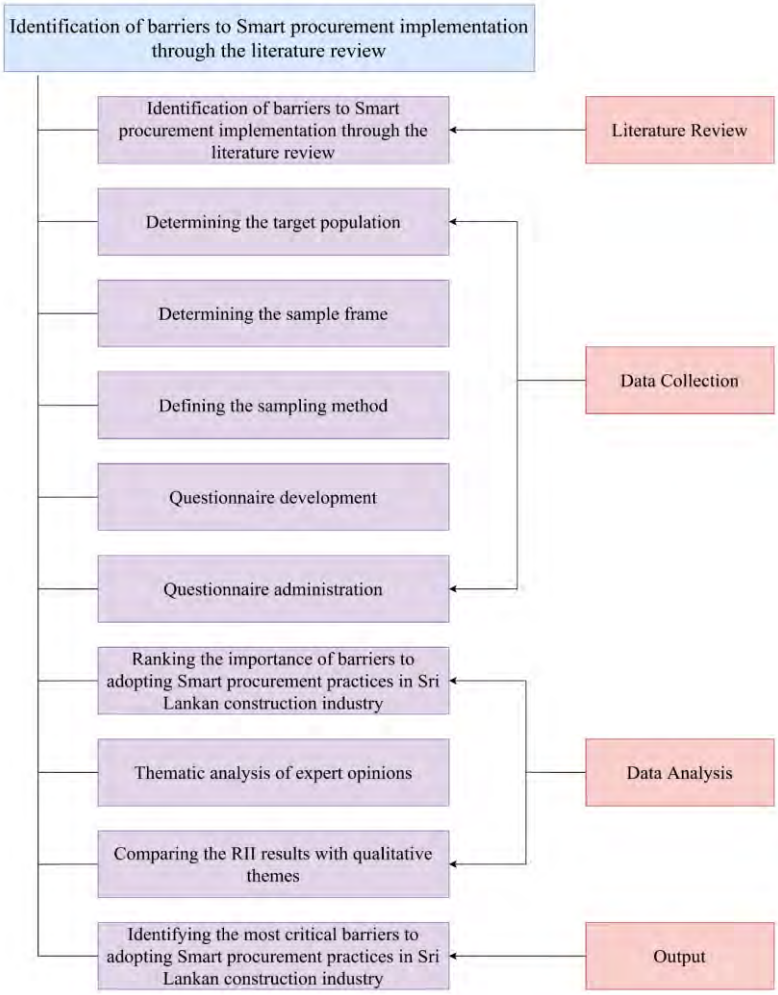



*Figure 1:Research design*

Figure 1 shows the research design of this study. Initially a literature review was conducted to identify the barriers to adopting smart procurement. Then a questionnaire survey was developed to collect both quantitative and qualitative data from respondents. The quantitative data were obtained using questions measured on a five-point Likert scale. Respondents were asked to evaluate the significance of identified barriers to smart procurement adoption in Sri Lanka. The qualitative data were collected through open-ended questions included in the questionnaire. Respondents were invited to assess the current level of smart procurement adoption in Sri Lanka and provide explanations for their assessment.

Objective 1 of the study was achieved through a comprehensive literature review. Objective 2 was addressed using a quantitative ranking method to evaluate and rank the perceived significance of barriers to adopting smart procurement. Objective 3 was addressed through qualitative thematic analysis, which was used to analyse respondents' opinions regarding the current level of smart procurement adoption in the construction industry in Sri Lanka. Accordingly, the overall research approach adopted in this study is a mixed approach.

The target population of this study includes personnel in the construction industry in Sri Lanka who are directly engaged in the procurement related operations and have satisfactory knowledge regarding the digital and smart procurement practices. Aforementioned target population includes quantity surveyors, architects and engineers.

The sampling frame is defined as professionals who has a minimum of 10 years of industry experience and have been directly exposed to procurement decision-making process. Purposive sampling was used to intentionally select professionals with significant industry experience and direct exposure to procurement decision-making processes. Purposive sampling was used because it allows the researcher to deliberately select participants who possess specific experience relevant to the research topic (Creswell, 2014). Data was collected from 60 respondents using a structured questionnaire shared online via Google Forms. The questionnaire consisted of three sections as follows:

- Demographic information
- Respondents' perceptions of the current level of smart procurement adoption in the construction industry in Sri Lanka, collected through open-ended responses.
- Assessment of the significance of identified barriers, measured using a 5-point Likert scale (1 = Very low significance, 5 = Very high significance).

## 3.1 DATA ANALYSIS

The objective 2 of this study is to assess the perceived significance of the barriers identified through the literature review for the Sri Lankan construction industry. To achieve this objective quantitative data was analysed using descriptive statistical methods. The Relative Importance Index (RII) can be used to quantify the relative importance of factors (Thiruchelvam & Uduwage, 2025). Therefore, RII is used to determine the relative significance of each barrier and to establish their ranking. The RII was calculated using the following formula:

$$RII = \frac{\sum W}{A \times N}$$

W = Weight assigned by respondents

A = Highest weight on the scale

N = Total number of respondents.

The barrier with the highest relative index was ranked first, while the barrier with the lowest relative index was ranked last.

Objective 3 of the study is to assess the perceived level of smart procurement adoption in Sri Lanka's construction industry. To achieve this, qualitative data collected were analysed using manual thematic analysis. To begin the analysis, all responses were carefully read multiple times to become familiar with the data. Key phrases and recurring ideas were highlighted and then directly grouped into themes.

# 4. RESULTS AND DISCUSSION

## 4.1 DEMOGRAPHIC INFORMATION

For this study, 60 questionnaires were distributed among the respondents who have at least minimum 10 years of experience in construction industry and among them 30 were returned with valid responses resulting the response rate of 50%. According to Malterud et al. (2015), studies involving participants with relevant expertise and focused research aims require fewer participants to generate sufficiently rich data. Therefore, the sample size of 30 for this analysis is considered sufficient.

The study collected responses from a total of 30 participants, representing professionals in the Sri Lankan construction industry. Among them, Quantity Surveyors (QS) constituted the largest group with 22 respondents (73%), followed by Engineers with 7 respondents (23%), and Architects with 1 respondent (4%).

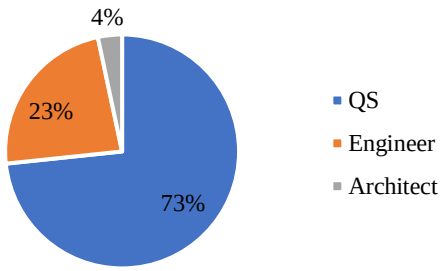



*Figure 2: Respondents' profession*

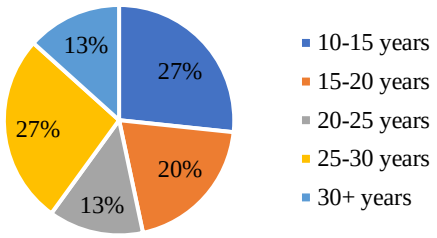



*Figure 3: Respondents' experience*

In terms of professional experience, 8 (27%) respondents had professional experience of 10-15 years, 6 (20%) respondents had experience of 15-20 years, 4 (13%) respondents had 20-25 years, another 8 (27%) respondents had 25-30 years and 4 (13%) respondents had over 30 years of experience. The respondents had an average working experience of about 21 years implying that the sample size has been made up of experienced industry professionals who have worked in the industry over a considerable period.

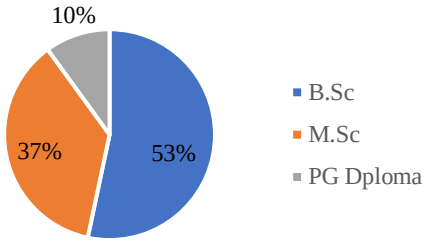



*Figure 2: Respondents' academic qualifications*

In terms of academic qualifications, 16 respondents (53%), 11 respondents (37%), and 3 respondents (10%), had achieved a bachelor, master, and postgraduate diploma respectively. This indicates that the respondents possess a satisfactory educational background relevant to their professional roles.

Overall, the demographic profile demonstrates that the study has reached well experienced and sufficiently qualified individuals in the construction professionals, which gives credible bases to the research findings.

## 4.2 RELATIVE IMPORTANCE OF BARRIERS TO SMART PROCUREMENT ADOPTION

While there are many barriers to the adoption of digital technologies reported in the literature, based on the applicability to developing-country like Sri Lanka, five key barriers were identified. The Relative Importance Index (RII) was used to evaluate and rank the perceived significance of barriers to adopting smart procurement in Sri Lanka's construction industry. Table presents the calculated RII values and corresponding rankings.

*Table 2: Relative Importance Index (RII) for barriers*

| Code | Factor | RII | Rank |
|---|---|---|---|
| **B5** | High implementation costs | 0.827 | 1 |
| **B4** | Limited management support | 0.760 | 2 |
| **B2** | Data integrity concerns | 0.733 | 3 |
| **B3** | Legal & regulatory challenges | 0.713 | 4 |
| **B1** | Cybersecurity concerns | 0.660 | 5 |

The findings of this study are largely related to previous research on electronic procurement adoption in construction. For example, Yevu et al. (2021a) also cited the high technology cost, absence of legal regulations, lack of management support, and inadequate technical capability as barriers to adoption of e-procurement. In their study, resistance to change and lack of trust were highlighted as the most relevant barriers. Similar findings related to Nigerian constriction industry, were reported by Precious et al. (2025), identifying high implementation cost, security concerns, and lack of expertise as key barriers to electronic procurement adoption, while security concern is emphasized as the most critical barrier affecting smart procurement adoption. Study by Inwere et al. (2025) on e-procurement adoption in Nigeria, identified lack of top management or government support, high implementation costs, limited technical expertise, and transaction security concerns as the main barriers to e-procurement implementation. Inwere et al. (2025) ranked lack of management or government support as the most

critical barrier. Comparable barriers have also been observed in other studies conducted in South Africa by Ibem and Laryea (2015) which highlighted unreliable IT infrastructure, cultural barriers, and limited technological access, while research by Tanoli (2025) in Pakistan noted resistance to change, lack of skilled workforce, and absence of policy guidelines as major barriers.

## 4.3 THEMATIC ANALYSIS

The thematic analysis of responses revealed that Smart procurement adoption in Sri Lanka's construction industry is currently partial and concentrated only within large-scale organization. Many respondents stated that they had "not come across such systems" or had observed them only in "very limited offices," while several explicitly stated that smart procurement is "not commonly seen in the industry" and that "proper procurement systems are not practicing in Sri Lanka in most organisations." All these responses suggest a low level of adoption.

*Table 3:Thematic findings*

| Theme | Summary of Findings | Evidence from Respondents |
|---|---|---|
| **Theme 1: Adoption inequality between larger and smaller organizations** | Smart procurement adoption is mainly concentrated in large organizations, while many small and medium contractors still rely on traditional procurement practices. | Respondents noted that "large and Tier-1 organizations use digital tools," but adoption "has not spread into the entire ecosystem." One respondent stated that "many Sri Lankan contractors still rely mainly on traditional methods, so large platforms like Oracle and Aconex are not yet widely used across the whole industry". |
| **Theme 2: Predominance of basic digitalization** | Most procurement procedures are still done manually, and digital tools are mostly utilized for simple communication rather than integrated smart systems. | According to respondents, procurement is still "manual" and "paper-based," where organizations often "just call and get the prices through e-mail," indicating limited use of advanced digital procurement systems. |
| **Theme 3: Barriers to adoption of smart technologies** | Adoption is hindered by technological, financial, and regulatory barriers, including inadequate infrastructure, lack of skills, and high investment costs. | Respondents mentioned that "the IT system is not being developed island wide" and "relevant software is not available with everyone." Additionally, they also highlighted "lack of knowledge," "moderate IT" literacy," "no capable staff to handle procurement systems," and that many organizations "do not have funds to start smart procurement systems." They also noted that government procurement process must follow "NPA Guidelines" and emphasized that "government support and standardized processes are key to successful implementation." |
| **Theme 4: Inadequate** | Due to their lack of readiness and resistance | Respondents stated a "significant gap between the desire for these technologies |

| Theme | Summary of Findings | Evidence from Respondents |
|---|---|---|
| **organizational readiness** | to change, many organizations are inadequately prepared for smart procurement. | and actual organizational readiness," noting that "it will take some time to change mind set of stakeholders," and that many organizations perceive the "initial investment to digitalization of the procurement is very costly." |

The findings from thematic analysis can relate to the existing literature. According to Chan and Owusu (2022), in new firms, the adoption of e-procurement is often constrained by inadequate standardization and lack of confidence related to legal concerns. Respondents also supported this perspective by mentioning that smart procurement has not yet diffused throughout the wider industry. The predominance of manual procurement is highlighted in the study by Gurgun et al. (2024) where it was revealed that construction companies are reluctant to adopt new technologies and procurement operations are often conducted using traditional procurement methods. The construction industry in Sri Lanka face high error rates, frequent disputes, and low productivity, mainly due to its reliance on traditional procurement systems (Hettiaarachchige et al., 2022). Epasinghe et al. (2018) found that most construction organizations in Sri Lanka primarily use basic software such as Microsoft Office, AutoCAD, and Microsoft Project, while the adoption of advanced software remains minimal suggesting that the industry's IT system is not developed adequately for implementation of smart procurement. Considering the theme Inadequate organizational readiness, the findings by Mohungoo et al. (2020) support the findings by emphasizing that insufficient stakeholder involvement and resistance to change significantly hinder adoption of smart procurement. Overall, the qualitative findings align closely with existing literature, confirming that the level of smart procurement adoption is low in Sri Lanka.

## 4.4 INTEGRATING QUANTITATIVE AND QUALITATIVE FINDINGS

When qualitative and quantitative insights were analysed together, a strong convergence of evidence regarding the barriers to Smart Procurement adoption was identified.

The highest ranked barrier in the RII analysis, high implementation costs was emphasized in responses, where financial limitations were described as a key reason why many organizations, especially small and medium scale organizations, are unable to invest in digital procurement systems. This alignment confirms that financial barriers are significant statistically and practically experienced within the industry.

Similarly, limited management support, which was ranked second in the RII results, is reflected in qualitative insights relating with inadequate organizational readiness. The gap between the desire for these technologies and actual organizational readiness and the need for stakeholder mindset shift were noted by the respondents in qualitative insights.

Furthermore, technical barriers identified in the RII analysis, such as data integrity and cybersecurity concerns, were also indirectly supported by respondents' comments regarding limited trust in digital systems and continued preference for manual processes. This indicates that organizations may be hesitant to transition fully to digital platforms due to perceived technological risks.

Finally, legal and regulatory challenges can be related to the qualitative comments highlighting the limitations in government procurement and the absence of standardized

digital practices across the sector. This shows that institutional frameworks are not yet fully aligned with the requirements of smart procurement systems.

## 5. CONCLUSIONS

Smart procurement refers to the use of digital technologies such as AI, BIM and blockchain into the procurement process. The existing studies have mainly focused on individual technologies rather than the broader concept of smart procurement and they have only examined barriers to the general digitalisation of construction industry rather than specifically exploring how these barriers relate to smart procurement within the sector. Therefore, this study examines the level of smart procurement adoption in Sri Lanka's construction sector while identifying and evaluating the key barriers affecting its effective implementation. After identifying barriers through the initial literature review, a mixed-method approach was used, where quantitative analysis using the RII was used to rank the significance of the identified barriers, while qualitative thematic analysis was employed to explore respondents' perceptions regarding the current level of adoption of smart procurement in Sri Lankan construction industry. The RII analysis revealed that high implementation costs (B5) and limited management support (B4) were the most critical barriers, ranking first and second, respectively. These findings suggest that the limited adoption is caused mainly due to organizational and financial factors rather than due to purely technical factors. The qualitative findings confirmed that smart procurement adoption in Sri Lanka remains low, with only large organizations being able to implement it meaningfully. due to limited digital infrastructure, lack of technical expertise, resistance to change, and financial limitations. This study, however, is restricted to the construction sector in Sri Lanka. Since Sri Lanka represents a developing economy, the findings may not be directly generalizable to other countries, particularly developed economies. Nevertheless, they may still offer useful insights for other developing countries facing similar barriers in adopting smart procurement practices to better understand the barriers and to guide the gradual transition toward smart procurement practices. Also, future studies could conduct comparative analyses between Sri Lanka and other developed and developing countries to examine how differences in technological maturity, organizational readiness, regulatory frameworks, and procurement practices influence smart procurement adoption. Furthermore, as the organizational classification of respondents (i.e., client, consultant, and contractor) was not captured in this study, future studies may consider incorporating this aspect to provide deeper insights into role-based differences in perceptions. Industry practitioners, organizational top management and policymakers can use the findings of this study to address adoption barriers by promoting digital solutions, strengthening management support, improving technological capabilities and regulatory support. This offers a path for future research for identifying practical strategies to mitigate these barriers and for further exploring how smart procurement can improve efficiency, transparency, and decision-making in construction procurement processes.

## 6. REFERENCES

Adebayo, V. O., & Evans, R. D. (2015). Adoption of e-procurement systems in developing countries: A Nigerian public sector perspective. *Proceedings of 2nd international conference on knowledge-based engineering and innovation (KBEI)* (pp. 20–25). https://doi.org/10.1109/KBEI.2015.7436015

Akande, O. K., John, A. B., Otemeata, E. A., Haruna, G. A., Oshineye, A. A., Akinbami, A. A., Afolami, S. K., & Akeremale, I. D. (2025, November). *Harnessing smart procurement strategies for public*

*building projects: A paradigm shift toward construction 5.0 framework in Abuja, Nigeria.* Proceedings of the 19th Built Environment Conference, ASOCSA. https://doi.org/10.64755/ecsb8436

Ali, S., Ahmad, M. A., Jenuwa, N., Dahlan, F. M., Bakar, N. A., & Zain, N. M. (2025). Challenges in adopting the e-tendering system among contractors in the Malaysian construction industry. *International Journal of Research and Innovation in Social Science (IJRISS), IX(*IX), 8942-8953. https://doi.org/10.47772/ijriss.2025.909000734

Bandara, D. M. U. S., Jayasinghe, J. A. S. K., & Coomasaru, P. (2024). Advancing digital technology adaptation in Sri Lankan construction firms. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadeva, & H. Chandanie (Eds.), *Proceedings of the 12th world construction symposium* (pp. 120–131). CIOB. https://doi.org/10.31705/WCS.2024.10

Bandara, D. W. J. W., Wimalaratne, P. L. I., Kulatunga, U., & Wijayasiri, A. (2025). Exploring the potential of blockchain technology adoption in the Sri Lankan construction industry: Opportunities and barriers to implementation. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th world construction symposium* (pp. 730–745). CIOB. https://doi.org/10.31705/WCS.2025.55

Bruzzi, S., Genco, V., & Balbi, N. (2019). The new frontiers of procurement in the digital age. Results of an empirical survey on procurement 4.0 in Italy. *Sinergie Italian Journal of Management, 37*(2), 93-118. https://doi.org/10.7433/s109.2019.06

Chan, A. P. C., & Owusu, E. K. (2022). Evolution of electronic procurement: Contemporary review of adoption and implementation strategies. *Buildings, 12*(2), 198. https://doi.org/10.3390/buildings12020198

Creswell, J. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). Sage Publications Ltd.

Epasinghe, E. A. K., Jayasena, H. S., Kolugala, L. M. B. N., & Wijewickrama, M. K. C. S. (2018, December). *Open BIM adoption in Sri Lankan construction industry*. Proceedings of FOSS4G Asia 2018 Conference. https://www.researchgate.net/publication/338605939

Fernando, I., Lingasabeshan, V., & Wimalaratne, P. L. I. (2025). Barriers to adopting digital twin technology for contract administration in Sri Lankan construction sector. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th world construction symposium* (pp. 256–272). CIOB. https://doi.org/10.31705/WCS.2025.20

Gamage, N., Ambagala, A.P.K.K., Nanayakkara, S., & Perera, S. (2025). Towards a framework for implementing blockchain technology in the construction industry of Sri Lanka. *Built Environment Project and Asset Management, 15*(3), 612–628. https://doi.org/10.1108/BEPAM-12-2023-0222

Gasco, M., Cucciniello, M., Nasi, G., & Yuan, Q. (2018). Determinants and barriers of e-procurement: A European comparison of public sector experiences. *Proceedings of the 51st Hawaii International Conference on System Sciences* (pp 2342-2351). http://doi.org/10.24251/hicss.2018.294

Gurgun, A. P., Kunkcu, H., Koc, K., Arditi, D., & Atabay, S. (2024). Challenges in the integration of e-procurement procedures into construction supply chains. *Buildings, 14*(3), 605–605. https://doi.org/10.3390/buildings14030605

Hamma-adama, M., & Ahmad, A.-B. S. (2021). Challenges and opportunities of e-procurement in the construction industry. *Journal of Construction Materials, 2*(4), 1-10. https://doi.org/10.36756/jcm.v2.4.7

Hettiaarachchige, N., Rathnasinghe, A., Ranadewa, K., & Thurairajah, N. (2022). Lean integrated project delivery for construction procurement: The case of Sri Lanka. *Buildings, 12*(5), 524. https://doi.org/10.3390/buildings12050524

Ibem, E. O., & Laryea, S. (2015). E-procurement use in the South African construction industry. *Journal of Information Technology in Construction (ITcon), 20*(23), 364–384. http://www.itcon.org/2015/23

Indunil, H. T. T. A., Bandara, R. P., & Buddhini P.H.Y. (2025). Barriers and solutions to adopting digital twin in Sri Lankan construction. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th world construction symposium* (pp. 230–242). CIOB. https://doi.org/10.31705/WCS.2025.18

Inwere, C. C., Ugulu, R. A., & Dike, B. U. (2025). Investigating the effect of e-procurement on project success in Nigeria. *Alvan Journal of Social Sciences (AJSS), 2*(2), 1-15. https://cdn.b12.io/client_media/6Rw1vQxq/d1b97338-6607-11f0-80bf-0242ac110002-

AJSS_5_INWERE_ET_AL_INVESTIGATING_THE_EFFECT_OF_E-PROCUREMENT_ON_PROJECT_SUCCESS.pdf

Issah, O., David, A., & Eric, D. B. (2024). Analyzing the influence of organizational culture and top management orientation on the relationship between e-procurement and firms' performance: A contingency factors perspective. *Project Management and Scientific Journal*, *7*(9), 93–116. https://doi.org/10.4314/pmsj.v7i9.6

Lee, K. L., & Shaharud-din, A. M. B. (2022). Procurement 4.0 and organizational performance in the Malaysian construction industry. *International Journal of Service Science, Management, Engineering, and Technology*, *13*(1), 1–22. https://doi.org/10.4018/ijssmet.314591

Malterud, K., Siersma, V. D., & Guassora, A. D. (2015). Sample size in qualitative interview studies: Guided by information power. *Qualitative Health Research*, *26*(13), 1753–1760. https://doi.org/10.1177/1049732315617444

Masoom, S., Shahid, H., Shahzaib, M., Naseer, S., Irfan, M., Musarat, M. A., & Alotaibi, A. (2025). Enhancing construction efficiency: Assessing the values and barriers of integrating e-procurement with BIM. *Journal of Asian Architecture and Building Engineering*, *Ahead-of-Print*. https://doi.org/10.1080/13467581.2025.2527976

Mbao, J. M. K., Mbugua, L. M., & Gitau, S. W. (2025). Adoption of e-procurement procedures and its influence on public construction projects in Kenya: A survey of parastatals in Kenya. *International Journal of Engineering Research & Technology*, *14*(8), 1-14. https://doi.org/10.5281/zenodo.18103645

Mohungoo, I., Brown, I., & Kabanda, S. (2020). A systematic review of implementation challenges in public e-procurement. In M. Hattingh, M. Matthee, H. Smuts, I. Pappas, Y. K. Dwivedi, & M. Mäntymäki (Eds.), *Responsible design, implementation and use of information and communication technology*, (pp. 46–58). Springer. https://doi.org/10.1007/978-3-030-45002-1_5

Naoum, S., & Egbu, C. (2015). Critical review of procurement method research in construction journals. *Procedia Economics and Finance*, *21*, 6–13. https://doi.org/10.1016/S2212-5671(15)00144-6

Nitharsan, N., & Francis, M. (2022). Adaptability of blockchain-based e-procurement system in Sri Lankan construction projects. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 10th world construction symposium* (pp. 63–75). CIOB. https://doi.org/10.31705/WCS.2022.6

Ojo-Fafore, E., & Laryea, S. (2024). Barriers to digitalization of procurement – A review. In S. Laryea, B. Li, E. Adu Essah, S. Mensah, H. Liu, & R. Yao (Eds.), *Proceedings of the WABER SuDBE conference 2024* (pp. 989–998). https://www.researchgate.net/publication/383490800

Okereke, R. A., Ihekweme, N. M., & Adegboyega, A. A. (2022). Impact of traditional procurement system on construction project delivery. *Journal of Project Management Practice*, *2*(2), 23–38. https://doi.org/10.22452/jpmp.vol2no2.2

Perera, S., Jin, X., Samaratunga, M., & Gunasekara, K. (2023a). Drivers and barriers to digitalisation: A cross-analysis of the views of designers and builders in the construction industry. *Journal of Information Technology in Construction*, *28*, 87–106. https://doi.org/10.36680/j.itcon.2023.005

Perera, S. D., Ranadewa, T., Parameswaran, A., & Weerasooriya, D. (2023b). Status quo of digitalisation in the Sri Lankan construction industry. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra & K. A. T. O. Ranadeva (Eds.), *Proceedings of the 11th world construction symposium* (pp. 944–959). CIOB. https://doi.org/10.31705/WCS.2023.76

Pittri, H., Godawatte, G. A. G. R., Esangbedo, O. P., Antwi-Afari, P., & Bao, Z. (2025). Exploring barriers to the adoption of digital technologies for circular economy practices in the construction industry in developing countries: A case of Ghana. *Buildings*, *15*(7), 1090. https://doi.org/10.3390/buildings15071090

Precious, O., Enyiinna, G. C., & Osuagwu, J. C. (2025). The effects of electronic procurement on building construction projects in rivers state, Nigeria. *International Journal of Emerging Trends in Engineering Research*, *13*(2), 50–66. https://doi.org/10.30534/ijeter/2025/031322025

Siriwardhana, M. S., Jayasena, H. S., Wijewickrama, M. K. C. S., & Kolugala, L. M. B. N. (2018). Suitable government initiative strategy for BIM implementation in Sri Lanka. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 7th World Construction Symposium* (pp. 519–526). CIOB. https://www.researchgate.net/publication/338607121

Tanoli, W. A. (2025). Assessing drivers, barriers and policy interventions for implementing digitalization in the construction industry of Pakistan. *Buildings*, *15*(15), 2798. https://doi.org/10.3390/buildings15152798

Thiruchelvam, K., & Uduwage-Don, N. L. S. (2025). Assessing SDG 7 performance: Identifying relevant KPIs for the Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th world construction symposium* (pp. 203–215). CIOB. https://doi.org/10.31705/WCS.2025.16

Uduwage-Don, N. L. S., Hadiwattege, C., & Panuwatwanich, K. (2023). Enhancing the responsiveness of bids in public procurement: The case of Sri Lanka. *Public Works Management & Policy*, *29*(3), 332–363. https://doi.org/10.1177/1087724X231191724

Wijesinghe, D., Rajapaksha, M., De Silva, L., & Herath, V. (2024). Implications of building information modelling (BIM) on project performance in high-end residential projects amidst economic crises: A case study of Sri Lanka (2020 -2023). In F. Zhang, R. Yu, C. Bischeri, T. Liu, & M. Khoshbakht (Eds.), *Proceedings of the 57th international conference of the architectural science*, (pp. 434–441). https://archscience.org/wp-content/uploads/2025/03/Implications-of-Building-Information-Modelling-BIM-on-project-performance-in-high-end-residential-projects-amidst-economic-crises_A-case-study-of-Sri-Lanka-2020-%E2%80%93-2023.pdf

Yaparathne, I. H. G. Y. M. W. U., Dias, D. D., & Guruge, K. (2025). Readiness to implement construction 4.0 applications in building construction projects in Sri Lanka. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium* (pp. 1176–1189). CIOB. https://doi.org/10.31705/WCS.2025.88

Yevu, S. K., & Yu, A. T. W. (2019). The ecosystem of drivers for electronic procurement adoption for construction project procurement. *Engineering, Construction and Architectural Management*, *27*(2), 411-440. https://doi.org/10.1108/ECAM-03-2019-0135

Yevu, S. K., Yu, A. T. W., & Darko, A. (2021a). Barriers to electronic procurement adoption in the construction industry: A systematic review and interrelationships. *International Journal of Construction Management*, *23*(6), 1–15. https://doi.org/10.1080/15623599.2021.1946900

Yevu, S. K., Yu, A. T. W., & Darko, A. (2021b). Digitalization of construction supply chain and procurement in the built environment: Emerging technologies and opportunities for sustainable processes. *Journal of Cleaner Production*, *322*(4), 129093. https://doi.org/10.1016/j.jclepro.2021.129093

Yevu, S. K., Yu, A. T. W., Nani, G., Darko, A., & Tetteh, M. O. (2022). Electronic procurement systems adoption in construction procurement: A global survey on the barriers and strategies from the developed and developing Economies. *Journal of Construction Engineering and Management*, *148*(1). https://doi.org/10.1061/(asce)co.1943-7862.0002213

Perera, H.V.D., Perera, B.A.K.S. and Mannapperuma, M.M.N., 2026. Barriers to use of leagile project management for stakeholder collaboration in green building constructions in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 292-305. DOI: https://doi.org/10.31705/WCS.2026.22. Available from: https://ciobwcs.com/papers/

# BARRIERS TO USE OF LEAGILE PROJECT MANAGEMENT FOR STAKEHOLDER COLLABORATION IN GREEN BUILDING CONSTRUCTIONS IN SRI LANKA

**H.V.D. Perera[1], B.A.K.S. Perera[2] and M.M.N. Mannapperuma[3]**

## *ABSTRACT*

*Leagile project management has been identified as a promising concept to address the dynamic complexities inherent in green building (GB) projects. However, stakeholder collaboration in green buildings received lack of consideration in traditional project management. Therefore, this study explores barriers to adopt 'Leagile Project Management' for improving stakeholder collaboration in GB projects. The research adapted interpretivism paradigm using qualitative research choice via a Delphi study to collect data. Manual content analysis was used to analyse data collected. The study identified 14 notable stakeholders collaborating challenges in green buildings with 16 key lean barriers and 16 key agile barriers that hinder the effective application of Leagile project management. Further, identified key Lean and Agile barriers were mapped related to each stakeholder collaboration challenges in green building constructions in Sri Lanka. The study identifies that stakeholder collaboration challenges in GB construction arise from a complex interplay of economic, organisational, and regulatory constraints. The combined Lean and Agile perspectives reveal common barriers, including resource limitations, insufficient leadership commitment, cultural resistance, and fragmented coordination among stakeholders. These factors collectively limit effective collaboration and hinder successful GB project delivery. The findings highlight the importance of identifying Leagile adoption barriers and their association with stakeholder collaboration challenges, emphasising the need for a more integrated and adaptive project management approach to address structural inefficiencies and behavioural issues, thereby enhancing stakeholder alignment, improving coordination, and supporting more effective and sustainable project outcomes.*

***Keywords:*** *Barriers; Leagile Project Management; Green Building Construction; Stakeholder Collaboration.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, pererahvd20@uom.lk
[2] Senior Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nawanjanam@uom.lk

# 1. INTRODUCTION

LeAgile project management is an integration of Lean and Agile methodologies designed to enhance efficiency and responsiveness in environments where traditional frameworks are less effective (Kashikar et al., 2016). Agile project management is characterised by its iterative and incremental processes, emphasizing flexibility, collaboration, and responsiveness to change (Demir et al., 2014). When combined with Lean principles which focus on reducing waste and optimizing supply chain performance, this hybrid approach, known as LeAgile project management, offers distinct advantages (Demir, 2013). By integrating Lean's waste minimization with Agile's iterative strategies, LeAgile enhances efficiency, accelerates delivery, and promotes stakeholder engagement (Demir, 2013). Accordingly, LeAgile strategies have been utilized to overcome limitations of traditional project management, leading to reduced costs, shorter lead times, and improved stakeholder collaboration (Spassova, 2023).

Green building (GB) is a sustainable approach aimed at reducing environmental, social, and economic impacts of constructions (Vijayan et al., 2023; Almakayeel et al., 2023). This is achieved through the use of energy-efficient materials, designs, and renewable energy sources (Almakayeel et al., 2023). Accordingly, effective inter-organisational collaboration among architects, engineers, contractors, clients, and regulatory bodies is essential for achieving certification standards and delivering high-performing GBs (Qiang et al., 2021). However, the adoption of GBs remains constrained by several challenges, including elevated initial costs, limited awareness of green technologies, and inadequate knowledge of sustainable practices (Agboola et al., 2024; Gou, 2020). Particularly, insufficient collaboration and communication among stakeholders emerges as a critical issue, often leading to misaligned objectives, delays in decision-making, and fragmented information flows (Alqadami et al., 2020; Larsson & Larsson, 2020).

In this context, the application of LeAgile strategies within construction supply chains is reflected in models such as Make-to-Stock (MTS), Assemble-to-Order (ATO), Design-to-Order (DTO), and Self Build-House (SBH) (Mostafa et al., 2016). These approaches highlight the potential for delivering cost-effective, customized, and sustainable outcomes when stakeholders operate as a unified team, particularly by optimising stakeholder collaboration (Oyombe et al., 2023; Stern, 2016). Indeed, LeAgile project management has been identified as a promising concept to address the dynamic complexities inherent in GBs (Demir et al., 2014), while Agile practices further enhance productivity by fostering cooperation, trust, and adaptability to evolving project needs (Stern, 2016). However, the adoption of Lean and Agile principles in GBs remains limited, particularly due to the under exploration of associated barriers that aggregated by stakeholder collaboration challenges, resulting in inefficiencies such as waiting, excess inventory, and defects in GB construction (Ekanayake et al., 2018). Therefore, this gap underscores the need for further investigation into the barriers of adopting LeAgile project management for enhancing stakeholder integration in GB construction (Ekanayake & Idar, 2022).

Accordingly, this research aimed to investigate barriers to integrate LeAgile project management with the stakeholder collaboration of GB constructions in Sri Lanka. The research has three objectives, 1) to investigate the notable stakeholder collaboration challenges in green building constructions in Sri Lanka, 2) to assess the key Lean barriers related to each notable stakeholder collaboration challenges in green building

constructions in Sri Lanka, and 3) to assess the key Agile barriers related to each notable stakeholder collaboration challenges in green building constructions in Sri Lanka.

# 2. LITERATURE REVIEW

## 2.1 GREEN BUILDING CONSTRUCTION PROJECTS

GB encompasses environmentally responsible and resource-efficient practices throughout a building's life cycle, from initial planning and design to demolition (Berardi, 2013). The concept integrates principles of sustainable development and energy efficiency, addressing global warming concerns (Liu et al., 2022). Consequently, GBs contribute to resource efficiency, waste reduction, and improved indoor environments, while significantly reducing greenhouse gas emissions compared to conventional buildings (Meena et al., 2022; Liu et al., 2022; Zhao et al., 2023). Further, GBs offer notable economic and social advantages by reduce maintenance and lifecycle costs through energy savings and lower $CO_2$ emissions, while also enhancing job productivity (Addy et al., 2022; Meena et al., 2022; Liu et al., 2022). Compared to conventional buildings, GBs can achieve 20–30% water savings and 40–50% energy savings, alongside improved indoor air quality (Meena et al., 2022). Socially, they promote occupant health, wellbeing, and productivity, and support social equity by providing healthier living environments, particularly in urban areas (Fu et al., 2020; Singh & Gupta, 2021). However, despite these benefits, GB projects involve unique risks due to reliance on innovative materials and technologies, requiring proactive risk management, stakeholder engagement, and continuous monitoring to ensure successful project delivery (Kibert, 2022; Javed et al., 2019).

## 2.2 STAKEHOLDER COLLABORATION CHALLENGES IN GREEN BUILDING CONSTRUCTION PROJECTS

GB constructions are inherently collaborative, requiring effective engagement among diverse stakeholders such as architects, engineers, contractors, clients, and regulatory bodies to achieve sustainability objectives (Winanda, 2024; Li et al., 2022). However, despite this necessity, stakeholder collaboration in GBs is often hindered by multiple interrelated challenges (Li et al., 2022). Figure 1 illustrates key stakeholder collaboration challenges in GBs.

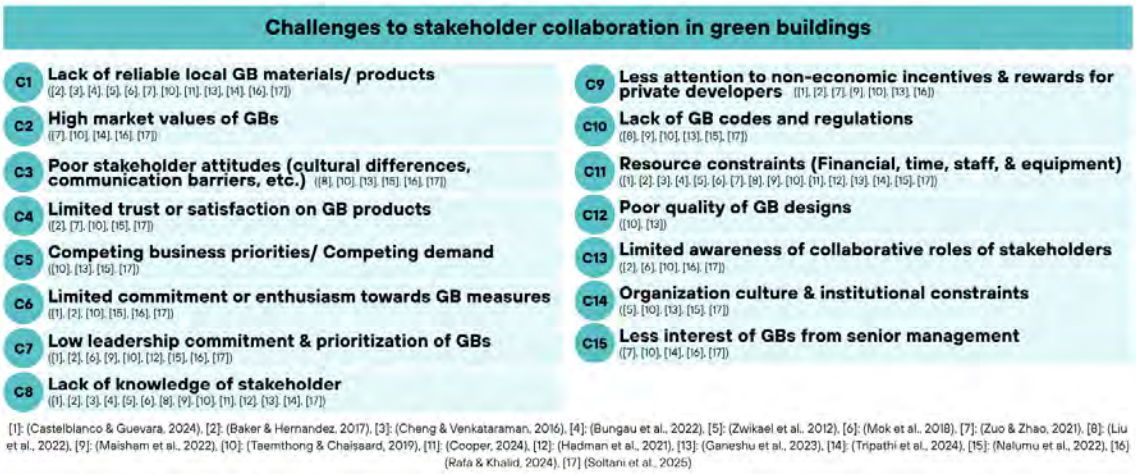



*Figure 1: Challenges to stakeholder collaboration in green buildings*

According to the Figure 1, a key issue lies in the lack of leadership commitment and limited interest from senior management towards GB initiatives, often resulting in low prioritisation of sustainability objectives (Castelblanco & Guevara, 2024). This is further exacerbated by insufficient stakeholder knowledge and limited awareness of collaborative roles, which restrict effective participation and coordination (Cooper, 2024; Zuo & Zhao, 2021). Additionally, organisational culture and institutional constraints, along with poor stakeholder attitudes and communication barriers, contribute to fragmented collaboration and reduced trust among project participants (Nalumu et al., 2022). Resource constraints, including financial, time, and technical limitations, as well as the high market value of GBs and lack of reliable local materials, further complicate stakeholder engagement (Baker & Hernandez, 2017). Moreover, the absence of adequate GB codes and regulations and limited attention to non-economic incentives for developers weaken motivation to collaborate (Cooper, 2024). Collectively, these challenges lead to inefficiencies, misalignment of objectives, and hinder the successful delivery of green building projects.

## 2.3 LEAGILE PROJECT MANAGEMENT

LeAgile project management combines the strengths of Agile and Lean approaches to improve construction project performance. Agile methods enhance client satisfaction, project transparency, risk management, and timely delivery, while maintaining flexibility to respond to changing requirements (Pinto, 2023). These characteristics align closely with the goals of sustainable construction, supporting more socially, economically, and environmentally responsible outcomes (Ershadi et al., 2021). In contrast, Lean project management focuses on improving efficiency by minimising waste and maximising value through continuous improvement practices such as Just-in-Time systems, quality management, and supplier coordination (Shah & Ward, 2003; Maradzano et al., 2019). It further emphasises collaboration, standardisation, and streamlined workflows to enhance overall project performance (Maradzano et al., 2019). Core practices including 5S, waste elimination, and teamwork contribute to consistent performance improvement (Shaqour, 2021; Tafazzoli et al., 2020). The integration of Agile and Lean is particularly effective when applied to incremental, process-level improvements in construction projects (Alavi & Aghakhani, 2021; Bhamra et al., 2020; Mostafa et al., 2016; Oyombe et al., 2023). Thus, the LeAgile approach provides a balanced framework to achieve both efficiency and adaptability in construction project delivery.

## 2.4 KEY LEAN BARRIERS AND AGILE BARRIERS OF LEAGILE PROJECT MANAGEMENT

Despite the growing adoption of LeAgile approaches in construction, a range of organisational, technical, and cultural barriers continue to hinder their effective implementation (Mostafa et al., 2016; Oyombe et al., 2023). Lean implementation is constrained by inadequate management commitment, lack of standardisation, and insufficient training programs (Rybkowski et al., 2017). Economic constraints, including high initial costs, also pose challenges (Sadeghi et al., 2022). Furthermore, poor stakeholder engagement, ineffective communication, and misalignment of incentives reduce efficiency, while limited focus on continuous improvement and inconsistent quality control hinder successful Lean application (Orsi et al., 2021; Stern, 2016). Key barriers to Agile implementation include cultural misalignment with Agile values, lack of leadership support, and insufficient training and understanding of Agile principles (Ng

et al., 2023). Additionally, fragmented supply chains, diverse project teams, and ineffective communication hinder collaboration (Pinto, 2023). Challenges such as inflexible contracts, time constraints, and difficulties in scaling Agile practices further limit its effective adoption (Ng et al., 2023; Sadeghi et al., 2022). LeAgile aligns well with GB objectives by combining Lean's waste minimisation with Agile's flexibility and responsiveness to design changes and fluctuating demands, which are common in GB projects (Demir et al., 2014; Kibert, 2022). This integration facilitates real-time data sharing, reduces rework, and enhances efficiency in a context constrained by economic and technical barriers (Ekanayake et al., 2018). Moreover, LeAgile promotes early stakeholder involvement and iterative feedback, helping to overcome fragmented traditional practices and misaligned project goals (Wen & Qiang, 2022). Given the complexity and uncertainty of construction projects, this approach supports improved collaboration, adaptability, and resource optimisation. Consequently, integrating LeAgile with stakeholder collaboration is essential to enhance project delivery and align GB projects with Sri Lanka's broader sustainability objectives. Despite the growing adoption of LeAgile approaches in construction, a range of organisational, technical, and cultural barriers continue to hinder their effective implementation. In the context of Sri Lanka, these challenges are further intensified in green building projects due to limited stakeholder collaboration, high costs, and low awareness of sustainable practices, which collectively hinder efficient project delivery (Ekanayake & Idar, 2022). Therefore, integrating LeAgile project management with stakeholder collaboration becomes critical to address these issues.

## 3. METHODOLOGY

Qualitative research focuses on phenomena related to kind and quality which explore the reasons for human behaviours and discover motives through in-depth interviews (Kothari, 2004). Delphi technique engages experts systematically and iteratively (Brady & O'Connor, 2014). Accordingly, a Delphi technique was employed as it gathers expert opinions in various domains, facilitating consensus and more profound expertise of a specific phenomenon (Gu et al., 2025). The number of Delphi rounds was decided based on the point at which the interviewees reached a consensus (Barrios et al., 2021).

*Table 1: Interviewees' profile*

| Expert | Designation | Compulsory Qualifications Experience in research /industry | | | | Additional Qualifications (Respondents must possess at least 3 qualifications) | | | | | Delphi rounds | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | In the construction field > 10 years | In LeAgile project management > 03 years | In GBs > 05years | In project management > 05 years | B.Sc. in Built environment / related field | M.Sc. in Built Environment / related field | Professional Qualifications in Built environment / GBs | Indexed publications in LeAgile project management and GB > 02 | Interest in GBs / LeAgile project management | R1 | R2 |
| E1 | Project Manager | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |

| Expert | Designation | Compulsory Qualifications Experience in research /industry | | | | Additional Qualifications (Respondents must possess at least 3 qualifications) | | | | | Delphi rounds | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | In the construction field > 10 years | In LeAgile project management > 03 years | In GBs > 05years | In project management > 05 years | B.Sc. in Built environment / related field | M.Sc. in Built Environment / related field | Professional Qualifications in Built environment / GBs | Indexed publications in LeAgile project management and GB > 02 | Interest in GBs / LeAgile project management | R1 | R2 |
| E2 | Engineer | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E3 | Project Manager | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| E4 | Construction Manager | √ | √ | √ | √ | √ | - | √ | - | √ | √ | √ |
| E5 | Project Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E6 | Project QS | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E7 | Construction Manager | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |
| E8 | Cost Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E9 | Project Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E10 | Construction Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E11 | Project Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E12 | Project Manager | √ | √ | √ | √ | √ | √ | √ | - | √ | √ | √ |
| E13 | Engineer | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ |

| | | |
|---|---|---|
| Delphi Rounds | R1P1 | To identify stakeholder collaboration challenges in green building constructions in Sri Lanka |
| | R1P2 | To identify Lean barriers related to each stakeholder collaboration |
| | R1P3 | To identify Agile barriers related to each stakeholder collaboration |
| | R2P1 | To assess the key Lean barriers related to each notable stakeholder collaboration challenges in green building constructions in Sri Lanka |
| | R2P2 | To assess the key Agile barriers separately related to each notable stakeholder collaboration challenges in green building constructions in Sri Lanka |

Consequently, two Delphi rounds were conducted through 13 semi-structured interviews to explore the alignment of LeAgile project management in fostering stakeholder collaboration in GBs, face to face, 60 - 75 minutes, based on interview guidelines. The experts were selected through purposive sampling, ensuring inclusion of individuals with specialized knowledge in project management, LeAgile project management, and GBs as identified in Table 1. Data saturation was achieved at the 11$^{th}$ interview. Two further interviews were conducted solely to validate saturation. Manual content analysis was applied, capturing context-specific information by systematically examining the content

(Linneberg & Korsgaard, 2021). Further, a 75% agreement threshold was adopted as the cutoff point following a similar study conducted by Alkaissy et al. (2022).

# 4. FINDINGS AND ANALYSIS

## 4.1 NOTABLE STAKEHOLDER COLLABORATION CHALLENGES IN GREEN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA (R1Q1)

The findings from Round 1 Phase I are presented in this section. At the end of the literature review, fifteen stakeholder collaboration challenges in GBs were recognised. Consequently, validity of literature findings for the GBs and identification of notable stakeholder collaboration challenges were performed in Round 1 Phase 1. Literature findings were authenticated, and fourteen stakeholder collaboration challenges were derived at the end of Round 1 Phase I, meeting the 75% cutoff. Findings derived at the end of Round 1 Phase I are tabulated in Table 2.

*Table 2: Notable stakeholder collaboration challenges in green buildings*

| | **Notable stakeholder collaboration challenges in green buildings** | **R1P1 (> 75%)** |
|---|---|---|
| C1 | Lack of reliable local GB materials/ products | √ |
| C2 | High market values of GBs | √ |
| C3 | Poor stakeholder attitudes (cultural differences, communication barriers, etc.) | √ |
| C4 | Limited trust or satisfaction on GB products | √ |
| C5 | Competing business priorities/ Competing demand | √ |
| C6 | Limited commitment or enthusiasm towards GB measures | √ |
| C7 | Low leadership commitment & prioritization of GBs | √ |
| C8 | Lack of knowledge of stakeholder | X |
| C9 | Less attention to non-economic incentives & rewards for private developers | √ |
| C10 | Lack of GB codes and regulations | √ |
| C11 | Resource constraints (Financial, time, staff, and equipment) | √ |
| C12 | Poor quality of GB designs | √ |
| C13 | Limited awareness of collaborative roles of stakeholders | √ |
| C14 | Organization culture & institutional constraints | √ |
| C15 | Less interest of GBs from senior management | √ |

As per the experts, material-related constraints emerge as a significant issue, particularly the lack of reliable local GB materials and products, which increases dependence on costly imports. This is closely linked with the high market value of GBs and broader resource constraints, including financial, time, and technical limitations, which collectively restrict stakeholder engagement. In addition, limited trust in GB products is evident, with concerns over quality and credibility, as reflected by E9, E11 who noted that such materials are often perceived as “inferior or experimental.”

Cultural and organisational factors further influence collaboration dynamics as per experts. Poor stakeholder attitudes, including resistance to change, cultural differences,

and communication barriers, hinder the adoption of GB practices. This is reinforced by organisational culture and institutional constraints, along with competing business priorities that reduce focus on sustainability objectives. A lack of commitment and enthusiasm towards GB measures is also observed by E1, E5, and E6, particularly at leadership level, where low prioritisation and limited interest from senior management affect decision-making processes. As E11 highlighted, "green practices are often viewed as unnecessary luxuries by clients," indicating underlying perception challenges. Regulatory and structural issues are also prominent. The lack of established GB codes and regulations, combined with limited awareness of collaborative stakeholder roles, contributes to fragmented project coordination. Although initially identified, the lack of stakeholder knowledge appears less critical compared to other systemic constraints. Furthermore, poor quality of GB designs and limited attention to non-economic incentives reduce motivation among developers, while weak collaboration practices persist, as stated by E2, "different parties in a project rarely collaborate on sustainability goals."

## 4.2 KEY LEAN BARRIERS RELATED TO EACH NOTABLE STAKEHOLDER COLLABORATION CHALLENGES IN GREEN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA (R1Q2, R2Q1)

This section presents the findings derived from Round 1 Phase II, and Round 2 Phase I. The literature review revealed sixteen key Lean barriers to stakeholder collaboration in GBs. Subsequently, validation of literature findings for the stakeholder collaboration of GBs were fulfilled in Round 1 Phase II. In Round 2 Phase I, experts were requested to map the key Lean barriers to notable stakeholder collaboration challenges in GBs. Findings derived at the end of Round 2 Phase I are tabulated in Table 3.

*Table 3: Key Lean barriers related to notable stakeholder collaboration challenges*

| Stakeholder collaboration challenges | Key Lean Barriers | R1P2 (> 75%) | R2P1 (> 75%) |
|---|---|---|---|
| C1 | L3, L5, L13, L16 | √ | √ |
| C2 | L3, L4, L6, L7 | √ | √ |
| C3 | L2, L5, L7, L8, L11, L13, L16 | √ | √ |
| C4 | L5, L7, L11, L12, L13 | √ | √ |
| C5 | L2, L8, L9, L15 | √ | √ |
| C6 | L1, L10, L13, L1, L16 | √ | √ |
| C7 | L3, L4, L6, L7, L9, L14 | √ | √ |
| C9 | L2, L8, L15 | √ | √ |
| C10 | L2, L4, L5, L9 | √ | √ |
| C11 | L3, L7, L9, L12 | √ | √ |
| C12 | L2, L9, L13 | √ | √ |
| C13 | L11, L16 | √ | √ |
| C14 | L1, L2, L13, L14 | √ | √ |
| C15 | L1, L2, L7 | √ | √ |

| |
|---|
| L1 Complexity of Lean tools, L2 Lack of standardization, L3 Economic constraints, L4 Environmental regulations, L5 Fragmented industry structure, L6 High initial costs, L7 Inadequate management commitment, L8 Inadequate performance metrics, L9 Inadequate research and development, L10 Inconsistent quality control, L11 Ineffective communication, L12 Inefficient project delivery systems, L13 Insufficient training programs, L14 Limited focus on continuous improvement, L15 Misalignment of incentives, L16 Poor stakeholder engagement |

As per the experts, several stakeholder collaboration challenges in GB projects are closely associated with Lean-related barriers. Economic constraints (L3), high initial costs (L6), and inadequate management commitment (L7) are consistently linked with issues such as high market values of GBs and low leadership prioritisation. Experts emphasised the financial burden, with E9 noting that "green buildings are perceived as expensive, which deters many stakeholders from investing," reflecting how cost-related barriers influence decision-making. Fragmented industry structure (L5), poor stakeholder engagement (L16), and ineffective communication (L11) are strongly connected to poor stakeholder attitudes, limited trust in GB products, and lack of awareness of collaborative roles. These findings highlight coordination difficulties across project participants.

Additionally, lack of standardisation (L2), misalignment of incentives (L15), and limited focus on continuous improvement (L14) are associated with organisational culture constraints and competing business priorities, indicating systemic inefficiencies. Insufficient training programs (L13) and inadequate research and development (L9) further relate to poor design quality and limited innovation in GB practices. Regulatory issues, particularly environmental regulations (L4), also align with the lack of GB codes and frameworks. As highlighted by E1, "the lack of data and independent verification of green products fuels distrust," reinforcing how quality control issues (L10) and weak institutional structures shape stakeholder perceptions and collaboration practices.

## 4.3 KEY AGILE BARRIERS RELATED TO EACH NOTABLE STAKEHOLDER COLLABORATION CHALLENGES IN GREEN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA (R1Q3, R2Q2)

This section presents the findings derived from Round 1 Phase III, and Round 2 Phase II. The literature review revealed sixteen key Agile barriers to stakeholder collaboration in GBs. Subsequently, validation of literature findings for the stakeholder collaboration of GBs were fulfilled in Round 1 Phase III. In Round 2 Phase II, experts were requested to map the key Agile barriers to notable stakeholder collaboration challenges in GBs. Findings derived at the end of Round 2 Phase II are tabulated in Table 4.

*Table 4: Key Agile barriers related to notable stakeholder collaboration challenges*

| Stakeholder collaboration challenges | Key Agile Barriers | R1P3 (> 75%) | R2P2 (> 75%) |
|---|---|---|---|
| C1 | A1, A5, A9, A12, A15 | √ | √ |
| C2 | A5, A8, A12 | √ | √ |
| C3 | A1, A2, A6, A9, A13, A14 | √ | √ |
| C4 | A1, A4, A5, A6, A9 | √ | √ |
| C5 | A1, A3, A7, A11, A12, A14 | √ | √ |

| Stakeholder collaboration challenges | Key Agile Barriers | R1P3 (> 75%) | R2P2 (> 75%) |
|---|---|---|---|
| C6 | A1, A2, A12 | √ | √ |
| C7 | A3, A4, A6, A15, A16 | √ | √ |
| C9 | A7, A11, A14 | √ | √ |
| C10 | A3, A4, A9 | √ | √ |
| C11 | A4, A10, A15, A16 | √ | √ |
| C12 | A1, A2, A8 | √ | √ |
| C13 | A4, A6, A10 | √ | √ |
| C14 | A2, A6, A9 | √ | √ |
| C15 | A1, A6, A11, A12, A14 | √ | √ |

A1 Complexity and uncertainty in projects, A2 Cultural misalignment with Agile values, A3 Difficulty in scaling Agile practices, A4 Diverse project teams, A5 Fragmented supply chains, A6 Inadequate leadership support, A7 Inconsistent application of Agile practices, A8 Inflexibility in contracts, A9 Lack of empirical evidence, A10 Lack of training and understanding of Agile principles, A11 Performance measurement and accountability, A12 Quality assurance concerns, A13 Regulatory and compliance issues, A14 Short-term focus, A15 Technological barriers, A16 Time constraints

Experts reveal that complexity and uncertainty in projects (A1), cultural misalignment (A2), and inadequate leadership support (A6) are strongly linked with poor stakeholder attitudes, limited commitment, and low prioritisation of GB initiatives. Resistance to change and short-term focus (A14) further influence competing business priorities and reduced interest from senior management. As E4 noted, “many senior professionals do not see the value in changing long-standing procedures,” reflecting cultural and behavioural barriers. Barriers such as fragmented supply chains (A5), diverse project teams (A4), and inconsistent application of Agile practices (A7) are associated with trust issues, lack of collaboration, and limited awareness of stakeholder roles. Inflexible contracts (A8) and regulatory constraints (A13) further connect with the absence of GB codes and regulations, restricting adaptability. Technological barriers (A15), lack of training (A10), and time constraints (A16) correspond with resource limitations and poor design quality, indicating gaps in implementation capacity. Additionally, lack of empirical evidence (A9) and quality assurance concerns (A12) contribute to distrust in GB products. As highlighted by E9, “the lack of data and independent verification… fuels distrust,” demonstrating how uncertainty and limited validation mechanisms influence stakeholder confidence and engagement.

## 5. DISCUSSION

The findings collectively demonstrate that stakeholder collaboration challenges in GB construction are systemic and multi-dimensional, cutting across material, organisational, and regulatory domains (Castelblanco & Guevara, 2024; Cooper, 2024). From a combined LeAgile perspective, both Lean and Agile barriers reinforce similar constraints, particularly in terms of economic pressures, weak leadership commitment, and fragmented stakeholder engagement (Alavi & Aghakhani, 2021; Ali & Sameh, 2024; Sadeghi et al., 2024). Cost-related issues and resource limitations restrict the adoption of collaborative practices, while lack of standardisation, inconsistent processes, and limited

training further weaken coordination mechanisms (Orsi et al., 2021; Lalmi et al., 2021). At the same time, Agile-related challenges such as cultural misalignment, resistance to change, and short-term orientation intensify these issues by reducing adaptability and responsiveness among stakeholders (Ng et al., 2023). Moreover, both perspectives converge on the importance of trust, communication, and institutional support (Rybkowski et al., 2018). Fragmented supply chains, ineffective communication, and absence of regulatory frameworks collectively hinder integration across project stakeholders (Chathuranga et al., 2023; Cooper, 2024). These overlapping barriers indicate that stakeholder collaboration in GBs is not constrained by a single factor, but rather by the interaction of structural inefficiencies, behavioural limitations, and implementation gaps within existing project management practices.

## 6. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the study identified that stakeholder collaboration challenges in GB construction are strongly influenced by interconnected economic, organisational, managerial, and regulatory barriers. The findings revealed that the most critical collaboration challenges include the lack of reliable local GB materials and products, high market values of GBs, poor stakeholder attitudes, limited trust in GB products, competing business priorities, weak leadership commitment, inadequate awareness of collaborative stakeholder roles, and resource constraints. These issues demonstrate that stakeholder collaboration in GB projects is not only a technical concern but also a behavioural and institutional challenge. The study further established that both Lean and Agile barriers significantly intensify these collaboration challenges. From the Lean perspective, barriers such as economic constraints, fragmented industry structures, inadequate management commitment, insufficient training programmes, ineffective communication, and poor stakeholder engagement were found to be highly influential. Similarly, the Agile perspective highlighted barriers including project complexity and uncertainty, fragmented supply chains, inadequate leadership support, technological barriers, diverse project teams, and quality assurance concerns as key contributors to ineffective collaboration in GB projects. The overlap between Lean and Agile barriers indicates that stakeholder collaboration problems are multidimensional and require integrated management approaches rather than isolated interventions.

The study contributes to existing knowledge by demonstrating how Lean and Agile barriers influence stakeholder collaboration challenges in GB projects. The findings highlight the need for stronger GB regulations, improved stakeholder training, better communication frameworks, greater leadership commitment, and incentive mechanisms to enhance collaboration and encourage GB adoption. Furthermore, organisations should adopt integrated LeAgile management approaches to improve coordination, trust, and project performance.

However, the study is limited by its context-specific scope and primarily based on qualitative research approach, which may affect the generalisability of the findings. In addition, reliance on stakeholder perceptions may introduce subjectivity. Future research could expand the sample scope, apply quantitative validation methods, and explore the implementation of integrated LeAgile approaches in different GB contexts.

Overall, the study highlights that effective stakeholder collaboration is critical to the successful delivery of GB projects and requires both organisational and regulatory improvements within the construction industry.

# 7. REFERENCES

Addy, M. N., Adinyira, E., Dadzoe, F., & Opoku, D. (2022). The market for green buildings in Sub-Saharan Africa: Experts perspective on the economic benefits in Ghana. *Journal of Construction in Developing Countries, 27*(1), 173–188. https://doi.org/10.21315/jcdc2022.27.1.10

Agboola, S. A., Idowu, F. A., Yusuf, F. M., & Musa, A. K. (2024). Challenges to sustainable green building practice in Nigeria. *FUDMA Journal of Sciences, 7*(6), 157–163. https://doi.org/10.33003/fjs 2023-0706-2114

Alkaissy, M., Arashpour, M., Li, H., Alaghmand, S. & Nezamian,A. (2022). Quantitative analysis of safety risks and relationship with delayed project completion times. *Risk Analysis, 42*(3), 580-591. https://doi.org/10.1111/risa.13778

Alavi, S., & Aghakhani, H. (2021). Identifying the effect of green human resource management practices on lean-agile (LEAGILE) and prioritizing its practices. *International Journal of Productivity and Performance Management, 72*(3), 599–624. https://doi.org/10.1108/ijppm-05-2020-0232

Ali, A., & Sameh, H. (2024). Developing a theoretical framework for enhancing green project approaches via Agile methodology. *Science Reports, 14*, 27786. https://doi.org/10.1038/s41598-024-78613-x

Alqadami, A. T., Zawawi, N. A. W. A., Rahmawati, Y., Alaloul, W., & Alshalif, A. F. (2020). Key success factors of implementing green procurement in public construction projects in Malaysia. In *The 5th International Conference on Civil and Environmental Engineering for Sustainability* (498, pp. 1-9). IOP Publishing Ltd. https://doi.org/10.1088/1755-1315/498/1/012098

Baker S, & Hernandez, M. (2017). Communicating with stakeholders when bad news is uncertain. *International Journal of Public Leadership, 13*(2), 85–97. https://doi.org/10.1108/IJPL-11-2016-0051

Barrios, M., Guilera, G., Nuno, L., & Gomez-Benito, J. (2021). Consensus in the delphi method: What makes a decision change?. *Technological Forecasting and Social Change, 163*, 120484. https://doi.org/10.1016/j.techfore.2020.120484

Berardi, U. (2013). Sustainable construction: Green building design and delivery. *Intelligent Buildings International 5*(1), 65–66. https://doi.org/10.1080/17508975.2012.756388

Bhamra, R., Nand, A., Yang, L., Albregard, P., Azevedo, G., Corraini, D., & Emiliasiq, M. (2020). Is leagile still relevant? A review and research opportunities. *Total Quality Management and Business Excellence, 32*(13–14), 1569–1593. https://doi.org/10.1080/14783363.2020.1750360

Brady, S. R. & O'Connor, M. K. (2014). Understanding how community organising leads to social change: The beginning development of formal practice theory. *Journal of Community Practice, 22*(1/2), 210-228. https://doi.org/10.1080/10705422.2014.901263

Castelblanco, G. & Guevara, J. (2024). Stakeholder dynamics: Rethinking roles and responsibilities in user-pay transport PPP projects. *Journal of Construction Engineering and Management, 150*(8), 05024009. https://doi.org/10.1061/JCEMD4.COENG-1447

Chathuranga, S., Jayasinghe, S., Antucheviciene, J., & Wickramarachchi, R. (2023). Practices driving the adoption of agile project management methodologies in the design stage of building construction projects, *Buildings, 13*(4), 1079. https://doi.org/10.3390/buildings13041079

Cooper, M. (2024 April 18). *Exploring the role of stakeholder collaboration in sustainable supply chain management*. Research Square. https://doi.org/10.21203/rs.3.rs-4286600/v1

Demir, S. T. (2013). *AgiLean PM: A unifiying strategic framework to manage construction projects*, [Doctoral thesis, Liverpool John Moores University]. LJMU Research Online. https://researchonline.ljmu.ac.uk/id/eprint/4509/1/157452_AgiLean_STD_2013_WithoutFigures.pdf

Demir, S. T., Bryde, D. J., & Sertyesilisik, B. (2014). Introducing AgiLean to construction project management. *Journal of Modern Project Management, 1*(3), 29-39. https://journalmodernpm.com/manuscript/index.php/jmpm/article/view/136

Ekanayake, H. (2019). Traditional project management approach, industry challenges and key attributes: A case study of construction project management in Sri Lanka. *Asia Pacific Journal of Advanced Business and Social Studies, 5*(1), 52-64. https://doi.org/10.25275/APJABSSV5I1BUS6

Ekanayake, H., & Idar, R. B. (2022). Innovative project management concepts and project performance: Construction project management in Sri Lanka. *American Journal of Multidisciplinary Research and Review (AJMRR), 1*(5), 29-37. https://www.ajmrr.com/wp-content/uploads/2022/11/D152937.pdf

Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. (2021). Incorporating environmental sustainability in project portfolio management by construction contractors. *International Journal of Structural and Civil Engineering Research, 10*(3) 123–127. https://doi.org/10.18178/ijscer.10.3.123-127

Fu, Y., Dong, N., Ge, Q., Xiong, F., & Gong, C. (2020). Driving-paths of green buildings industry (GBI) from stakeholders' green behavior based on the network analysis. *Journal of Cleaner Production, 273*, 122883. https://doi.org/10.1016/j.jclepro.2020.122883

Gou, Z. (2020). The shift of green building development in China from a voluntary to mandatory approach. In Z. Gou (Ed.), *Green Building in Developing Countries: Policy, Strategy and Technology* (pp. 1-21). Springer Cham. DOI: 10.1007/978-3-030-24650-1_1

Gu, C., Reefke, H., & Yates, N. (2025). Autonomous vehicle adoption and supply chain social sustainability: Delphi study and expert interviews. *International Journal of Physical Distribution & Logistics Management, 55*(3), 275-306. https://doi.org/10.1108/IJPDLM-01-2024-0027

Javed, N., Thaheem, M. J., Bakhtawar, B., Nasir, A. R., Khan, K. I. A., & Gabriel, H. F. (2019). Managing risk in green building projects: Toward a dedicated framework. *Smart and Sustainable Built Environment, 9*(2), 156–173. https://doi.org/10.1108/sasbe-11-2018-0060

Kashikar, A., Mehta, D., Motichandani, B., & Chaitanya, P. D. (2016). A case study on agile and lean project management in construction industry. *IOSR Journal of Mechanical and Civil Engineering, 13*(4), 31–39. https://doi.org/10.9790/1684-1304013139

Kibert, C. J. (2022). *Sustainable construction: GB design and delivery* (5th ed.). Wiley. https://content.e-bookshelf.de/media/reading/L-18059417-6ed6ba0f1d.pdf

Kothari, C. R. (2004). *Research methodology: Methods and techniques* (2nd ed.). New Age International (Pvt) Ltd. Publishers. https://www.scirp.org/reference/ReferencesPapers?ReferenceID=1285422

Lalmi, A., Fernandes, G., & Souad, S.B. (2021). Synergy between traditional, agile and lean management approaches in construction projects: Bibliometric analysis. *Procedia Computer Science, 196*, 732-739. https://doi.org/10.1016/j.procs.2021.12.070

Larsson, J., & Larsson, L. (2020). Integration, application and importance of collaboration in sustainable project management. *Sustainability, 12*(2), 585. https://doi.org/10.3390/su12020585

Li, Y., Li, M., Sang, P., Chen, P., & Li, C. (2022). Stakeholder studies of green buildings: A literature review. *Journal of Building Engineering, 54*, 104667. https://doi.org/10.1016/j.jobe.2022.104667

Linneberg, M.S. and Korsgaard, S. (2021). Coding intercultural fieldwork data: A hands-on approach. In D. S. A. Guttormsen, J. Lauring, and M. Chapman (Eds.) *Field Guide to Intercultural Research* (pp. 93-105). Edward Elgar Publishing. https://doi.org/10.4337/9781788970129.00015

Liu, T., Chen, L., Yang, M., Sandanayake, M., Miao, P., Shi, Y., & Yap, P. (2022). Sustainability considerations of GBs: A detailed overview on current advancements and future considerations. *Sustainability, 14*(21), 14393. https://doi.org/10.3390/su142114393

Maradzano, I., Matope, S., & Dondofema, R. A. (2019). Application of lean principles in the south African construction industry. *The South African Journal of Industrial Engineering, 30*(3), 210-223. https://doi.org/10.7166/30-3-2240

Meena, C. S., Kumar, A., Jain, S., Rehman, A. U., Mishra, S., Sharma, N. K., Bajaj, M., Shafiq, M., & Eldin, E. T. (2022). Innovation in green building sector for sustainable future. *Energies, 15*(18), 6631. https://doi.org/10.3390/en15186631

Mostafa, S., Chileshe, N., & Abdelhamid, T. (2016). Lean and agile integration within offsite construction using discrete-event simulation: A systematic literature review. *Construction Innovation, 16*(4), 483-525. *http://dx.doi.org/10.1108/CI-09-2014-0043*

Nalumu, D.J., Mensah, H., Amponsah, O., & Takyi, S.A. (2021). Stakeholder collaboration and irrigation practices in Ghana: Issues, challenges, and the way forward. *SN Applied Sciences, 3*(576), 1-16. https://doi.org/10.1007/s42452-021-04407-9

Ng, P.L., Maqsood, T., Khalfan, M., & Rahmani, F. (2023). AgiBuild: A Scaled agile framework for building adaptation projects. *Buildings, 13*(12), 3019. https://doi.org/10.3390/buildings13123019

Orsi, A., Abdelhamid, T. S., Pellicer, E., & GuillénGuillamón, I. (2021). Improving GB project management processes through the lean approach. *Lean Construction Journal, 19*, 156-179. https://doi.org/10.60164/d1g8c3e2f

Oyombe, G. G., Awino, Z. B., Ogutu, M., & Njihia, J. M. (2023). How leagile strategy and strategic partnership affect competitive advantage of construction supply chains. *Journal of Business Strategy, Finance and Management, 4*(2), 184–201. https://doi.org/10.12944/jbsfm.04.02.02

Pinto, H. W. (2023). Exploring the implementation of agile project management in the United States construction industry: Benefits, challenges, and success factors. *Journal of Entrepreneurship and Project Management, 7*(7), 11–23. https://doi.org/10.53819/81018102t4163

Qiang, G., Cao, D., Wu, G., Zhao, X., & Zuo, J. (2021). Dynamics of collaborative networks for GB projects: Case study of Shanghai. *Journal of Management in Engineering, 37*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000892

Rybkowski, Z. K., Forbes, L. H., & Tsao, C. C. Y. (2018). The evolution of lean construction education (Part 1 of 2): At US-based universities. In V. AGonzález (Ed.) , *Proceedings of 26th Annual Conference of the International Group for Lean Construction* (pp. 1013-1023). IGLC26. https://doi.org/10.24928/2018/0447

Sadeghi, S., Akbarpour, A., & Abbasianjahromi, H. (2022). Provide a lean and agile strategy for an antifragile sustainable supply chain in the construction industry (residential complex). *Cleaner Logistics and Supply Chain, 5*(4), 100079. https://doi.org/10.1016/j.clscn.2022.100079

Singh, A., & Gupta, K. (2021). An overview of the green building construction in India. *International Journal of Engineering Applied Sciences and Technology, 6*(2), 144-150. https://doi.org/10.33564/ijeast.2021.v06i02.022

Shah, R., & Ward, P. T. (2003). Lean manufacturing: Context, practice bundles, and performance. *Journal of Operations Management, 21*(2), 129–149. https://doi.org/10.1016/s0272-6963(02)00108-0

Shaqour, E. (2021). The impact of adopting lean construction in Egypt: Level of knowledge, application, and benefits. *Ain Shams Engineering Journal, 13*(2), 101551. https://doi.org/10.1016/j.asej.2021.07.005

Spassova, A. (2023). *Innovative project management with FIDIC contracts* (1st ed). Taylor & Francis. https://doi.org/10.4324/9781003272892

Stern, T. V. (2016). *Lean and agile project management: How to make any project better, faster, and more cost effective* (2nd ed). Routledge. https://doi.org/10.4324/9780429343414

Tafazzoli, M., Mousavi, E., & Kermanshachi, S. (2020). Opportunities and challenges of green-lean: An integrated system for sustainable construction. *Sustainability, 12*(11), 4460. https://doi.org/10.3390/su12114460

Vijayan, D. S., Devarajan, P., Sivasuriyan, A., Stefańska, A., Koda, E., Jakimiuk, A., Vaverková, M. D., Winkler, J., Duarte, C. C., & Corticos, N. D. (2023). A state of review on instigating resources and technological sustainable approaches in green construction. *Sustainability, 15*(8), 6751. https://doi.org/10.3390/su15086751

Winanda, L. a. R., Yami, N., Kartika, D., Manaha, Y. P., & Ma'ruf, A. (2024). Achieving green construction rating in building projects with fuzzy system approach. In *The 4th Aceh International Symposium on Civil Engineering (AISCE 2023)* (Volume 476, 01024). E3S Web of Conferences. https://doi.org/10.1051/e3sconf/202447601024

Zhao, W., Peng, P., Guo, B., Deng, X., & Wu, W. (2023). Comprehensive social cultural and economic benefits of green buildings based on improved AHP FCE method. *Buildings, 13*(11), 311. https://doi.org/10.3390/buildings13020311

Zuo, J., & Zhao, Z. (2014). Green building research current status and future agenda: A review. *Renewable and Sustainable Energy Reviews, 30*, 271–281. https://doi.org/10.1016/j.rser.2013.10.021

Delpachitra, Y.K., Jayasena, H.S. and Wijekoon, C., 2026. Beyond functionality: The gap between materiality and compensatory expectations in e-procurement. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 306-319. DOI: https://doi.org/10.31705/WCS.2026.23. Available from: https://ciobwcs.com/papers/

# BEYOND FUNCTIONALITY: THE GAP BETWEEN MATERIALITY AND COMPENSATORY EXPECTATIONS IN E-PROCUREMENT

**Y.K. Delpachitra[1], H.S. Jayasena[2], and C. Wijekoon[3]**

## *ABSTRACT*

*E-procurement is increasingly adopted in construction to improve efficiency and compliance; however, limited understanding of how material affordances align with users' expected affordances constrains its overall utilization. This research evaluates the extent to which e-procurement systems' material affordances meet user expectations across procurement stages. Given the fragmented nature of affordance theory applications in this domain, an exploratory literature review utilising purposive sampling and manual qualitative content analysis was adopted. Material affordances were mapped across procurement planning, supplier selection and bidding, contract management, delivery and payment, and procurement closure. Conversely, expected affordances were systematically derived from documented adoption challenges, including security, infrastructure, supply chain interoperability, human capacity, and legal uncertainty. Comparative analysis reveals significant gaps between expected and material affordances, particularly regarding system resilience, accessibility under limited connectivity, usability, and long-term adaptability to dynamic project variations. The study concludes that while e-procurement offers compliance benefits, a critical misalignment persists users theoretically expect systems to compensate for environmental deficits, yet current material affordances presuppose ideal operating conditions. Addressing this design-reality gap is essential for the sustainable adoption of e-procurement systems.*

***Keywords:*** *E-procurement; Expected affordances; Materiality; System resilience; User perception.*

## 1. INTRODUCTION

The concept of affordance originates from the action possibilities offered to an individual, simply defined as the relationship between the abilities of the user and the features of the surrounding environment (Gibson, 2014). Refining this concept for sociotechnical systems, affordance is defined as the inherent capabilities or any physical properties of the system which are available within itself, existing independently of a specific user's

[1] Post Graduate Student, Department of Building Economics, University of Moratuwa, Sri Lanka, delpachitrayk.24@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk
[3] Senior Lecturer, School of Civil Engineering and Built Environment, Liverpool Jhon Moores University, United Kingdom, K.A.Wijekoon@ljmu.ac.uk

skills or any other contextual limitations (Jayasena et al., 2023). In contrast, the technology is often understood in terms of the functionality and features it provides, representing what the system is design to do (Faraj & Azad, 2013). However, unlike 'functionality,' which describes what a system is designed to do, an 'affordance' represents the complementarity between the system's material properties and the user's ability to perceive and use them for action (Evans et al., 2017; Gibson, 2014).

Building on this sociotechnical perspective, recent Information Systems (IS) research highlights that IT affordances extend beyond static system features to represent relational action potentials emerging between technology and organisational context (Pedrola et al., 2023). To accurately distinguish these affordances from basic system functionality (Valbø, 2021), the affordance process is often conceptualised as a continuum comprising existence, perception, actualisation, and effect (Pedrola et al., 2023; Pozzi et al., 2014). While this framework is increasingly utilised to evaluate digital transformation within logistics and supply chain management (Albrecht et al., 2024), a significant gap remains in understanding the actualisation phase when environmental constraints, such as poor digital infrastructure, limit system operation. Under these constrained conditions, this study posits that users formulate "compensatory expectations," wherein they anticipate the technical system to compensate for external deficits and bridge the gap between materiality and successful actualisation. This concept draws upon established principles of compensatory expectations in behavioural psychology, which describe how individuals anticipate specific mechanisms to counterbalance perceived deficits or a lack of control (Seta et al., 2010). By translating this psychological framework into the domain of Information Systems and sociotechnical affordances, this study explores how operational barriers theoretically shape user expectations in restrictive environments.

On the other hand, expected affordances represent users' expectations of the technology based on their requirements or previous understanding. This distinction is commonly used by practitioners to develop solutions that can achieve user expectations (Cook, 2022). To establish a clear structural comparison between the system's inherent capabilities and the users' needs, this study will henceforth use the term "material affordances" interchangeably with materiality.

However, organizations often operate under significant constraints, such as fragmented infrastructure, limited digital skills, and regulatory uncertainty, which limit the ability to reach some expected affordances (Laryea & Ibem, 2014; Yevu et al., 2023). This gives rise to compensatory expectations, where users expect technological systems to compensate for such external constraints.

While e-procurement is widely adopted in the construction industry to increase efficiency and compliance, existing studies primarily focus on system functionality and adoption barriers, with limited attention given to how material affordances align with users' expected affordances across procurement stages within the construction industry. Furthermore, the role of compensatory expectations in explaining this misalignment remains underexplored. This represents a critical research gap, as such misalignment can significantly affect the effective utilisation of e-procurement systems, which constrains the overall use of e-procurement. Addressing this alignment is critical to identifying functional gaps that hinder adoption. Therefore, this paper aims to evaluate the extent to which the materiality of e-procurement systems meets user expectations.

## 2. METHODOLOGY

To achieve the research aim, a comprehensive review of existing literature was conducted. While a systematic literature review is often the standard for evidence-based analysis (Mengist et al., 2020; Purssell & Mccrae, 2020), the emerging and fragmented nature of affordance-based research limits its applicability and necessitates a more adaptive approach. Consequently, an explorative literature review approach was adopted, as it effectively maps uncharted theoretical landscapes and organises new research directions (Asmussen & Møller, 2019). Instead of exhaustive sampling, purposive sampling was employed to identify literature discussing specific phenomena related to e-procurement challenges and affordances. Literature was sourced from Scopus, Web of Science, and Google Scholar.

The search was restricted to English-language publications from the year 2000 onwards. Inclusion criteria prioritized peer-reviewed journal articles, conference proceedings, and authoritative institutional frameworks (such as the PMBOK Guide) to ensure academic rigor. Documents were initially screened and prioritised by thematic relevance through title and abstract review. The search process concluded upon reaching data saturation: the point at which new sources yielded no novel themes regarding e-procurement limitations or materiality. Ultimately, a sample of 40 unique documents was selected for analysis.

Under this approach, the research was conducted in three distinct phases utilising manual qualitative content analysis:

1. Identification of Material Affordances: Standard procurement guidelines and established e-procurement literature were reviewed to catalogue the inherent system capabilities across the procurement lifecycle.
2. Derivation of Expected Affordances: Literature documenting adoption challenges was sourced using keywords such as “e-procurement,” “digital procurement,” “challenges,” “limitations,” and “construction.” It should be mentioned that this derivation is interpretive rather than deterministic. When users encounter challenges, these act as indicators of anticipated affordances. In such contexts, users formulate “compensatory expectations,” anticipating that the system’s materiality will bridge environmental gaps. Thus, challenges were analytically coded as unmet user expectations to generate the summarized findings presented in Table 1.
3. Comparative Evaluation: A comparative analysis was performed to identify alignment gaps between the material affordances of the system and the expected affordances of the users. To operationalize this, a tick (✓) was assigned if the reviewed literature provided explicit evidence that the system’s capabilities fulfilled the expected affordance. A cross (✗) was assigned if the literature indicated an unmet need or a reliance on ideal environmental conditions that the system could not independently compensate for. The results of this coding process are aggregated and presented in Table 2.

## 3. ANALYSIS AND FINDINGS

This section presents the findings derived from the manual qualitative content analysis, wherein the selected literature was utilised as qualitative data sources to map the material and expected affordances.

## 3.1 MATERIALITY OF E-PROCUREMENT

E-procurement is an internet-based technological solution that uses information technology to support and streamline the procurement process (Presutti, 2003), managing purchasing phases such as need identification, negotiation, sourcing, ordering, receipt (Croom & Brandon-Jones, 2005). To effectively evaluate these phases, it is necessary to examine the materiality of e-procurement.

In this context, PMBOK, alongside the 2024 procurement guidelines of Sri Lanka, makes a significant contribution to the field of project management by defining the essential materiality required within a general procurement system. These affordances are categorised by using PMBOK and the 2024 procurement guidelines into five distinct phases of the procurement process (National Procurement commission, 2024; Project Management Institute, 2021), as illustrated in Figure 1.

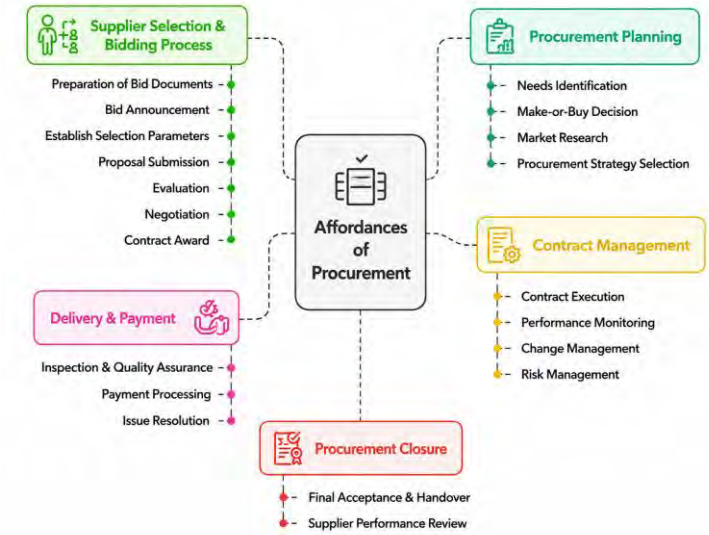



*Figure 1: Affordances of procurement*

The identification of materiality across procurement stages was conducted through a structured coding process. Recurring system functionalities were extracted from the reviewed literature and grouped according to their functional relevance to procurement stages. This approach enabled the systematic mapping of capabilities of procurement across the e-procurement lifecycle and is consistent with exploratory literature review approaches that emphasise pattern identification and thematic organisation.

### 3.1.1 Procurement Planning (A)

Procurement planning involves planning purchasing activities within a specified timeframe (Agaba & Shipman, 2007). E-procurement systems afford several key capabilities at this stage, particularly regarding information retrieval and decision support, enabling need identification, make-or-buy decision-making, market research, and procurement strategy selection (Chan & Lee, 2003). The assessment of system benefits against implementation costs contributes to the system's materiality (Panda & Sahu, 2012), while application of e-design enables the digital setting of purchasing requirements (Chang et al., 2013). Rather than replacing expert judgment, e-procurement affords enhanced need identification through expanded information access and efficient workflows (Chan & Lee, 2003; Kumar et al., 2017; World bank Group, 2011). The

systems afford a robust information base, providing historical data and market details research and analysis (Chan & Lee, 2003; Premathilaka & Fernando, 2020). This capability for information retrieval enables buyers to collect data on market conditions and potential suppliers, affording supplier selection (Choi & Chang, 2006), price bidding (Stein & Wyld, 2003), and contract negotiation (Bichler et al., 2002). Properly configured, these tools afford market awareness, improving customer-supplier relationships (Bartezzaghi & Ronchi, 2005). Ultimately, e-procurement affords the evaluation and setting up of trading partner groupings and efficient supplier performance rating to support procurement strategy selection (Abu Bakar et al., 2016; Presutti, 2003). While this materiality primarily supports accessing information and making decisions, it is less effective in handling contextual challenges such as user limitations or unstable environments.

### 3.1.2 Supplier Selection & Bidding Process (B)

Supplier selection is the process by which purchasers find, assess, and enter into contracts with suppliers (Beil, 2011). The system affords electronic tendering, sourcing, auctions, marketplaces, and catalogue purchasing (Aboelmaged, 2010; Vaidya et al., 2006). This materiality is achieved through e-sourcing and e-evaluation capabilities that gather comprehensive supplier data, allowing construction businesses to choose suppliers directly via the digital platform (Chang et al., 2013). Tools such as e-RFQs, and e-catalogues facilitate supplier evaluation against predefined criteria (Aboelmaged, 2010; Vaidya et al., 2006). Furthermore, these systems afford secure proposal submissions and online bidding mechanisms, including reverse auctions with pre-qualified suppliers (Schrader et al., 2004). Overall, they afford enhanced competition, broader supplier participation, streamline the submission, and more competitive pricing (Davila et al., 2003; Schrader et al., 2004). Additionally, the system affords transparent negotiation and contract awarding through digital platforms using digital contracts and order processing, reducing administrative costs (Aboelmaged, 2010). While this materiality enhances the effectiveness and transparency of supplier engagement, it relies heavily on dependable digital infrastructure and system interoperability, offering limited solutions for accessibility, integration difficulties, and different supplier capabilities.

### 3.1.3 Contract Management (C)

Contract management encompasses the contractual requirements that both parties must fulfill (Cruz & Marques, 2013). Procurement technologies afford streamlined contract execution by minimizing the time and cost required to create purchase orders (Aboelmaged, 2010). Management information systems afford robust procurement monitoring, enabling organisations to evaluate compliance with service-level agreements (Vaidya et al., 2006). Additionally, organised processes, such as formal bid review and comprehensive request-for-proposal systems, afford controlled variation and support efficient contract administration (Schrader et al., 2004). However, given the highly dynamic nature of construction projects, characterised by frequent design variations and material price fluctuations tied to global logistics, effective contract management necessitates rapid, transparent adjustments. While this materiality primarily supports administrative control, compliance, and monitoring, there is limited evidence of affordances enabling flexibility or adaptation to dynamic project conditions commonly seen in construction.

### 3.1.4 Delivery and Payment (D)

Digital solutions afford procedural transparency and compliance, increasingly supporting delivery, payment, and quality assurance process (Croom & Jones, 2007). This enables a material post-procurement environment focused heavily on delivery tracking and work performance improvement (Kademaunga & Phiri, 2019; Chang et al., 2013). the system affords the capacity to confirm supplier certifications, manufacturer capabilities, and past on-time delivery performances (Schrader et al., 2004). Data security is important to afford online payments, and the system ensures that the online purchases are appropriately documented in organizational financial systems and communicated to suppliers (Vaidya et al., 2006). These features decrease transaction costs (Davila et al., 2003) and reduce the time required to establish purchase orders, process payment, track shipments, and service registration (Aboelmaged, 2010). Ultimately, e-procurement platforms afford improved coordination, and the timely identification of delivery and payment issues through increased supply chain visibility (Aboelmaged, 2010; Davila et al., 2003). While this materiality improves transaction efficiency, traceability, and financial compliance, it relies heavily on secure system environments and provides limited support for managing disruptions, delays, or failures.

### 3.1.5 Procurement Closure (E)

E-procurement systems afford procurement closure by offering accessible management data to analyse supplier performance and track adherence to service-level agreements (Vaidya et al., 2006). The system affords early performance indicator creation, outcome monitoring, and post-award evaluations to ensure delivery reliability and quality capability (Vaidya et al., 2006; Schrader et al., 2004). This efficiency allows procurement personnel to focus on strategic closure tasks, such as supplier ratings and performance reviews. Long-term strategic efficiency is achieved when joint-learning techniques, such as mutual competency creation, are utilised (Chang et al., 2013). Finally, the system affords the integration of procurement activities with core organisational processes (Mora Cortez et al., 2023). Materiality at this stage mainly support supplier assessment, documentation, and performance evaluation. Nevertheless, there is little evidence of affordances that facilitate feedback integration, organisational learning, or continuous system improvement, which remains essential for sustained efficacy.

## 3.2 CHALLENGES IN E-PROCUREMENT

Despite its potential, e-procurement faces several challenges and limitations that hinder its utilisation. Prominent among these are security-related challenges, including access control, data protection, and system recovery, alongside the complexity and cost, and mandatory digital signatures, which clashes with users' preference for traditional methods (Mohungoo et al., 2020). Vulnerabilities such as data breaches, hacking, transaction errors, and unauthorised access significantly reduce organizational confidence and decision-making (Gilbert & Celestin, 2025; Huber et al., 2004; Saeed & Leitch, 2003; Yen & Ng, 2002). Furthermore, the ease of information leakage and disclosure of sensitive material exacerbates confidentiality issues, erode user trust and increase risk of financial loss (Makoba et al., 2017; Ting & Wong, 2003).

Technical infrastructure presents significant barriers. Constraints in ICT infrastructure, characterised by limited broadband coverage, unreliable internet connectivity, high internet costs, and outdated equipment, impact small and medium-sized businesses as

well as rural areas (Gilbert & Celestin, 2025; Huber et al., 2004; Inusah et al., 2025; Toktaş-Palut et al., 2014). In the construction context, these constraints are particularly acute at the "edge" of operations, i.e., on temporary or remote project sites where digital infrastructure is rarely established prior to mobilisation. The implementation of e-procurement systems in the construction industry is constrained by low digital capacity and limited access to technology resources under the ICT infrastructure (Laryea & Ibem, 2014). Additionally, firms operating in remote areas are severely impacted by unpredictable internet access, power shortage, and poor network conditions, which hinder their ability to participate effectively in e-procurement procedures (Makoba et al., 2017). The adoption of e-procurement technologies in developing nation contexts has also been shown to be severely restricted by inadequate ICT infrastructure and unstable power supplies (Ibem & Laryea, 2015). Furthermore, construction relies heavily on a tiered network of subcontractors and localised material suppliers (SMEs), exacerbating integration challenges. Additionally, poor system interoperability between legacy and new e-procurement platforms, as well as incompatible supplier systems across this fragmented network, leads to workflow disruptions, complex system integration, and frequent system failures (Huber et al., 2004; Toktaş-Palut et al., 2014). This is in line with research showing that two of the biggest problems with construction e-procurement systems are inability to integrate different web-based applications into a single platform (Gurgun et al., 2024; Laryea & Ibem, 2014). Additionally, disparities in software systems and technological incompatibilities lead to operational inefficiencies and challenges in managing procurement papers, raising the risk of system failure and malfunction (Makoba et al., 2017).

Organisational and human factors also constrain adoption. These include resistance to updating systems from traditional manual procedures, driven by poor digital skills, insufficient training, limited technical expertise, and high staff turnover (Eadie et al., 2010; Toktaş-Palut et al., 2014). In addition, mandatory documentation requirements, bureaucratic rigidity, inconsistent organisational priorities, and poor leadership commitment further restrict the adoption of e-procurement systems (Eadie et al., 2010; Toktaş-Palut et al., 2014). Further indicates that inadequate knowledge of e-procurement systems, lack of user competence, and resistance to technological change, and insufficient understanding of e-procurement systems hider the adoption, especially in settings where old methods are firmly established (Laryea & Ibem, 2014). Furthermore, established cultural factors have been found to be important barriers affecting system implementation and user acceptance (Ibem & Laryea, 2015).

From a legal perspective, challenges in e-procurement include variations in traditional practices, unclear electronic contract enforceability, ambiguous electronic signature procedures, and limited policy support, all of which create uncertainty in implementation (Eadie et al., 2010; Yevu et al., 2023). Moreover, traditional government requirements, such as compulsory printed documentation, conflict with electronic tendering principles and delay digital transformation (Nawi et al., 2017). Legal jurisdictional inconsistencies, legal liability issues, electronic transaction insecurity, and dangers related to data privacy and confidentiality in digital procurement environments all contribute to these difficulties (Ting & Wong, 2003).

Finally, e-procurement adoption is further limited by systemic issues, including a lack of clear guidance and benchmark models due to its comparatively recent development. External factors beyond organisational control, such as material supply chain volatility

and rapid technological shifts, hinder implementation (Nawi et al., 2017). Moreover, adoption is severely constrained by industry-wide fragmentation, conservative methods, limited IT investment, and the fundamentally project-based character of construction activities (Laryea & Ibem, 2014)

Collectively, these recurring challenges highlight not only barriers to adoption yet reveal underlying mismatches between system capabilities and user expectations. Therefore, rather than being treated as isolated issues, they are interpreted in this study as analytical indicators of expected affordances, forming the foundation for the subsequent comparative analysis between expected and material affordances.

## 3.3 DERIVING EXPECTED E-PROCUREMENT AFFORDANCES

By analysing the identified challenges discussed in the previous section, expected affordances can be systematically derived. This approach posits that where users face a challenge, they inherently hold an expectation for a specific affordance to overcome it. However, a critical distinction must be made between facilitating conditions, such as internet connectivity or legal frameworks, and the material affordances of the system. While facilitating conditions are environmental factors required for action capability, in contexts where these conditions are lacking, users often expect the technical subsystem to compensate. For instance, stability under poor connectivity is interpreted here not as a demand for better infrastructure, but as an expectation for specific system capabilities (e.g., offline functionality or low-bandwidth resilience) that afford operation despite environmental limitations. Consequently, the derived expectations in Table 1 reflect the system properties users anticipate will bridge these environmental gaps.

*Table 1: Summary of expected affordances listed through challenges*

| Challenge Category | Expected Affordances of E-Procurement | Referred Sources |
|---|---|---|
| Security-related challenges | • Secure access control | 1, 11 |
| | • Data protection, confidentiality and privacy assurance | 3, 4, 5, 6 |
| | • System recovery resilience | 1 |
| | • Cybersecurity assurance | 2, 6, 11 |
| Digital signature complexity | • User-aligned electronic authentication | 1 |
| | • Simplified digital signature execution | 1 |
| ICT infrastructure limitations | • Reliable system performance under connectivity constraints | 2, 6, 8, 10, 11, |
| | • Accessibility under limited broadband conditions | 2, 8, 9, 14 |
| System interoperability issues | • Compatibility between legacy and new systems | 10, 11, 12, 14 |
| | • System reliability through error handling and fault tolerance | 6 |
| Human capacity limitations | • Intuitive ease of use for users with limited digital skills | 10, 12, 14 |
| | • Reduced reliance on manual processes | 10, 13 |

| | | |
|---|---|---|
| | • Operational continuity in high staff turnover environments | 10, 13 |
| Organizational rigidity | • Streamlined procedures to reduce bureaucratic burden | 10, 13 |
| | • Consistent organizational engagement | 10, 13, 14 |
| Legal and regulatory uncertainty | • Electronic contract enforceability | 5, 7, 13 |
| | • Consistent electronic signature procedures | 7, 13 |
| | • Regulatory compliance alignment | 5, 7 |
| Traditional government practices | • Electronic tendering compliance with institutional standards | 15 |
| | • Digital transformation facilitation | 15 |
| Lack of benchmark Materiality models | • Clear guidance on system capabilities | 15 |
| | • Structured implementation pathways | 15 |
| External environmental factors | • Adaptability to market conditions | 15 |
| | • Resilience to fast technological advances | 14,15 |

Sources: 1: Mohungoo et al., (2020), 2: Gilbert & Celestin, (2025), 3: Saeed & Leitch, (2003), 4: Yen & Ng, (2002), 5: Ting & Wong, (2003), 6: Makoba et al., (2017), 7: Yevu et al., (2023) , 8: Ibem & Laryea, (2015), 9: Inusah et al., (2025) 10: Toktaş-Palut et al., (2014) ,11: Huber et al., (2004) ,12: Gurgun et al., (2024) , 13: Eadie et al., (2010), 14: Laryea & Ibem, (2014), 15: Nawi et al., (2017)

With this understanding, users expect the system to afford a secure, reliable platform that aligns with their operational needs, specifically requiring robust access control, system recovery, data protection, and cybersecurity assurance to mitigate risks and unauthorised access.

Regarding ICT limitations, users expect stable system performance, compatibility with legacy platforms, and seamless interoperability with supplier to ensure resilience against workflow disruptions, especially for rural or SME users facing connectivity constraints.

To addressing human and organisational challenges, users expect intuitive systems that reduce manual processes, accommodate limited digital skills or higher staff turnover, and streamline procedures to reduce bureaucratic rigidity and documentation burdens.

From a regulatory perspective, expectations centre on reliable electronic contracting, consistent e-signature processes, and proper alignment with legal requirements.

Finally, users expect clear guidance on system capabilities, flexible implementation pathways, and adaptability to shifting market conditions and rapid technological advancements to effectively manage systemic uncertainty.

A summary of the expected affordances derived from the identified challenges is shown in Table 1.

### 3.4 MATERIAL AFFORDANCES VS EXPECTED AFFORDANCES

Having identified the expected affordances, they were compared with the material affordances across each stage, as shown in the Table 2.

*Table 2: Comparison between expected affordances and the material affordances in each stage*

| Expected Affordances | Procurement Stages | | | | | Referred Sources |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | |
| Secure access control | ✗ | ✓ | ✓ | ✓ | ✗ | 1, 2, 3 |
| Data protection and confidentiality | ✗ | ✓ | ✓ | ✓ | ✗ | 1, 3 |
| System recovery resilience | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Cybersecurity assurance | ✗ | ✓ | ✓ | ✓ | ✗ | 1, 3 |
| User-aligned electronic authentication | ✗ | ✓ | ✓ | ✓ | ✗ | 1, 2, 3 |
| Simplified digital signature execution | ✗ | ✓ | ✓ | ✓ | ✗ | 2 |
| Reliable system performance under connectivity constraints | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Accessibility under limited broadband conditions | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Compatibility between legacy and new systems | ✗ | ✗ | ✓ | ✓ | ✓ | 3, 4 |
| Seamless interoperability with supplier systems | ✗ | ✓ | ✓ | ✓ | ✗ | 1, 3 |
| Intuitive ease of use for users with limited digital skills | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Reduced reliance on manual processes | ✓ | ✓ | ✓ | ✓ | ✓ | 2, 5 |
| Operational continuity in high staff turnover environments | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Streamlined procedures to reduce bureaucratic burden | ✓ | ✓ | ✓ | ✓ | ✗ | 2, 6, 11 |
| Consistent organizational engagement | ✓ | ✓ | ✓ | ✗ | ✓ | 3, 4, 5, 7 |
| Electronic contract enforceability | ✗ | ✓ | ✓ | ✗ | ✓ | 1, 2, 3 |
| Consistent electronic signature procedures | ✗ | ✓ | ✓ | ✓ | ✗ | 2 |
| Regulatory compliance alignment | ✗ | ✓ | ✓ | ✓ | ✓ | 2, 3, 8 |
| Electronic tendering compliance with institutional standards | ✗ | ✓ | ✗ | ✗ | ✗ | 2 |
| Digital transformation facilitation | ✓ | ✓ | ✓ | ✓ | ✓ | 2, 4, 5 |
| Clear guidance on system capabilities | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Structured implementation pathways | ✗ | ✗ | ✗ | ✗ | ✗ | - |
| Adaptability to market conditions | ✓ | ✓ | ✗ | ✗ | ✓ | 1, 5, 9 |
| Resilience to fast technological advances | ✗ | ✗ | ✗ | ✗ | ✗ | - |

Source: 1: Schrader et al., (2004), 2: Aboelmaged, (2010), 3: Vaidya et al., (2006), 4: Mora Cortez et al., (2023), 5: Chang et al., (2013), 6: Davila et al., (2003), 7: Panda & Sahu, (2012), 8: Croom & Brandon-Jones, (2007), 9: Chan & Lee, (2003) ,10: Abu Bakar et al., (2016), 11: Kumar et al., (2017).

As shown in Table 2, e-procurement systems mainly support regulatory compliance, security, and administrative efficiency; however, there are differences between the expected affordances and material affordances of e-procurement systems in several areas. These key gaps are evident in system resilience, accessibility, usability, long-term adaptability, and organizational support, especially in situations with limited resources

and limited connectivity. Although current e-procurement systems have streamlined procurement procedures, limitations remain in supporting organizational learning, systematic technological evaluation, and sustained capability development, highlighting the need for further development to meet users' expectations. Ultimately, the synthesis of these findings directly addresses the research objective by demonstrating that while materiality aligns with functional and compliance-driven expectations, a persistent gap exists where users theoretically expect the system to compensate for the fragmented and resource-constrained realities of the construction environment.

## 4. CONCLUSIONS

This study evaluates the extent to which the materiality of e-procurement systems meets users' expectations and was conducted through an exploratory literature review. The findings show that e-procurement satisfactorily covers most expectations related to security, administrative efficiency, and regulatory compliance, which reduces the use of manual procedures and bureaucratic burdens. However, key expected affordances related to system resilience, accessibility, usability, adaptability to market conditions and technological change, and organisational support remain unmet, especially in contexts with limited resources and connectivity. Most importantly, this research highlights a theoretical distinction in that users often expect the system's materiality to compensate for environmental limitations. For instance, expectations for stability under poor connectivity or legal enforceability reveal that users anticipate the technical subsystem (i.e., the e-procurement system) to bridge gaps in the external environment. Current e-procurement systems, however, largely presuppose an ideal operating environment, resulting in a design-reality gap where these compensatory expectations are left unsupported.

Therefore, to fully integrate e-procurement sustainably, it is necessary for future research and development to move beyond functional compliance and focus on context-aware affordances. Specifically, solutions must be identified that enable systems to function resiliently within constrained environments, to fulfil these remaining expectations and reduce constraints on the sustainable adoption of e-procurement systems.

## 5. LIMITATIONS AND FUTURE RESEARCH

Mapping documented challenges to user expectations, this research relies on the compensatory expectation framework for its key findings. As an exploratory study, it identifies the potential spectrum of user expectations rather than claiming universal prevalence. For instance, users facing systemic barriers, such as poor internet connectivity, might seek manual workarounds or abandon the system entirely. Within this theoretical framework, such actions are interpreted as symptoms of latent compensatory expectations. While this approach effectively models what users theoretically expect systems to overcome, future empirical research is required. Specifically, user surveys and observational case studies in construction environments are needed to quantify the frequency of these expectations and determine the specific thresholds at which unmet expectations lead to system abandonment.

## 6. REFERENCES

Aboelmaged, M. G. (2010). Predicting e-procurement adoption in a developing country. *Industrial Management and Data Systems*, *110*(3), 392–414. https://doi.org/10.1108/02635571011030042

Abu Bakar, N., Peszynski, K., Azizan, N., & Sundram, V. P. K. (2016). Abridgment of traditional procurement and e-procurement: Definitions, tools and benefits. *Journal of Emerging Economies and Islamic Research*, *4*(1), 1-18. https://doi.org/10.24191/jeeir.v4i1.9080

Agaba, E., & Shipman, N. (2007). Public procurement reform in developing countries: The Uganda experience. In G. Piga & K. Thai (Eds.), *Advancing public procurement: Practices, innovation and knowledge sharing* (pp. 373-391). PR Academics Press. https://ippa.org/images/BOOKS/IPPC2/Chapter_16.pdf

Albrecht, T., Baier, M.-S., Gimpel, H., Meierhöfer, S., Röglinger, M., Schlüchtermann, J., & Will, L. (2024). Leveraging digital technologies in logistics 4.0: Insights on affordances from intralogistics processes. *Information Systems Frontiers*, 26(2), 755–774. https://doi.org/10.1007/s10796-023-10394-6

Asmussen, C. B., & Møller, C. (2019). Smart literature review: A practical topic modelling approach to exploratory literature review. *Journal of Big Data*, *6*(1), 1-18. https://doi.org/10.1186/s40537-019-0255-7

Bartezzaghi, E., & Ronchi, S. (2005). E-sourcing in a buyer-operator-seller perspective: Benefits and criticalities. *Production Planning and Control*, *16*(4), 405–412. https://doi.org/10.1080/09537280500063459

Beil, D. R. (2011, February 15). *Supplier selection*. Wiley Encyclopedia of Operations Research and Management Science. https://doi.org/10.1002/9780470400531.EORMS0852

Bichler, M., Kalagnanam, J., Katircioglu, K., King, A. J., Lawrence, R. D., Lee, H. S., Lin, G. Y., & Lu, Y. (2002). Applications of flexible pricing in business-to-business electronic commerce. *IBM System Journal*, *41*(2), 287-302. https://doi.org/DOI:10.1147/sj.412.0287

Chan, J. K. Y., & Lee, M. K. O. (2003). SME e-procurement adoption in Hong Kong-the roles of power, Trust and Value. *In Proceedings of the 36th Annual Hawaii International Conference on System Sciences*, USA. https://doi.org/DOI:10.1109/HICSS.2003.1174388

Chang, H. H., Tsai, Y. C., & Hsu, C. H. (2013). E-procurement and supply chain performance. *Supply Chain Management*, *18*(1), 34–51. https://doi.org/10.1108/13598541311293168

Choi, J. H., & Chang, Y. S. (2006). A two-phased semantic optimization modeling approach on supplier selection in eProcurement. *Expert Systems with Applications*, *31*(1), 137–144. https://doi.org/10.1016/j.eswa.2005.09.022

Cook, D. (2022). Affordances. In J. C. K. Tham (Ed.), *Keywords in design thinking: A lexical primer for technical communicators & designers* (pp. 51–53). The WAC Clearinghouse; University Press of Colorado. https://doi.org/10.37514/TPC-B.2022.1725.2.07

Croom, S., & Brandon-Jones, A. (2007). Impact of e-procurement: Experiences from implementation in the UK public sector. *Journal of Purchasing and Supply Management*, *13*(4), 294–303. https://doi.org/10.1016/j.pursup.2007.09.015

Croom, S. R., & Brandon-Jones, A. (2005). Key issues in e-procurement: Procurement implementation and operation in the public sector. *Journal of Public Procurement*, *5*(3), 367–387. https://doi.org/DOI:10.1108/JOPP-05-03-2005-B004

Cruz, C. O., & Marques, R. C. (2013). Contract management. In *Infrastructure public-private partnerships* (pp. 83–111). Springer. https://doi.org/10.1007/978-3-642-36910-0_4

Davila, A., Gupta, M., & Palmer, R. J. (2003). Moving procurement systems to the internet: The adoption and use of e-procurement technology models. *European Management Journal*, *21*(1), 11–23. https://doi.org/10.1016/S0263-2373(02)00155-X

Eadie, R., Perera, S., & Heaney, G. (2010). Identification of e-procurement drivers and barriers for UK construction organisations and ranking of these from the perspective of quantity surveyors. *Journal of Information Technology in Construction*, *15*, 23–43. http://www.itcon.org/2010/2

Evans, S. K., Pearce, K. E., Vitak, J., & Treem, J. W. (2017). Explicating affordances: A conceptual framework for understanding affordances in communication research. *Journal of Computer-Mediated Communication*, *22*(1), 35–52. https://doi.org/10.1111/jcc4.12180

Faraj, S., & Azad, B. (2013). The materiality of technology: An affordance perspective. In P. M. Leonardi, B. Nardi, & J. Kallinikos (Eds.), *Materiality and organizing: Social interaction in a technological world*

(pp. 237–258). Oxford University Press. https://doi.org/10.1093/ACPROF:OSO/9780199664054.003.0012

Gibson, J. J. (2014). *The ecological approach to visual perception* (Classic Edition). Psychology Press. https://doi.org/10.4324/9781315740218

Gilbert, T., & Celestin, M. (2025). Challenges and opportunities of implementing e- procurement in public institutions: a comparative study of comesa countries. *International Journal of Engineering Research and Modern Education*, *10*(1), 2455–4200. https://doi.org/10.5281/zenodo.15059264

Gurgun, A. P., Kunkcu, H., Koc, K., Arditi, D., & Atabay, S. (2024). Challenges in the integration of e-procurement procedures into construction supply chains. *Buildings*, *14*(3). 605. https://doi.org/10.3390/buildings14030605

Huber, B., Sweeney, E., & Smyth, A. (2004). Purchasing consortia and electronic markets: Procurement direction in integrated supply chain management. *Electronic Markets*, *14*(4), 284–294. https://doi.org/10.1080/10196780412331311739

Ibem E. O & Laryea, S. (2015). E-procurement use in the South African construction industry. *Journal of Information Technology in Construction, 20, 364-384.* http://www.itcon.org/2015/23

Inusah, Y., Kazaz, A., & Ulubeyli, S. (2025). Barriers to e-tendering implementation in the construction industry: A comprehensive review and analysis of a decade and beyond. *Sustainability*, *17*(5), 2052. https://doi.org/10.3390/su17052052

Jayasena, H. S., Thurairajah, N., Perera, B. A. K. S., & Siriwardena, M. (2023). Affordance-led framework of understanding of BIM adoption. *International Journal of Architectural Research: Archnet-IJAR*, *18*(4), 937–954. https://doi.org/10.1108/ARCH-02-2023-0028

Kademaunga, C. K., & Phiri, J. (2019). Factors affecting successful implementation of electronic procurement in government institutions based on the technology acceptance model. *Open Journal of Business and Management*, *7*(4), 1705–1714. https://doi.org/10.4236/ojbm.2019.74118

Kumar, V., Chibuzo, E. N., Garza-Reyes, J. A., Kumari, A., Rocha-Lona, L., & Lopez-Torres, G. C. (2017). The impact of supply chain integration on performance: Evidence from the UK food sector. *Procedia Manufacturing*, *11*, 814–821. https://doi.org/10.1016/j.promfg.2017.07.183

Laryea, S., & Ibem, E. O. (2014). Patterns of technological innovation in the use of e-procurement in construction. *Journal of Information Technology in Construction*, *19*, 104–125. http://www.itcon.org/2014/6

Makoba, N., Nyamagere, G., & Eliufoo, H. (2017). E-procurement risks and mitigation: The case for Tanzania construction companies. *International Journal of Construction Engineering and Management*, *6*(4), 180–186. https://doi.org/10.5923/j.ijcem.20170604.06

Mengist, W., Soromessa, T., & Legese, G. (2020). Ecosystem services research in mountainous regions: A systematic literature review on current knowledge and research gaps. *Science of the Total Environment*, *702*, 134581. https://doi.org/10.1016/j.scitotenv.2019.134581

Mohungoo, I., Brown, I., & Kabanda, S. (2020). A systematic review of implementation challenges in public e-procurement. In M. Hattingh, M. Matthee, H. Smuts, I. Pappas, Y. K. Dwivedi, & M. Mäntymäki (Eds.), *Responsible design, implementation and use of information and communication technology* (pp. 46-58). https://doi.org/10.1007/978-3-030-45002-1_5

Mora Cortez, R., Cabanelas, P., & Charterina, J. (2023). Online reverse auctions research in marketing versus SCM: A review and future directions. *Industrial Marketing Management*, *115*, 439–454. https://doi.org/10.1016/j.indmarman.2023.10.011

National Procurement Commission. (2024). *Procurement manual 2024*. https://www.cs.sp.gov.lk/css/csw/supply/2025_09_02_03_en.pdf

Nawi, M. N. M., Deraman, R., Adewale Bamgbade, J., Zulhumadi, F., & Riazi, S. R. M. (2017). E-Procurement in Malaysian construction industry: Benefits and challenges in implementation. *International Journal of Supply Chain Management*, *6*(1), 209–213. https://repo.uum.edu.my/id/eprint/21949/1/IJSCM%206%201%202017%20209%20213.pdf

Panda, P., & Sahu, G. P. (2012). E-procurement implementation: Critical analysis of success factors' impact on project outcome. *SSRN, Ahead-of-Print*. http://ssrn.com/abstract=2019575

Pedrola, P., Vitari, C., Raguseo, E., & Pigni, F. (2023, November 22). *An organization and process-based framework of IT affordances for the IS discipline*. 15th Mediterranean Conference on Information

Systems (MCIS) and the 6th Middle East & North Africa Conference on digital Information Systems (MENACIS), Madrid, Spain. https://amu.hal.science/hal-04299465v1/document

Project Management Institute. (2021). *A guide to the project management body of knowledge (PMBOK guide)* (7th ed.). Project Management Institute. https://www.pmi.org/standards/pmbok

Premathilaka, K. M., & Fernando, R. L. S. (2020). Critical success factors affecting e-procurement adoption in public sector organizations in Sri Lanka. *Vidyodaya Journal of Management*, *6*(11), 73–102. https://vjm.sljol.info/articles/57/files/submission/proof/57-1-115-1-10-20210517.pdf

Presutti, W. D. (2003). Supply management and e-procurement: Creating value added in the supply chain. *Industrial Marketing Management*, *32*(3), 219–226. https://doi.org/10.1016/S0019-8501(02)00265-1

Pozzi, G., Pigni, F., & Vitari, C. (2014). *Affordance theory in the IS discipline: A review and synthesis of the literature.* AMCIS 2014 Proceedings, Savannah, United States. https://shs.hal.science/halshs-01923663v1/document

Purssell, E., & Mccrae, N. (2020). *How to perform a systematic literature review* (1st edition). Springer. https://link.springer.com/book/10.1007/978-3-030-49672-2

Saeed, K. A., & Leitch, R. A. (2003). Controlling sourcing risk in electronic marketplaces. *Electronic Markets*, *13*(2), 163–172. https://doi.org/10.1080/1019678032000067172

Schrader, R. W., Schrader, J. T., & Eller, E. P. (2004). Strategic implications of reverse auctions. *Journal of Business-to-Business Marketing*, *11*(1–2), 61–82. https://doi.org/10.1300/J033v11n01_05

Seta, J. J., Seta, C. E., & Erber, M. W. (2010). The role of cost in generating expectations and value: A personal equity-comparison theory analysis. *Basic and Applied Social Psychology*, *14*(1), 103-119. https://doi.org/10.1207/s15324834basp1401_8

Stein, A., & Wyld, D. C. (2003). The 20% solution?: A case study on the efficacy of reverse auctions. *Management Research News*, *26*(5), 1-20. https://doi.org/10.1108/01409170310783439

Ting, S. K., & Wong, H. Y. (2003). *Legal challenges & strategies in e-procurement in construction.* University of Auckland. https://www.cs.auckland.ac.nz/research/conferences/w78/papers/W78-08.pdf

Toktaş-Palut, P., Baylav, E., Teoman, S., & Altunbey, M. (2014). The impact of barriers and benefits of e-procurement on its adoption decision: An empirical analysis. *International Journal of Production Economics*, *158*, 77–90. https://doi.org/10.1016/j.ijpe.2014.07.017

Vaidya, K., Sajeev, A. S. M., & Callender, G. (2006). Critical factors that influence e-procurement implementation success in the public sector. *Journal of Public Procurement*, *6*(1-2), 70–99. https://doi.org/10.1108/JOPP-06-01-02-2006-B004

Valbø, B. (2021, November). *The IS-notion of affordances: A mapping of the application of affordance theory in information systems research.* Forty-fourth Information Systems Research Seminar in Scandinavia, Norway. https://aisel.aisnet.org/iris2021/2/

World Bank Group. (2011). *E-procurement reference guide*. https://documents1.worldbank.org/curated/en/751741468163749785/pdf/882160WP0Box380ementReferenceGuide.pdf

Yen, B. P. C., & Ng, E. O. S. (2002). Migrating procurement onto the internet. *Electronic Commerce Research*, *2*, 113–134. https://doi.org/10.1023/A:1013348303943

Yevu, S. K., Yu, A. T. W., & Darko, A. (2023). Barriers to electronic procurement adoption in the construction industry: a systematic review and interrelationships. *International Journal of Construction Management*, *23*(6), 964–978. https://doi.org/10.1080/15623599.2021.1946900

Deheragoda, H., De Silva, G.H.S.P., and Jinthusan, M., 2026. Beyond the envelope: Examining project management as a catalyst for higher-performance building design. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 320-333. DOI: https://doi.org/10.31705/WCS.2026.24. Available from: https://ciobwcs.com/papers/

# BEYOND THE ENVELOPE: EXAMINING PROJECT MANAGEMENT AS A CATALYST FOR HIGHER-PERFORMANCE BUILDING DESIGN

**H. Deheragoda[1], G.H.S.P. De Silva[2] and M. Jinthusan[3]**

## *ABSTRACT*

*Improving energy efficiency in building design is increasingly vital as the global construction sector confronts rising energy demands and environmental challenges. In Sri Lanka, the early design phase often lacks strategic integration of energy considerations, limiting the effectiveness of sustainable outcomes. This research investigates how project management (PM) strategies (strategies and tools), influence energy-efficient decision-making of design teams during the pre-construction stage of building projects. The authors adopted a mixed-methods approach, combining qualitative insights from seven semi-structured interviews with architects, engineers, and project managers, followed by quantitative data collected via a questionnaire administered to 42 professionals. The study explored the implementation and impact of PM approaches including Building Information Modelling (BIM), Integrated Project Delivery (IPD), Value Engineering (VE), and Early Contractor Involvement (ECI). Data were analysed using descriptive statistics and thematic coding to uncover trends and relationships. The findings revealed that BIM and VE are the most influential approaches in guiding sustainable design decisions, particularly when applied early in the project lifecycle. Success factors included early stakeholder collaboration, clearly defined energy goals, and performance-based planning. However, key barriers such as limited awareness, high upfront costs, and weak communication persist. The study recommends aligning PM practices with sustainability targets and enhancing stakeholder engagement to promote energy-efficient design in Sri Lankan construction projects.*

***Keywords:*** *Building Projects; Decision-making; Design Stage; Energy Efficiency; Project Management.*

## 1. INTRODUCTION

The successful completion of a construction project involves effective PM. Effective PM depends on proper process integration and personnel coordination throughout construction projects. However, to coordinate processes and stakeholders throughout the construction project, the PM team must make a significant effort to make the right

[1] Academic Instructor, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, hansi.de@sliit.lk
[2] Senior Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, priyanwada.d@sliit.lk
[3] Student, Liverpool John Moores University, UK , jinthusan1711@gmail.com

decisions at the right time, as decision-making has become increasingly important due to today's sustainability movements and global building practices (Bakht & El-Diraby, 2015). Given these sustainability concerns, modern building construction projects must focus on mitigating the significant environmental impacts they could create. With this rising global emphasis on sustainability, PM is found to be a key determinant of success, especially in energy efficiency initiatives with complex technical and environmental targets that require a robust management framework compared to conventional projects.

According to the growing body of knowledge, buildings account for nearly 40% of global energy consumption, which highlights the need to improve energy efficiency (Laustsen, 2008). In construction projects, energy efficiency focuses on reducing its consumption and carbon emissions in buildings, with building geometry, envelope elements, renewable energy integration, and regulations influencing performance (Shove, 2018). Despite the growing emphasis on energy efficiency in building projects, many projects continue to underperform due to the weak integration of PM approaches with design-stage decision-making processes. The poor practices of PM often fail to ensure early stakeholder collaboration, clear communication, and the timely incorporation of energy objectives, thereby limiting the adoption of effective passive and active design solutions within the project. In this regard, Project managers play a significant role in coordinating stakeholders and supporting energy-efficient design, using decision-making methods such as Value Engineering, BIM, and Building Energy Modelling (Lucas et al., 2025).

Among these solutions, one of the best moves would be to apply effective management approaches, such as IPD, lean construction, and agile project management, to support collaboration and decision-making, and to use technologies and techniques such as Multi-Criteria Decision Analysis (MCDA) (Ingrao et al., 2018). However, challenges remain in implementing energy-efficient construction projects, particularly in developing countries, due to limited resources, technological constraints, and organisational weaknesses (Yadollahi et al., 2014). This challenge is particularly significant in the Sri Lankan construction context. Despite the context, it is compounded by rising material costs (Carlander & Thollander, 2023), limited professional awareness (Palm & Bryngelson, 2023), and weak enforcement of sustainability regulations (Palm & Bryngelson, 2023), further constraining the implementation of energy-efficient measures.

Although previous studies have extensively explored building energy efficiency, sustainable construction practices, and stakeholder management, limited research has specifically examined how PM approaches influence design team decision-making toward energy efficiency during the building design phase, particularly in the Sri Lankan context. This lack of focused understanding, represents a significant empirical and contextual research gap. Therefore, this study aims to investigate how PM approaches influence the design team's energy efficiency decisions in building projects and the author, set the following objectives to bridge the research gap,

- Identify PM practices relevant to energy efficiency decisions in building design.
- Investigate the impact of PM practices on energy efficiency decisions taken by the design team.
- Explore effective PM practices that promote energy-efficient decisions in building construction projects.

# 2. LITERATURE REVIEW

Adopting energy-saving practices helps reduce environmental impacts, especially in developing economies (da Cunha & de Aguiar, 2020). Integrating passive designs and thermal optimisation strategies, through proper improvements in building orientation, materials, and integrated systems, can enhance the energy performance of a building (Abu Dabous & Hosny, 2025).

## 2.1 UNDERSTANDING THE CORE CONCEPTS

Successful completion of energy-efficient buildings requires integrating technical design strategies, adhering to proper PM practices, and collaborating with a multidisciplinary team throughout their lifecycles. These building designs also need to ensure occupant comfort, functional and operational performance, while minimising energy consumption and environmental impacts (Riabchuk et al., 2024). To meet these requirements, by reducing operational energy while contributing to sustainability and carbon reduction targets, designers frequently adopt a combination of active and passive strategies, such as natural ventilation, optimal building orientation, thermal insulation, high-performance HVAC systems, energy-efficient lighting, and renewable energy technologies (Iqbal et al., 2021).

***Energy Efficiency in Building Design:*** Energy efficiency in building construction aims to reduce power consumption and minimise environmental impact through advanced materials and techniques (Riabchuk et al., 2024). Sustainable approaches, including energy-efficient operations, integrated heat exchangers, and intensified processes, support global carbon reduction goals while enhancing occupant comfort.

***Key Energy Efficiency Strategies and Technologies:*** Building efficiency is achieved via passive design strategies, optimal orientation, insulation, and natural ventilation, combined with high-performance Heat Ventilation and Air Conditioning (HVAC) and lighting systems and renewable energy integration (Iqbal et al., 2021). These approaches improve building autonomy from fossil fuels and enhance overall operational performance.

PM in construction involves risk identification, prioritisation, and mitigation to manage complex schedules and multiple stakeholders. Traditional PM addresses linear project goals (Lalmi et al., 2025), while lean construction optimises value and reduces waste. Agile PM introduces flexibility to dynamic projects, minimising inefficiencies through performance-based planning (Frank et al., 2004).

The design process progresses from conceptual (vision and feasibility) to schematic (spatial layout), detailed (technical and system integration), and production (full documentation) stages (Svalestuen et al., 2015). Architects, Engineers, and Quantity Surveyors form core design teams, where architects lead design vision, engineers ensure technical feasibility, and quantity surveyors manage costs (Gunasekara et al., 2023). Effective collaboration and proactive leadership improve innovation and sustainable outcomes (Sagar et al., 2023). Effective PM practices strengthen collaboration, coordinate efforts among stakeholders, and incorporate sustainability considerations from inception through the completion of the building construction project (Meng, 2012). Energy-efficient building performance is also influenced by the PM practices used. Therefore, comprehending the role of PM in the building design process is timely to

identifying approaches that can enhance the successful delivery of high-performance buildings.

## 2.2 PM APPROACHES RELEVANT TO ENERGY EFFICIENCY DECISIONS

The successful delivery of high-performance buildings relies on effective PM practices that promote collaboration, knowledge sharing, and informed decision-making. Through a comprehensive Literature review of sustainable construction, high-performance buildings, and PM. Three criteria guided the selection:

- Frequency of application of PM practices in sustainable and energy-efficient building projects,
- Its contribution in improving stakeholder collaboration and project performance, and
- Potential influence on energy-efficiency decisions during the building design process.

Accordingly, IPD, BIM, VE, ECI, Design Charrettes, Risk Management, and Communication Planning were identified as the most relevant PM for investigation. Since these are actively contribute to meeting energy-efficiency objectives by enhancing interdisciplinary collaboration, facilitating the evaluation of design options, minimising project risks, and integrating sustainability considerations throughout the design process, they provide an appropriate foundation for examining how PM can act as a motivator for high-performance building design.

*Table 1: PM approaches relevant to energy efficiency decisions*

| PM Strategy | Description | Source |
|---|---|---|
| Integrated Project Delivery (IPD) | Encourages early involvement of all participants, promoting collaboration, sustainability, and energy-efficient outcomes | [1], [2], [3] |
| Building Information Modeling (BIM) | Integrates multidisciplinary data for energy-focused design decisions, reducing operational costs and environmental impacts | [4], [5], |
| Value Engineering (VE) | Balances cost, performance, and lifecycle considerations to enhance energy efficiency and resource utilization | [6], [7], [8] |
| Early Contractor Involvement (ECI) | Aligns design, cost, constructability, and sustainability, reducing redesign and energy waste | [9], [10], [11] |
| Design Charrettes | Collaborative workshops promote stakeholder alignment, resource optimization, and innovation in sustainable design | [12], [13], [14] |
| Risk Management | Risk Management: Identifies and mitigates environmental, technical, and project risks affecting energy efficiency | [15], [16], [17] |
| Communication Planning | Strengthens collaboration, reduces misunderstandings, and builds trust among stakeholders, critical for sustainable project delivery | [18], [19] |

Sources: [1] (Kahvandi et al., 2017), [2] (Jones, 2014), [3] (Yee, 2017), [4] (Azhar, Khalfan and Maqsood, 2012), [5] (Volk, Stengel and Schultmann, 2014), [6] (Ilayaraja and Zafar Eqyaabal, 2015), [7] (Chen et al., 2022), [8] (Rachwan, Abotaleb and Elgazouli, 2016), [9] (Walker and Lloyd-Walker, 2012), [10] (Wondimu et al., 2016), [11] (Wondimu, Klakegg and Lædre, 2020), [12] (Kilbane and Roös, 2022), [13] (Palmer, 2013), [14] (Bahadorestani,

Naderpajouh and Sadiq, 2020), [15] (Chapman, 2001), [16] (Goral, 2007), [17] (Shang et al., 2005), [18] (Khoury, 2019), [19] (Whyte, 1996)

# 3. RESEARCH METHODOLOGY

In light of comprehensive literature review, authors selected a mixed method approach to achieve the set objectives.

In the phase I, Author administered a questionnaire survey among industry professionals and 33 complete responses were taken for analysis. The quantitative data were analysed using descriptive statistical tools, such as weighted averages, percentage counts, and means, using a 5-point Likert scale to assess the significance of factors influencing energy-efficiency decisions. Under phase II, Qualitative insights were obtained from seven semi-structured interviews conducted with architects, engineers, and project managers, through purposive sampling based on, direct involvement in building design or PM activities, experience working on projects incorporating sustainability or energy-efficiency objectives, a minimum of three years of professional experience in the construction industry and willingness to share professional insights regarding PM and energy-efficiency decision-making. Data collected were then analysed thematically using a deductive approach to identify key patterns, barriers, and improvement strategies. Integrating survey and interview findings enabled the identification of key obstacles, expert-proposed solutions, and practical recommendations for aligning PM approaches with energy-efficient design, providing both empirical evidence and actionable insights for sustainable construction practice.

*Table 2: Likert scale.*

| Value | Range | Scale |
|---|---|---|
| 1 | 1.00-1.08 | Low |
| 2 | 1.81-2.60 | Very low |
| 3 | 2.61-3.40 | Moderate |
| 4 | 3.41-4.20 | High |
| 5 | 4.21-5.00 | Very high |

Assumption made.

- The distance between “very high" and "high” is the same between “high” and “moderate”.
- A consequence of the above would be that the distance between “high” and “very high” is five times greater than that between “low” and “very low”.

# 4. DATA ANALYSIS AND DISCUSSION

## 4.1 QUALITATIVE DATA ANALYSIS

### 4.1.1 Respondent Profile

The interview participants included Architects, Engineers, Project Managers, and Quantity Surveyors. Their professional experience ranged from three to thirty-five years. This diverse group of professionals provided valuable perspectives on PM practices,

design decision-making, and sustainability challenges within the construction industry. The following Table 3 summarises the Respondents demographic Information.

*Table 3: Demographics details*

| Interview | Job Role | Years of Experience |
|---|---|---|
| Respondent 01 (R1) | Chartered Architect | 7 years |
| Respondent 02 (R2) | Architect | 5 years |
| Respondent 03 (R3) | Civil Engineer | 35 years |
| Respondent 04 (R4) | Project Manager | 6 years |
| Respondent 05 (R5) | Site Engineer | 12 years |
| Respondent 06 (R6) | Assistant Quantity Surveyor | 4 years |
| Respondent 07 (R7) | Site Quantity Surveyor | 3 years |

### 4.1.2 Qualitative Findings

***Key PM Approaches Influencing Energy Efficiency:*** Qualitative findings highlighted the importance of early collaboration and integrated planning for achieving energy-efficient building outcomes. Participants ($R_3$, $R_4$, $R_5$, $R_6$ and $R_7$) emphasised that approaches such as IPD, BIM, VE, and ECI ($R_1$ and $R_2$) play an important role in supporting energy-efficient design decisions. Early stakeholder involvement enables project teams to establish sustainability objectives and integrate energy-saving measures during the design stage. Respondents explained that collaborative project environments encourage knowledge sharing and allow different professionals to contribute their expertise to design solutions. This collaborative approach helps ensure that sustainability considerations are incorporated into project planning and decision-making processes from the beginning of the project lifecycle.

***Impact of PM Approaches on Design Phase Decisions:*** The participants ($R_1$, $R_2$, $R_4$, $R_7$) emphasised that PM approaches significantly influence energy-efficiency decisions during the design phase. The respondents also highlighted that early stakeholder involvement enables project teams to conduct energy performance analyses, evaluate design alternatives, and incorporate sustainability objectives into design solutions. Also, they noted that collaboration among design team professionals enables teams to balance energy performance with cost, constructability, and project constraints. Meanwhile, $R_3$, $R_5$, and $R_6$ highlighted the importance of balancing constructability, cost, and performance through effective team coordination, informed trade-offs, accurate cost estimation, and ongoing feedback from quantity surveyors. This integrated decision-making process helps ensure that sustainable solutions are both technically feasible and financially viable.

The respondent's opinion on the impact of PM approaches suggests that early stakeholder engagement and integrated decision-making are crucial to achieving energy performance goals in building projects. The reason behind their opinion may be that early engagement allows the design team to incorporate sustainability into core design at no cost during the design stage, resulting in savings of millions in the building's operational stage.

***Role of Specific PM Approaches in Energy-Efficient Design:***

*IPD:* All the participants except $R_6$ emphasised that IPD promotes early collaboration among project stakeholders. Through integrated planning, teams can establish shared sustainability objectives and ensure that energy-efficiency considerations are incorporated into design decisions from the beginning of the project.

*BIM:* BIM was widely recognised as a critical tool for supporting energy-efficient design decisions. Participants ($R_1$, $R_3$, $R_5$) highlighted that BIM allows project teams to simulate building performance, test different design alternatives, and analyse energy consumption before construction begins. This enables more informed decision-making and improves coordination among project stakeholders.

*VE:* All the Respondents confirmed VE as an effective strategy for balancing cost control with sustainability objectives. By evaluating alternative materials, systems, and construction methods, VE allows project teams to identify solutions that maintain or improve energy performance while remaining cost-effective.

*ECI:* Participants expressed varying perspectives regarding ECI. While some respondents ($R_3$, $R_4$) believed that early contractor involvement may influence design decisions toward construction practicality, others ($R_5$, $R_6$, $R_7$) emphasised that contractor expertise can improve constructability and help identify practical energy-saving opportunities.

*Sustainability Charrettes:* Respondents ($R_2$, $R_3$, $R_4$) described Sustainability Charrettes as collaborative workshops that encourage interdisciplinary discussion and innovation. These sessions bring together professionals from different disciplines to explore sustainable design solutions and incorporate energy-efficiency considerations during early project planning. $R_7$ pointed out that charrettes encourage idea sharing and may bring about better sustainability results.

***Adoption of Energy-Efficient Building Solutions:*** The findings revealed that PM approaches such as IPD, ECI, and BIM facilitate the adoption of energy-efficient building features. These approaches enable early collaboration and allow project teams to incorporate sustainable solutions such as improved building envelopes and daylight optimisation during the design stage. Respondents $R_3$, $R_4$, and R5 highlighted how IPD and ECI help prevent scheduling and budget issues by involving contractors early.

However, participants noted that traditional procurement methods, such as design–bid–build, often delay sustainability integration because contractors are involved only after the design stage is complete. It creates a knowledge gap, as the design is frozen when the contractor proposes a more efficient solution at the construction stage, and it may cost a considerable amount and delay progress in incorporating these solutions into the design. Therefore, opportunities to incorporate energy-efficient solutions may be missed. However, methods such as ECI and IPD can analyse real-time constructability, as contractors can confirm resource availability and labour costs, thereby avoiding cost overruns, as respondents mentioned. Also, the IPD creates a win-win solution by establishing a shared risk-and-reward concept. This may motivate stakeholders, as everyone's profit depends on the building's performance.

***Early Planning and Goal Setting for Energy Efficiency:*** All respondents except $R_5$ emphasised the importance of establishing energy-efficiency targets early in project development. Clear sustainability objectives guide design decisions, influence material selection, and encourage environmentally responsible practices. R3 affirmed that early

planning also helps project teams control costs and avoid expensive modifications later in the project lifecycle.

***Role of Communication and Collaboration:*** Effective communication and collaboration among project stakeholders were identified as essential factors for achieving energy-efficient project outcomes by all the respondents. They all emphasised that project managers play a critical role in coordinating stakeholder activities and ensuring that sustainability objectives remain a priority throughout the project lifecycle. Strong leadership and open communication help maintain alignment between design objectives, budget constraints, and environmental performance goals.

***Technological Tools Supporting Energy Efficiency:*** Participants highlighted the importance of digital tools for managing energy efficiency in building projects. BIM is integrated with energy simulation software such as Autodesk Insight, Green Building Studio, Energy Plus, DesignBuilder, and IES, enabling project teams to analyse building performance and evaluate design alternatives. These tools also support compliance with sustainability standards and allow quantity surveyors to integrate cost considerations with energy performance analysis.

***Challenges in Implementing Energy-Efficient Design:*** Despite the benefits of PM approaches, participants identified several barriers to implementing energy-efficient design practices. Key challenges include budget limitations, limited stakeholder awareness, and resistance to change (R1, R2, R4, R5 and R7). Many respondents noted that clients often focus on initial construction costs rather than long-term operational benefits. To address these challenges, experts recommended early stakeholder education, lifecycle cost analysis, and clear energy-efficiency targets during project planning.

***Integration of Energy Efficiency in Project Management:*** All participants emphasised that energy efficiency should be integrated into the core practices of PM and treated with the same level of importance as traditional project objectives such as time, cost, and quality. Regular monitoring of energy performance, sustainability cost analysis, and collaborative decision-making were identified as key practices for achieving energy-efficient project outcomes.

## 4.2 QUANTITATIVE DATA ANALYSIS

### 4.2.1 Respondent Demographics

The questionnaire survey received 42 responses from Sri Lankan construction professionals, representing an 84% response rate. Respondents were predominantly Quantity Surveyors (38.1%), followed by Project Managers (19%), Engineers (19%), and Architects (14.3%), with smaller representation from Sustainability Consultants, Technical Managers, and Electrical Engineers. Most participants had less than five years of experience in the construction industry (52.4%) and in pre-contract stage involvement (71.4%), although some mid- and senior-level professionals were also included. Notably, 69% of respondents participated in projects focused on energy-efficiency goals, suggesting strong familiarity with sustainable design practices. Most current projects were residential (34.8%) and commercial (33.3%), with smaller numbers in mixed development, apartments, infrastructure, and government buildings.

### 4.2.2 Quantitative Findings

***Experience and Implementation of PM Approaches***

Table 3 presents the level of implementation of PM strategies for supporting energy-efficient design decisions.

*Table 3: Project management approaches supporting energy-efficient design*

| PM Strategy | Mean Score | Rank | Interpretation |
|---|---|---|---|
| Value Engineering (VE) | 3.52 | 1 | High |
| Building Information Modelling (BIM) | 3.50 | 2 | High |
| Sustainability Charrettes | 3.50 | 2 | High |
| Integrated Project Delivery (IPD) | 3.10 | 4 | Moderate |
| Early Contractor Involvement (ECI) | 2.98 | 5 | Moderate |

Analysis of PM approaches usage showed that VE (3.52), Building BIM (3.50), and Sustainability Charrettes (3.50) were the most highly applied approaches for supporting energy-efficient design decisions. IPD and ECI are being moderately used. These results suggest that professionals in Sri Lanka are actively adopting collaborative and technology-enabled PM approaches, with VE, BIM, and Sustainability Charrettes being the most practical tools for enhancing sustainability outcomes during design.

***Impact of PM Approaches on Energy-Efficient Decisions***

*Table 1: Influence of PM strategies on energy-efficiency decisions*

| PM Strategy | Mean Score | Rank | Interpretation |
|---|---|---|---|
| Value Engineering (VE) | 3.57 | 1 | High |
| Building Information Modelling (BIM) | 3.52 | 2 | High |
| Sustainability Charrettes | 3.31 | 3 | Moderate |
| Integrated Project Delivery (IPD) | 3.29 | 4 | Moderate |
| Early Contractor Involvement (ECI) | 3.02 | 5 | Moderate |

The study found that VE and BIM (3.52) had the high influence on design teams' energy-efficiency decisions, while Sustainability Charrettes, IPD and ECI had the moderate influence.

***Critical Project Stages for Energy-Efficiency Decisions***

The below Table 5 summarises the level of criticality of project stages for energy efficiency decisions.

*Table 2: Critical project stages for energy-efficiency decisions*

| Project Stage | Mean Score | Rank | Interpretation |
|---|---|---|---|
| Conceptual Design | 3.45 | 1 | High |
| Detailed Design | 3.43 | 2 | High |
| Construction | 3.36 | 3 | Moderate |
| Post-Construction | 3.31 | 4 | Moderate |
| Schematic Design | 3.26 | 5 | Moderate |

The findings demonstrate that energy-efficiency decisions are most strongly influenced during the conceptual and detailed design stages. Interviewees consistently emphasized the importance of establishing energy targets early to avoid costly redesign and missed opportunities later in the project lifecycle. It emphasises the importance of early-stage decisions.

***Practices Encouraging Energy Efficiency***

*Table 3: Approaches encouraging energy-efficient design*

| Approaches | Mean Score | Rank | Interpretation |
|---|---|---|---|
| Sustainability Champion | 3.74 | 1 | High |
| Incentives for Sustainable Design | 3.69 | 2 | High |
| BIM for Energy Analysis | 3.62 | 3 | High |
| Energy Performance Reviews | 3.60 | 4 | High |
| Energy Goals in Project Brief | 3.55 | 5 | High |
| Training and Capacity Building | 3.48 | 6 | High |
| Early Energy Consultant Involvement | 3.45 | 7 | High |

The appointment of sustainability champions and the use of incentives emerged as the most effective approaches for encouraging energy-efficient decision-making. Interviewees also stressed the importance of clear project objectives, stakeholder engagement, and leadership commitment.

***Early Collaboration and Multidisciplinary Engagement:*** Early collaboration between project managers and design teams was universally recognised as critical for achieving energy-efficiency outcomes. Most respondents rated early collaboration as very important or highly important, reinforcing the need for multidisciplinary engagement. Including energy consultants and quantity surveyors from the outset ensures that energy-efficiency objectives are clearly communicated, properly integrated, and effectively implemented throughout the project lifecycle.

***Barriers to Energy Efficiency:*** Several key barriers were identified that limit the effectiveness of PM approaches in promoting energy-efficient design. These included delayed integration of energy objectives, low stakeholder awareness, resistance to sustainability adoption, high upfront costs, limited technical expertise, poor interdisciplinary coordination, compressed project schedules, regulatory complexity, and uncertainty regarding emerging technologies. These barriers highlight that achieving energy efficiency in the Sri Lankan construction context requires early planning, education, financial justification, and clear policies.

***Additional PM Practices Recommended:*** Respondents suggested additional approaches to strengthen energy efficiency, emphasising early stakeholder involvement, integrated design planning, and establishing clear energy goals at project inception. They recommended the use of Lifecycle Cost Analysis, BIM-enabled energy simulations, and thermal performance assessments, alongside sustainability audits, workshops, collaborative contracts, and adherence to green building standards. Innovative approaches, including AI and machine learning, were also noted as potential enablers. Collectively, these practices indicate that energy efficiency should be treated as a measurable, collaborative, and integrated objective throughout the project lifecycle.

# 5. DISCUSSION

The findings demonstrate that PM strategies play a significant role in facilitating energy-efficient design decisions in Sri Lankan building projects. BIM and VE emerged as the most influential strategies due to their ability to support performance analysis, informed decision-making, and cost optimisations. Similarly, studies of Bangladesh and Sri Lankan SMEs highlighted that BIM assists in the proper communication of project decisions related to design, visualisation, collaboration, and simulation across many applications (Datta et al., 2023; Lukson et al., 2024). Moreover, researchers have identified the importance of employing VE during the design stage to optimise project costs (Nejatyan et al., 2023).

Additionally, interview participants highlighted the value of integrated collaboration through IPD and Sustainability Charrettes, particularly during the early design stages. At the same time, researchers recognise IPD as a unique and creative approach to project management for the Sri Lankan construction landscape (Lukson et al., 2024). The study further confirms that energy-efficiency outcomes are heavily dependent on early planning and stakeholder engagement. Both quantitative and qualitative findings indicate that the conceptual and detailed design stages offer the greatest opportunity to influence building performance. This finding aligns with previous studies that argue that early design decisions determine the majority of lifecycle energy performance.Despite the recognised benefits of energy-efficient design, several implementation barriers remain. High initial costs, limited awareness, and weak collaboration continue to restrict the adoption of sustainable solutions within the Sri Lankan construction sector. Project managers should adopt more proactive approaches, including early stakeholder involvement, sustainability champions, performance monitoring, and BIM-enabled energy analysis. Altogether, the results demonstrate that successful integration of energy efficiency requires a collaborative project environment, clear sustainability objectives, and the strategic application of PM practices throughout the design process.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1 CONCLUSIONS

PM approaches strongly influence energy-efficiency decisions during the design phase of building projects. The findings show that structured approaches such as IPD, BIM, VE, and ECI help integrate sustainability into design by improving stakeholder coordination and ensuring that energy, cost, and constructability objectives are considered together. Early stakeholder involvement among architects, engineers, project managers, quantity surveyors, and sustainability consultants is essential for embedding energy goals from the planning stage and developing innovative design solutions. Digital technologies, particularly BIM integrated with tools such as Autodesk Insight, Energy Plus, and Design Builder, support evidence-based decision-making through energy simulations, performance evaluation, and design optimisation. In addition, VE and ECI improve the selection of cost-effective, feasible, and constructible energy-efficient solutions while minimising design changes.

Despite these benefits, several barriers limit implementation, including budget constraints, limited stakeholder awareness, resistance to change, and unclear energy-efficiency targets. Clients focus on high initial costs rather than long-term operational and

environmental benefits, which further reduces the adoption of sustainable practices. Therefore, the study emphasises the need for early collaborative PM frameworks, BIM-based simulations, regular VE reviews, stronger contractor involvement, stakeholder training, and supportive environments.

These findings provide practical insights for project managers, architects, engineers, clients, and policymakers seeking to improve sustainability outcomes through more collaborative and structured project delivery approaches.

### 6.2 RECOMMENDATIONS

At the industry level, there is an alarming need for government policies, incentives, and regulatory frameworks to encourage and mandate energy-efficient design practices. It is the industry's responsibility to educate every Professional on various topics through training and awareness programmes on energy-efficient design principles and sustainable construction practices, while Construction organisations adopt integrated, collaborative PM approaches that foster early engagement of every responsible stakeholder throughout the design process. At the project level, energy-efficiency objectives should be clearly defined during project initiation and incorporated into project briefs, design reviews, and decision-making processes.

### 6.3 LIMITATIONS AND FURTHER RESEARCH

Although the study included professionals from several disciplines, only one interview participant held the role of Project Manager, and project managers represented 19% of the questionnaire respondents. Furthermore, a considerable proportion of survey respondents possessed fewer than five years of industry experience. Consequently, the findings should be interpreted as reflecting the collective perspectives of multidisciplinary project stakeholders rather than exclusively those of highly experienced project managers. Nevertheless, the inclusion of architects, engineers, quantity surveyors, and other professionals is justified because energy-efficiency decisions are inherently collaborative and require contributions from multiple stakeholders throughout the design process. The study is limited by its focus on project managers within formal construction organisations, excluding the perspectives of other stakeholders, smaller firms, and the informal sector, which may affect the generalizability of the findings. Additionally, reliance on self-reported data may introduce reporting bias; however, the study still provides valuable insights into how PM supports energy-efficiency decisions in building projects. Table 1 below presents the Likert scale used in data collection and analysis.

Future research could expand the sample of senior project managers and experienced practitioners to further validate and extend the findings. Further studies may also investigate the role of emerging technologies, such as artificial intelligence, advanced energy modelling tools, and digital PM platforms, in supporting energy-efficiency decision-making throughout the building lifecycle.

## 7. ACKNOWLEDGEMENTS

The authors extend sincere appreciation to the Sri Lanka Institute of Information Technology (SLIIT) and the Liverpool John Moores University, UK (LJMU) for their continuous support and for providing the institutional resources required to successfully conduct this research.

# 8. REFERENCES

Abu Dabous, S. and Hosny, F. (2025) 'A review of building envelope retrofitting methods for improving energy efficiency, aesthetic, and indoor environmental quality', *Energy Nexus, 18,* 100407. https://doi.org/10.1016/j.nexus.2025.100407.

Aga, D.A., Noorderhaven, N. and Vallejo, B. (2016) 'Transformational leadership and project success: The mediating role of team-building', *International Journal of Project Management,* 34(5), pp. 806–818. https://doi.org/10.1016/j.ijproman.2016.02.012.

Bahadorestani, A., Naderpajouh, N. and Sadiq, R. (2020) 'Planning for sustainable 55 stakeholder engagement based on the assessment of conflicting interests in projects', *Journal of Cleaner Production,* 242, 118402. https://doi.org/10.1016/j.jclepro.2019.118402.

Bakht, M. N., & El-Diraby, T. E. (2015). Synthesis of decision-making research in construction. *Journal of Construction Engineering and Management, 141(9*), 04015027. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001016

Carlander, J., & Thollander, P. (2023). Barriers to implementation of energy-efficient technologies in building construction projects — Results from a Swedish case study. *Resources, Environment and Sustainability, 11,* 100097. https://doi.org/10.1016/j.resenv.2022.100097

Chapman, R.J. (2001) 'The controlling influences on effective risk identification and assessment for construction design management', *International Journal of Project Management,* 19(3), pp. 147–160. https://doi.org/10.1016/S0263-7863(99)00070-8.

Chen, W.T., Merrett, H. C., Liu, S., Fauzia & N, Liem, F. D, (2022) 'A Decade of Value Engineering in Construction Projects', *Advances in Civil Engineering, 2022,* 2324277. https://doi.org/10.1155/2022/2324277.

da Cunha, S.R.L. and de Aguiar, J.L.B. (2020) 'Phase change materials and energy efficiency of buildings: A review of knowledge', *Journal of Energy Storage, 27,* 101083. https://doi.org/10.1016/j.est.2019.101083.

Datta, S. D., Sobuz, M. H. R., Mim, N. J., & Nath, A. D. (2023). Investigation on the effectiveness of using building information modeling (BIM) tools in project management: a case study. *Revista de La Construccion, 22*(2), 306–320. https://doi.org/10.7764/RDLC.22.2.306

Demirkesen, S., & Ozorhon, B. (2017). Impact of integration management on construction project management performance. *International Journal of Project Management*, 35(8), 1639–1654. https://doi.org/10.1016/j.ijproman.2017.02.004

Gunasekara, D., Indikatiya, I., Perera, B., & Senaratne, S., (2023) 'Managing intragroup conflicts within project design teams during pre-contract stage that effect the project deliverables in Sri Lanka', *Construction Innovation*, 23(2), pp. 406–424. https://doi.org/10.1108/CI 05-2020-0078.

Hettiarachchi, I., Rotimi, J. O. B., Shahzad, W. M., & Kahandawa, R. (2025). Bridging sustainability and performance: Conceptualizing net-zero integration in construction supply chain evaluations. *Sustainability*, 17(13), 5814. https://doi.org/10.3390/su17135814

Ingrao, C., Messineo, A., Beltramo, R., Yigitcanlar, T., & Ioppolo, G. (2018). How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. *Journal of Cleaner Production*, 201, 556–569. https://doi.org/10.1016/j.jclepro.2018.08.080

Ilayaraja, K. and Zafar Eqyaabal, M. (2015) 'Value Engineering in Construction', *Indian Journal of Science and Technology,* 8(32), pp. 3–10. https://doi.org/10.17485/ijst/2015/v8i32/87285.

Iqbal, M., Ma, J., Ahmad, N., Hussain, K., & Usmani, M.S., (2021) 'Promoting sustainable construction through energy-efficient technologies: an analysis of promotional strategies using interpretive structural modeling', *International Journal of Environmental Science and Technology*, 18(11), pp. 3479–3502. https://doi.org/10.1007/s13762-020-03082-4.

Jones, B. (2014) 'Integrated project delivery (IPD) for maximizing design and construction considerations regarding sustainability', *Procedia Engineering,* 95(Scescm), pp. 528–538. https://doi.org/10.1016/j.proeng.2014.12.214.

Azhar, S., Khalfan, M. and Maqsood, T. (2012) 'Building information modeling (BIM): Now and beyond', *Australasian Journal of Construction Economics and Building*, 12(4), pp. 15–28. https://doi.org/10.5130/ajceb.v12i4.3032.

Kahvandi, Z., Saghatforoush, E., Alinezhad, M., & Noghli, F., (2017) 'Integrated Project Delivery (IPD) Research Trends.', *Journal of Engineering, Project, and Production Management,* 7(2), pp. 99–114. https://doi.org/10.32738/jeppm.201707.0006.

Khoury, K.B. (2019) 'Effective communication processes for building design, construction, and management. *Buildings, 9(5), 112*. https://doi.org/10.3390/buildings9050112.

Kilbane, S. and Roös, P.B. (2022) Charrette! An urgent response toward resilient and sustainable cities and landscapes, *Resilient and Sustainable Cities: Research, Policy and Practice*. Elsevier Inc. https://doi.org/10.1016/B978-0-323-91718 6.00015-3.

Laustsen, J. (2008). Energy efficiency requirements in building codes: Energy efficiency policies for new buildings. International Energy Agency (IEA)

Lalmi, A., Boumali, B., Fernandes, B., & Boudemagh, S.S., (2025) 'Identifying the most used traditional PM practices in construction industry', *Procedia Computer Science*, 256, pp. 1756–1763. https://doi.org/10.1016/j.procs.2025.02.315.

Lucas, S., Koukou, M. K., Aleksiejuk-Gawron, J., Justino, J., Rafael, S., Livieratos, A. D., Tourou, P. (2025). Training for sustainable and healthy building for 2050 Part 2: Incorporation of new knowledge and dissemination for the sustainability of the trans-European training experience. *Buildings*, 15(9), 1512. https://doi.org/10.3390/buildings15091512

Lucas, H., Berdahl, S., Chernyakhovskiy, I., Gokhale-Welch, C., Cox, S., & Hecht, A. (2024). *Strategies and good practices to support robust stakeholder engagement in multi-sector energy transition planning*. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy24osti/88389.pdf

Lukson, E. E., Ranadewa, K. A. T. O., Parameswaran, A., Wijerathna, M. R. D. P., & Kodituwakku, D. (2024). Integrated Project Delivery Implementation Among Construction SMEs in Sri Lanka: Barriers and Strategies. *World Construction Symposium*, 619–633. https://doi.org/10.31705/WCS.2024.49

Meng, X. (2012) 'The effect of relationship management on project performance in construction', *International Journal of Project Management*, 30(2), pp. 188–198. https://doi.org/10.1016/j.ijproman.2011.04.002.

Nejatyan, E., Sarvari, H., Hosseini, S. A., & Javanshir, H. (2023). Determining the Factors Influencing Construction Project Management Performance Improvement through Earned Value-Based Value Engineering Strategy: A Delphi-Based Survey. *Buildings*, *13*(8), *1964*. https://doi.org/10.3390/buildings13081964

Palm, J., & Bryngelson, E. (2023). Energy efficiency at building sites: barriers and drivers. *Energy Efficiency*, *16*(2), 18. https://doi.org/10.1007/s12053-023-10088-7

Riabchuk, V., Hagel, L., Germaine, F., & Zharova, A., (2024) 'Utility-based context-aware multi-agent recommendation system for energy efficiency in residential buildings', *Information Fusion*, *112*, 102559. https://doi.org/10.1016/j.inffus.2024.102559.

Shove, E. (2018). What is wrong with energy efficiency? *Building Research & Information*, 46(7), 779–789. https://doi.org/10.1080/09613218.2017.1361746

Svalestuen, F., Frøystad, K., Drevland, F., Ahmad, S., Lohne, J., & Lædre, O., (2015) 'Key Elements to an Effective Building Design Team', *Procedia Computer Science*, *64*, 247–254. https://doi.org/10.1016/j.procs.2015.08.636.

Volk, R., Stengel, J. and Schultmann, F. (2014) 'Building Information Modeling (BIM) for existing buildings - Literature review and future needs', *Automation in Construction*, 38, pp. 109–127. https://doi.org/10.1016/j.autcon.2013.10.023.

Walker, D.H.T. and Lloyd-Walker, B. (2012) 'Understanding early contractor involvement (ECI) procurement forms', Association of Researchers in Construction Management, *ARCOM 2012 – Proceedings of the 28th Annual Conference*, 2, 877–887.

Wondimu, P.A., Hailemichael, E., Hosseini, A., Lohne, J., Torp, O., Lædre, O., (2016) 'Success Factors for Early Contractor Involvement (ECI) in Public Infrastructure Projects', *Energy Procedia*, *96*, 845–854. https://doi.org/10.1016/j.egypro.2016.09.146.

Yadollahi, M., Mirghasemi, M., Zin, R.M., & Singh, B., (2014) 'Architect critical challenges as a project manager in construction projects: A case study', *Advances in Civil Engineering*, *2014*, 205310. https://doi.org/10.1155/2014/205310.

Vu, M.L. and Nguyen, T.Q., 2026. BIM consultancy cost formation in design-stage public projects: Evidence from Vietnam. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 334-348. DOI: https://doi.org/10.31705/WCS.2026.25. Available from: https://ciobwcs.com/papers/

# BIM CONSULTANCY COST FORMATION IN DESIGN-STAGE PUBLIC PROJECTS: EVIDENCE FROM VIETNAM

**Manh Luan Vu[1] and Quan T. Nguyen[2]**

## *ABSTRACT*

*This study examines the structure and estimation of Building Information Modelling (BIM) consultancy cost estimates in public construction projects. While BIM adoption is expanding rapidly, limited empirical evidence exists on how BIM-related costs are structured in practice, particularly in consultancy-driven project environments. Using a multiple case study approach, the research analyses BIM consultancy cost estimation reports from four public construction projects in Vietnam, focusing on design-stage implementation. The study investigates the composition of BIM consultancy costs, the allocation of BIM personnel roles, and the factors influencing cost estimation practices. The findings indicate that BIM cost estimates are primarily driven by labour inputs associated with BIM managers, coordinators, and modellers, while software licences and technical resources constitute a relatively small share of the overall consultancy budget. The results further show that project complexity, implementation stage, procurement arrangements, information requirements and scope specification significantly influence BIM cost estimation. By providing empirical evidence derived from approved cost estimation documents used in project planning, this study contributes to a clearer understanding of BIM cost estimation structures as governance-dependent processes and offers practical insights for project owners planning BIM implementation in consultancy-driven construction environments.*

***Keywords:*** *BIM; BIM implementation cost estimation; BIM team structure; Construction cost estimation; Public construction projects.*

## 1. INTRODUCTION

BIM has become a central component of digital transformation in the global Architecture, Engineering and Construction (AEC) industry. Rather than a standalone software tool, BIM functions as an integrated information management process supporting collaboration across the lifecycle of built assets (Borrmann et al., 2018; Sacks et al., 2018). Numerous studies indicate that BIM can improve interdisciplinary coordination, reduce design conflicts and enhance project transparency, thereby contributing to improved project performance and lifecycle value (Azhar, 2011; Bryde et al., 2013; Lu et al., 2014). Consequently, many governments have introduced policies encouraging or mandating BIM adoption in public construction projects as part of broader digitalisation strategies for the built environment. Alongside these global developments, emerging

[1] PhD Candidate, Faculty of Urban Management, Hanoi Architectural University, Vietnam, E-mail: luanvm@hau.edu.vn
[2] Associate Professor, PhD, Faculty of Construction Economics and Management, Hanoi University of Civil Engineering, Vietnam, E-mail: quannt@huce.edu.vn

construction markets have also promoted BIM adoption in public construction projects. However, BIM implementation remains uneven, particularly due to uncertainties regarding the estimation of costs associated with BIM implementation during project planning stages (European Commission, 2021; Gharaibeh et al., 2024).

In Vietnam, BIM adoption has been supported by an evolving regulatory framework. The government approved a national BIM roadmap and subsequently established mandatory BIM application requirements for specified categories of construction projects (Government of Vietnam, 2024). In parallel, construction investment cost management is regulated by Decree No. 10/2021/ND-CP, which defines the structure of project cost estimates and the role of consultancy services in determining construction investment costs (Government of Vietnam, 2021). Within this framework, BIM implementation in many projects is typically delivered through consultancy services and incorporated into project cost estimates (Ministry of Construction, 2021). More recently, Circular No. 09/2024/TT-BXD provides explicit guidance on estimating BIM-related costs within consultancy services, including regulatory limits for BIM expenditures across project stages (Ministry of Construction, 2024).

In this context, BIM-related expenditures are primarily defined at the planning stage through cost estimation documents rather than reflecting actual project expenditures. Despite the recognised benefits of BIM, the financial implications and cost estimation practices associated with BIM implementation remain insufficiently understood because existing research has largely focused on the economic benefits of BIM adoption rather than the structure of BIM implementation costs (Bryde et al., 2013; Mitchell et al., 2023).

Comparatively fewer studies have examined how BIM implementation costs are structured and estimated during project planning. This gap is particularly relevant in consultancy-driven BIM implementation environments. In many emerging construction markets, including Vietnam, BIM services are frequently procured as specialised consultancy packages within public construction projects (Nguyen et al., 2021; Pham et al., 2024). In such contexts, BIM implementation costs are largely composed of labour inputs associated with BIM specialists, including BIM managers, BIM coordinators and BIM modellers, together with supporting costs such as software licences and computing infrastructure (Hardin & McCool, 2015; Kumar, 2015). As a result, BIM cost estimation is strongly influenced by assumptions regarding team composition, labour allocation and the scope of BIM activities across project phases.

Despite the growing integration of BIM within regulatory frameworks, empirical evidence on how BIM consultancy costs are structured in real construction projects remains limited. Existing studies rarely explain how BIM cost estimation is shaped by project-specific information requirements, procurement strategies, and institutional cost estimation frameworks. As a result, there is limited understanding of the mechanisms through which BIM consultancy cost structures are formed and formalised in practice.

To address this gap, this study investigates the structure and estimation of BIM implementation costs in public construction projects through multiple case studies in Vietnam. The research analyses BIM consultancy cost estimation documents and procurement records to identify key cost components and examine BIM personnel allocation within consultancy-based BIM services. Through cross-case comparison, the study explains how BIM consultancy cost estimates are formed under different implementation conditions, including Exchange Information Requirement (EIR)-driven

information management, integrated design–BIM processes and Terms Of Reference (TOR)-based estimation approaches.

# 2. LITERATURE REVIEW

BIM has significantly transformed how construction projects are designed, coordinated and managed by enabling integrated information management across the lifecycle of built assets (Borrmann et al., 2018; Sacks et al., 2018). Through digital models integrating geometric and non-geometric information, BIM facilitates structured data exchange, interdisciplinary coordination, and improved decision-making (Ngo et al., 2020). In developing construction markets such as Vietnam, BIM has been increasingly promoted as a mechanism for improving productivity, coordination and information transparency in construction projects (Pham et al., 2024).

Despite these recognised benefits, existing research has focused primarily on performance improvements, such as reduced design conflicts and enhanced coordination, while comparatively limited attention has been given to the structure and estimation of BIM implementation costs (Bryde et al., 2013; Lu et al., 2014). This gap creates uncertainty for project owners when planning BIM adoption in real construction projects.

## 2.1 BIM IMPLEMENTATION COSTS

BIM implementation costs refer to the investments required to establish and operate digital modelling and information management processes throughout the lifecycle of a construction project (Sacks et al., 2018). These costs arise not only from technological investments but also from organisational changes associated with BIM-based workflows, including adjustments to coordination processes, data management practices and professional competencies (Borrmann et al., 2018; Hardin & McCool, 2015).

Existing studies identify key cost components, including labour inputs, software licensing, hardware infrastructure, staff training and digital information management systems such as Common Data Environment (CDE) (Borrmann et al., 2018; Hardin & McCool, 2015; Sacks et al., 2018). Labour costs are often reported as the dominant component, although empirical quantification remains limited (Lu et al., 2014).

In the Vietnamese context, BIM-related expenditures typically include modelling activities, software and hardware investments, training programmes and digital information systems (Nguyen, 2024; Pham et al., 2024). Empirical evidence suggests that BIM adoption may require additional upfront investment, despite potential improvements in cost estimation and quantity take-off (Mai et al., 2025). However, practical guidance on how BIM costs should be incorporated into project cost estimates remains limited.

Existing studies tend to conceptualise BIM implementation costs primarily as technical or resource-based expenditures, with limited attention to how these costs are shaped by project-specific information requirements, procurement strategies, and institutional cost estimation frameworks.

## 2.2 BIM CONSULTANCY SERVICES

In many construction markets, BIM implementation is delivered through specialised consultancy services rather than internal capabilities. BIM consultants provide expertise

in modelling, coordination and information management, enabling project stakeholders to adopt BIM workflows (Hardin & McCool, 2015; Kumar, 2015).

Typical consultancy services include BIM modelling, interdisciplinary coordination and digital information management processes (Borrmann et al., 2018; Sacks et al., 2018). These services increasingly extend to advisory functions such as establishing modelling standards, managing data exchange protocols and operating CDEs (European Commission, 2021).

In emerging BIM markets such as Vietnam, consultancy firms play a central role in BIM implementation and industry diffusion (Nguyen et al., 2021).

## 2.3 BIM RESOURCE STRUCTURES

BIM implementation relies on specialised team structures involving BIM managers, BIM coordinators and BIM modellers (Barnes & Davies, 2014; Sacks et al., 2018). These roles correspond to strategic management, interdisciplinary coordination and technical modelling functions within BIM workflows (Hardin & McCool, 2015)

Labour inputs associated with these roles vary across project stages, with modelling concentrated in design phases and coordination extending throughout the project lifecycle (Lu et al., 2014). In Vietnam, BIM adoption also requires organisational adjustments and the development of digital competencies within project teams (Dao & Nguyen, 2021).

Despite this, limited research has examined how BIM personnel allocation translates into cost structures within consultancy contracts, particularly in terms of quantifying the contribution of labour and other cost components. As a result, project owners often face difficulties in estimating BIM costs based on team composition and project requirements. Furthermore, existing studies provide limited empirical evidence on how variations in information requirements, levels of integration with design processes, and institutional estimation norms influence BIM personnel allocation and resulting cost structures.

This study addresses this gap by using approved cost estimation documents to quantify how BIM consultancy costs are proportionally structured in practice. Through cross-case analysis, the study examines how BIM cost estimation is shaped by different implementation approaches, including EIR-driven information requirements, integration with design consultancy processes, and reliance on TOR-defined scope and standardised estimation norms.

Based on the reviewed literature, BIM implementation costs in consultancy-driven environments can be interpreted as a structured consultancy service pricing mechanism shaped not only by resource requirements but also by information governance processes and institutional cost estimation frameworks. As shown in Figure 1, BIM consultancy cost structures consist of direct resource costs (labour and technical resources) and indirect consultancy components (management costs, profit and taxes).

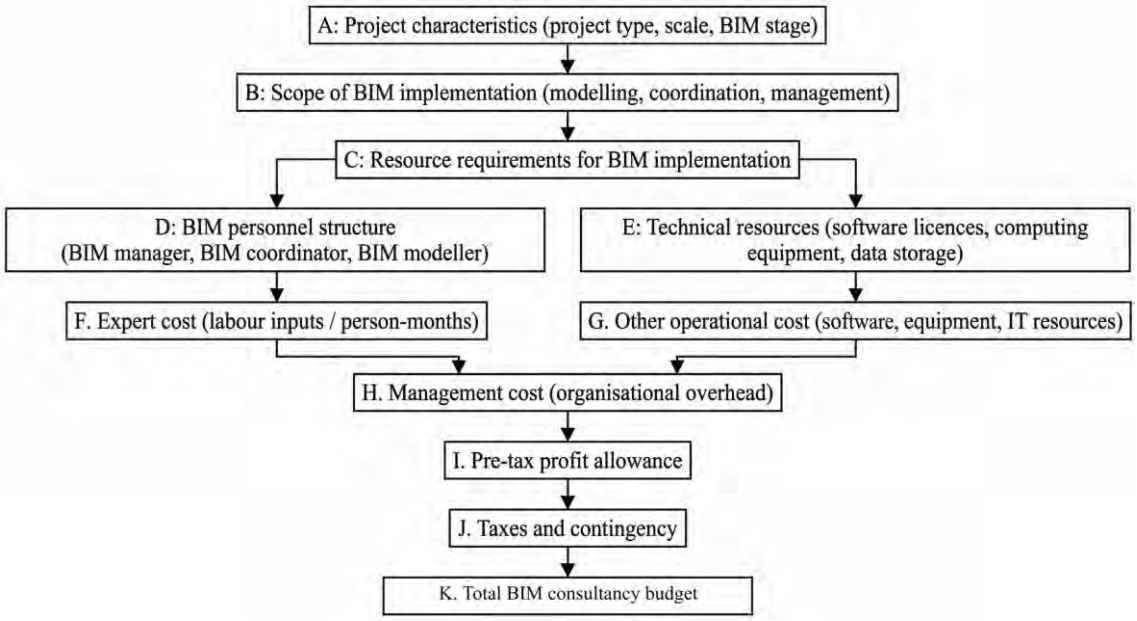



*Figure 1: Structure of BIM consultancy cost estimation in consultancy-driven BIM implementation environments*

This framework provides the basis for analysing BIM cost estimation as a governance-dependent and institutionally shaped process rather than a purely technical expenditure.

## 3. RESEARCH METHODOLOGY

This study adopts a multiple case study approach with document analysis to examine the structure and estimation of BIM implementation costs in public construction projects. Multiple case studies are particularly suitable for investigating contemporary phenomena within their real-world contexts and for identifying recurring patterns across cases (Yin, 2018). Document analysis provides a systematic means of examining organisational and project records to generate empirical insights from existing documentation (Bowen, 2009). The research focuses on identifying recurring patterns in BIM cost structures within consultancy-driven environments.

The empirical analysis is based on four public construction projects in Vietnam in which BIM implementation costs were formally estimated and approved as part of project consultancy packages. Given the limited number of cases, the study is intended to provide indicative insights into BIM cost estimation practices, not to generalise the findings. This limitation also reflects data accessibility constraints, as detailed cost estimation documents are not publicly disclosed in most cases. Publicly available procurement information, such as tender plans, typically reports only aggregated contract values rather than detailed cost breakdowns, which constrains large-sample empirical analysis of BIM cost structures in this context. These cases were selected based on three criteria: (1) BIM implementation was conducted within public construction investment procedures; (2) BIM-related costs were explicitly identified in project documentation, either as standalone consultancy packages or as components integrated within design consultancy services; and (3) sufficient documentation was available to analyse cost breakdown structures and BIM personnel allocations. The analysed documents include project approval decisions, BIM consultancy cost estimates, detailed cost breakdown tables, and appendices describing work scopes and professional inputs, providing information on

project characteristics, cost components, and the organisation of BIM-related activities. The selected projects represent both standalone BIM consultancy packages and integrated design–BIM consultancy arrangements, as well as different levels of BIM scope specification, including EIR-driven implementation, task-based integrated BIM processes, and TOR-defined scope aligned with standardised estimation norms.

To analyse BIM implementation costs, the study applies an analytical framework consisting of three dimensions: BIM cost components, BIM personnel structures, and estimation factors influencing BIM consultancy costs. The first dimension examines how BIM cost components, such as labour inputs, software licenses, and technical resources, are represented within project cost estimates. The second dimension focuses on BIM personnel structures, particularly the roles of BIM managers, BIM coordinators, and BIM modelers and their allocation across project activities. The third dimension considers contextual and institutional factors influencing BIM consultancy cost estimation, including project characteristics, implementation stage, procurement arrangements, and the level of BIM scope specification (e.g., EIR-driven requirements, integration with design processes, and reliance on TOR-defined scope and estimation norms).

The analysis was conducted in two main stages. First, BIM-related information was identified and extracted from project documentation, including cost estimates, consultancy scopes, and references to BIM personnel roles. The extracted information was then organised according to the three analytical dimensions of the study: BIM cost components, BIM personnel structures, and BIM cost estimation factors. Second, within-case analysis was conducted to examine how BIM costs were structured and estimated in each project individually. This was followed by cross-case comparison to identify recurring cost patterns and differences in cost composition, labour allocation, and estimation approaches across the four cases. Such analytical procedures are consistent with established case study research methods that combine within-case understanding with cross-case pattern identification (Yin, 2018).

## 4. EMPIRICAL CASE CONTEXT

This study examines four BIM consultancy packages implemented in public construction projects in Vietnam. In the Vietnamese procurement system, BIM implementation is typically delivered as consultancy services and incorporated into design consultancy cost estimates. The anonymised analysed cases (Case A – Case D) were identified from officially approved BIM cost estimation documents issued for public investment projects.

The selected cases involve BIM implementation during the detailed design or construction drawing design stages. Case A and Case B represent standalone BIM consultancy packages focusing on modelling, coordination, and structured information management governed by formal EIR. In contrast, Case C and Case D represent integrated design–BIM consultancy packages in which BIM activities are embedded within broader design consultancy contracts. However, they differ in the level of scope definition and cost structuring: Case C reflects a detailed, task-based BIM implementation supported by EIR and TOR, whereas Case D represents a more standardised approach in which BIM scope is defined through TOR, yet cost estimation relies more heavily on predefined regulatory norms. Despite these differences, all cases require bidders to prepare and submit a BIM Execution Plan (BEP) as part of the procurement process. This distinction provides an analytical basis for examining BIM

cost estimation across different levels of scope specification rather than fundamentally different procurement types. Table 1 summarises the key characteristics of the analysed cases.

*Table 1: Characteristics of the analysed BIM consultancy cases*

| Case | Project category | Procurement arrangement | BIM consultancy scope | Estimated BIM services value |
|---|---|---|---|---|
| Case A | Public building project | Standalone BIM consultancy (EIR/BEP/CDE) | Modelling, coordination, CDE, BEP, data exchange | ~ VND 1.71 billion |
| Case B | Public facility project | Standalone BIM consultancy (EIR-based) | Modelling, coordination, structured information management | ~ VND 4.13 billion |
| Case C | Public hospital project | Integrated design–BIM consultancy | Task-based BIM (modelling, coordination, QTO, documentation) | ~ VND 0.82 billion |
| Case D | Public hospital project | Integrated design–BIM consultancy | TOR-defined BIM, standardised estimation norms | ~ VND 0.92 billion |

***Source:*** *Developed by the authors based on the BIM cases documentation*

The cases collectively illustrate how BIM services are delivered under different implementation logics. Cases A and B demonstrate EIR-driven standalone consultancy approaches, in which BIM implementation includes structured information management processes such as data exchange protocols and coordination governance. Cases C and D illustrate integrated design–BIM consultancy approaches, where BIM activities are embedded within design processes, with varying degrees of task specification and reliance on standardised estimation norms. The analysed documentation also shows that BIM implementation relies on specialised personnel roles, including BIM managers, BIM coordinators and BIM modellers. These roles extend beyond modelling to include coordination and information management functions, depending on project requirements.

The BIM consultancy cost estimation documents provide structured information on how BIM costs are calculated within the Vietnamese construction cost management framework. Despite variations in format, these documents consistently include: (1) total consultancy cost estimates, (2) labour cost breakdowns specifying personnel and working time, and (3) operational costs related to technical resources such as software and computing infrastructure. In Cases A and B, cost estimation reflects the inclusion of structured information management activities such as CDE setup and BEP development. In Cases C and D, cost estimation reflects the integration of BIM within design consultancy processes, with either detailed task-based allocation (Case C) or standardised estimation norms linked to TOR-defined scope (Case D). This empirical structure provides the basis for the analysis in the following section, which examines BIM consultancy cost structures and the factors shaping their estimation in practice.

# 5. RESULTS

## 5.1 STRUCTURE OF BIM CONSULTANCY COST

The analysis of the four cases suggests a broadly consistent structure in BIM consultancy cost estimation across the analysed projects. Despite variations in documentation formats, the estimation approach follows a standard consultancy pricing framework applied in the Vietnamese construction sector. Within this framework, BIM consultancy costs comprise expert costs, management costs, other operational costs, and contractual allowances such as pre-tax profit and taxes. Expert costs represent direct labour inputs, while management costs cover organisational overhead. Across the cases, labour inputs included activities related to modelling, coordination and information management.

In Case C, labour inputs are structured through detailed task-based BIM activities, whereas in Case D, cost estimation is aligned with TOR-defined scope but calculated using standardised regulatory norms. Other operational costs include technical resources, i.e. software licences and computing infrastructure. These findings show that BIM consultancy cost estimates include both modelling-related activities and information management functions within project delivery processes (refer Table 2).

*Table 2: Structure of BIM consultancy cost components*

| Cost component | Description | Cost driver |
|---|---|---|
| Expert cost | Labour inputs associated with BIM managers, BIM coordinators and BIM modellers involved in project implementation | Team size, component and working duration |
| Management cost | Organisational overhead costs incurred by consultancy firms in managing BIM services | Share of expert cost and organisational structure |
| Other operational cost | Costs related to software licences, computing equipment and other technical resources required for BIM implementation | Technical resource requirements |
| Pre-tax profit | Profit allowance incorporated into consultancy service pricing | Contractual pricing structure |
| Taxes and contingency | Taxes and contingency allowances applied according to project financial regulations | Regulatory and contractual requirements |

***Source:*** *Developed by the authors based on the BIM cases documentation*

These components illustrate how BIM consultancy cost estimates are organised within approved project cost structures. Table 3 complements this structure with quantitative distribution of BIM cost components together with total labour input across the cases. The notation in the final column indicates the number of personnel and corresponding total labour input (person-days) for each role (e.g., 1(45)/3(135)/11(495) denotes 1 BIM manager with 45 person-days, 3 BIM coordinators with 135 person-days, and 11 BIM modellers with 495 person-days). Management costs mainly represent consultancy overheads, whereas other costs include software, computing infrastructure and related BIM operational resources.

*Table 3: Indicative distribution of BIM consultancy cost estimates and labour input based on approved estimation documents*

| Case | Total BIM cost estimates (VND) | Labour (%) | Management (%) | Others (%) | Profit & Tax (%) | Total labour input (person/person-days) |
|---|---|---|---|---|---|---|
| A | 1,711,706,000 | 53.69 | 29.53 | 4.38 | 12.40 | 1(45)/3(135)/11(495) |
| B | 4,133,787,696 | 51.54 | 25.77 | 10.64 | 12.05 | 1(216)/5(872)/7(1044) |
| C | 819,934,000 | 45.97 | 25.28 | 17.06 | 11.68 | 1(41)/1(56)/5(177) |
| D | 915,000,000 | 53.18 | 29.25 | 5.84 | 11.73 | 1(19)/4(76)/15(300) |

***Source**: Developed by the authors based on the BIM consultancy cost estimations.*

The variation in labour input and personnel composition across cases reflects different estimation approaches, including role-based, discipline-based, and task-based BIM implementation.

## 5.2 DOMINANCE OF LABOUR INPUTS IN BIM CONSULTANCY COSTS

Labour inputs constitute the largest share of BIM consultancy cost estimates across all cases. As shown in Table 3, labour accounts for approximately 45.97% to 53.69% of total cost estimates, followed by management costs (25.28%–29.53%), while other components contribute smaller proportions. Labour costs are primarily determined by the number of specialists and the duration of their involvement, calculated using standard professional rates. The cross-case comparison shows that labour shares exceed 50% in Cases A and B (53.69% and 51.54%, respectively), while lower proportions are observed in Cases C and D (45.97% and 48.54%). Although technical resources are included, they represent a relatively small share of total costs, with operational costs ranging from 4.38% to 17.06%. Labour allocation patterns varied depending on implementation structure and scope definition. In Case D, labour allocation follows standardised estimation norms, resulting in a more stable distribution across cost components compared to cases with more detailed task-based or EIR-defined scopes. Overall, the results indicate a relatively consistent cost structure across cases in which labour remains the dominant component, complemented by substantial management and indirect costs.

## 5.3 BIM PERSONNEL STRUCTURES IN CONSULTANCY SERVICES

BIM implementation typically involves three core roles: BIM managers, BIM coordinators and BIM modellers. Across the analysed cases, modelling activities consistently account for the majority of labour input. In Case A, BIM modellers represent 495 of 675 person-days (~73%), compared to 135 for coordinators and 45 for management roles, while a similar pattern is observed in Case D (300 of 395 person-days, ~76%). In contrast, different structuring approaches are observed in Cases B and C. In Case B, BIM labour is embedded within discipline-based teams, making the distribution of roles less explicitly separated but still dominated by modelling-related activities. In Case C, labour is organised through a task-based allocation with a total of 117 person-days, reflecting a more activity-oriented structuring of BIM work. Despite these differences, modelling remains the dominant labour component across all cases. The results indicate three distinct labour structuring logics: role-based (Cases A and D), discipline-based (Case B), and task-based (Case C), which correspond to different ways of organising and estimating BIM consultancy labour inputs. In role-based estimation,

labour is defined through explicit BIM roles; in discipline-based estimation, BIM work is embedded within design teams; and in task-based estimation, labour is derived from explicitly defined BIM activities.

### 5.4 KEY FACTORS INFLUENCING BIM CONSULTANCY COST

The cross-case comparison indicates that BIM cost estimation varies across projects according to several observable factors. First, the stage of implementation is associated with differences in cost magnitude. Case A involves design-stage BIM with extended scope, while Case B spans multiple stages, resulting in higher labour input. Case C reflects a more limited scope with lower total labour requirements. Second, differences in implementation approach are reflected in the structure of cost estimates. Compared to Case A, Case B exhibits a more formalised, EIR-driven structure with clearly defined coordination and information management components. Case C reflects integrated, task-based BIM implementation, while Case D follows a TOR-defined approach in which cost estimation is aligned with standardised norms. Third, variations in project complexity are associated with differences in labour demand. Case B involves multiple technical disciplines and extensive coordination requirements, while Case C has a simpler structure with lower coordination intensity. Finally, the presence of formal information requirements (e.g., EIR) and scope definitions (e.g., TOR) is reflected in the organisation of BIM cost estimates, particularly in relation to coordination activities, data management processes, and labour allocation. Overall, the results show that BIM consultancy cost estimates vary across cases in relation to project stage, implementation approach, project complexity, and the structure of defined BIM requirements.

## 6. DISCUSSION AND IMPLICATIONS FOR THE OWNERS

### 6.1 BIM CONSULTANCY COST STRUCTURES IN PRACTICE

The analysed projects indicate that BIM consultancy costs in Vietnamese public construction projects are formalised through consultancy pricing and procurement mechanisms rather than treated as standalone digital technology expenditure. Across all four cases, BIM implementation was incorporated into officially approved consultancy cost estimates, where cost items were organised under standard construction investment cost categories, including expert costs, management costs, operational costs, pre-tax profit and value-added tax (VAT). This structure suggests that BIM implementation is institutionalised as part of consultancy services embedded within public investment planning and approval systems. This finding extends previous BIM cost studies, which have mainly examined BIM benefits, adoption costs, or cost–benefit relationships (Bryde et al., 2013; Gharaibeh et al., 2024; Lu et al., 2014), by showing how BIM consultancy costs are formally translated into approved project cost structures. While prior studies commonly identify labour, software, hardware and training as key BIM cost elements (Borrmann et al., 2018; Hardin & McCool, 2015; Sacks et al., 2018), the present cases further show how these elements are reorganised within public-sector consultancy pricing categories, including expert costs, management costs, operational costs, profit and VAT.

The reviewed estimation documents further show that BIM implementation was operationalised through different scope-definition mechanisms across projects. In Cases A and B, BIM consultancy services were organised through relatively explicit EIR-oriented implementation structures involving BIM execution planning, coordination

management and CDE setup activities. For example, the detailed labour schedule in Case A included dedicated work items for BIM execution planning and CDE establishment prior to modelling activities, together with coordination and clash-handling tasks during implementation. Similarly, the cost documentation in Case B was approved as a standalone BIM consultancy package with a total estimated value exceeding VND 4.13 billion, indicating a relatively formalised implementation arrangement within the procurement structure. By contrast, Case C reflected a more integrated implementation mechanism in which BIM-related activities were embedded directly within the design consultancy process. The approved estimation structure combined design consultancy and BIM-related implementation under the same consultancy arrangement, while the detailed estimation tables allocated BIM activities through task-oriented work items associated with design coordination and model-based deliverables. This produced a more explicit operational linkage between BIM tasks and design production activities compared with the standalone consultancy arrangements observed in Cases A and B. Another variation can be observed in Case D, where BIM implementation was still formally defined through a dedicated BIM estimation structure but relied more heavily on predefined regulatory norms and standardised cost calculation logic. The estimation tables explicitly linked management costs to a fixed percentage of expert costs (55% × Ccg), while pre-tax profit and VAT were also calculated through predefined formulas. This suggests a more norm-based institutional logic in which BIM consultancy pricing was stabilised through standardised estimation procedures rather than through highly customised scope definition.

The cases reveal notable differences in the visibility of operational and technical resources within BIM consultancy estimation structures. In Cases A and D, the estimation appendices explicitly identified items such as CDE licensing, Autodesk AEC software, workstation depreciation, internet infrastructure and meeting-related coordination expenses as separate operational cost categories. The presence of these items indicates that BIM cost structures extend beyond modelling outputs and include broader information management and coordination infrastructure required to support BIM-enabled project delivery. Apparently, the analysed cases suggest that BIM consultancy cost structures are shaped by implementation arrangements, procurement mechanisms and institutional estimation procedures established during project planning. Rather than reflecting a uniform technical pricing model, BIM cost estimation appears to operate as a governance-dependent process in which project scope definition, coordination requirements and regulatory estimation logic collectively influence how consultancy costs are organised and formalised.

## 6.2 LABOUR-INTENSIVE NATURE OF BIM IMPLEMENTATION

Despite differences in implementation arrangement and estimation structure, labour consistently remained the dominant component of BIM consultancy cost estimates across all analysed cases. Table 3 shows that labour accounted for approximately 45.97%–53.69% of total BIM consultancy cost estimates, exceeding all other cost categories. This result is consistent with previous studies suggesting that BIM implementation is labour- and expertise-intensive (Hardin & McCool, 2015; Lu et al., 2014; Sacks et al., 2018), but the present study adds empirical detail by quantifying labour shares and personnel/person-day allocations in approved consultancy cost estimates. However, the detailed estimation appendices suggest that this labour intensity was associated not only

with modelling production, but also with coordination, information exchange and management-related activities embedded within BIM workflows.

The labour allocation structure in Case A illustrates this pattern clearly. Although BIM modelers accounted for most total person-days (495 out of 675 person-days), the detailed labour schedule also allocated substantial effort to BIM management and coordination functions, including BIM execution planning, CDE setup, clash coordination, model updating and quantity extraction activities. These activities indicate that BIM implementation required continuous coordination and information management effort extending beyond geometric model production alone. Case B demonstrates an even stronger labour-intensive pattern within an EIR-driven implementation context. The approved estimation structure allocated more than VND 2.06 billion to expert costs alone, while management costs exceeded VND 1.06 billion. This distribution suggests that formalised information exchange and governance requirements substantially increased the organisational and coordination effort associated with BIM implementation. In this respect, the findings reinforce previous studies arguing that BIM adoption depends heavily on interdisciplinary coordination and specialised professional expertise rather than purely technical modelling capability (Hardin & McCool, 2015; Sacks et al., 2018). At the same time, labour intensity varied depending on implementation structure. In Case C, BIM activities were integrated more directly into design consultancy workflows through task-based allocation mechanisms. Although labour remained the largest cost component, operational expenditures became relatively more visible within the estimation structure due to tighter integration between BIM tasks and design production activities. Meanwhile, Case D exhibited a more stabilised labour allocation pattern linked to predefined estimation norms and TOR-defined scope. The detailed expert allocation table in Case D identified 20 BIM personnel distributed across management, coordination and modelling roles, with modelling specialists representing the largest group (15 out of 20 personnel).

Another important observation is that management and indirect costs consistently occupied a substantial proportion of total BIM consultancy estimates across all projects. This indicates that BIM implementation in public projects functions not simply as a technical modelling exercise, but as a coordinated consultancy service requiring supervision, information control, coordination management and administrative support throughout project delivery. Accordingly, labour demand appears to be shaped not only by modelling workload, but also by the organisational complexity associated with managing BIM-enabled workflows in consultancy-driven project environments.

## 6.3 IMPLICATIONS FOR PROJECT OWNERS AND COST PLANNING

The findings provide several practical implications for project owners. First, BIM budgeting should prioritise labour estimation, particularly team size, role allocation, and working duration. Given that labour accounts for approximately 46–54% of total BIM consultancy cost estimates, small variations in team composition or project duration can significantly affect overall budgets. Second, implementation arrangement has important budgeting implications for project owners. More detailed BIM scope definition may improve cost transparency and project control but can also increase managerial complexity and coordination effort during implementation. Third, project complexity and interdisciplinary coordination requirements directly influence labour demand and overall BIM cost estimates. Projects involving multiple technical disciplines or intensive

coordination requirements tend to exhibit higher labour intensity and greater variability in cost distribution. Finally, defining clear information requirements (EIR) and scope specifications (TOR) is critical for improving cost transparency and estimation reliability. The cross-case analysis suggests that more detailed information requirements can improve cost clarity and project control but may also increase labour demand, while more standardised approaches can simplify budgeting at the expense of analytical precision. More broadly, project owners face a trade-off between standardised estimation approaches and more detailed, task-based approaches, with implications for both cost accuracy and management complexity. These findings indicate that effective BIM cost planning requires aligning estimation approaches with project-specific implementation logic rather than relying solely on standardised cost norms.

## 7. CONCLUSIONS

This study provides empirical insights into the structure and estimation of BIM consultancy cost estimates in public construction projects based on document analysis of approved cost estimation reports. The findings confirm that BIM cost estimates in the analysed context follow consultancy-based pricing structures and vary systematically depending on implementation approach. These differences reflect distinct BIM implementation mechanisms identified across the analysed cases. For project owners, the findings highlight the importance of clearly defining BIM scope, team composition and information requirements during project planning. More broadly, project owners face a trade-off between standardised estimation approaches, which simplify budgeting, and more detailed task-based approaches, which improve cost transparency but increase complexity.

The main contribution of this study is to demonstrate that BIM consultancy cost estimates are formed through identifiable implementation mechanisms rather than through purely technical resource calculations. Across the analysed cases, BIM cost structures were shaped by different implementation logics, including EIR-driven consultancy, integrated design–BIM delivery, and TOR-based estimation approaches embedded within institutional cost management frameworks. Although the findings are derived from Vietnamese public construction projects, the observed patterns may also be relevant to other consultancy-driven BIM environments operating under comparable regulatory and procurement conditions. However, because the analysis is based on four approved public project cases and focuses on planned cost estimation documents rather than realised expenditures, the findings should be interpreted as indicative evidence of BIM cost estimation practices rather than generalisable evidence of actual implementation costs. In this respect, the study primarily reflects how BIM costs are structured and institutionalised within project planning and procurement systems. Future research may extend this work by examining larger datasets, comparing BIM cost estimation practices across different regulatory environments, and investigating the relationship between estimated BIM consultancy costs and actual project performance outcomes.

## 8. ACKNOWLEDGEMENTS

The authors acknowledge the use of artificial intelligence tools (including ChatGPT and Gemini) to support language editing. All AI-assisted outputs were carefully reviewed and revised by the authors, who take full responsibility for the final content of the manuscript.

# 9. REFERENCES


Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, *11*(3), 241-252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

Barnes, P., & Davies, N. (2014). *BIM in Principle and in Practice*. ICE publishing London.

Borrmann, A., Konig, M., Koch, C., & Beetz, J. (2018). *Building Information Modeling–Technology Foundations and Industry Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, *9*(2), 27-40. https://doi.org/10.3316/QRJ0902027

Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of building information modelling (BIM). *International Journal of Project Management*, *31*(7), 971-980. https://doi.org/10.1016/j.ijproman.2012.12.001

Dao, Q. V., & Nguyen, T.-Q. (2021). A case study of BIM application in a public construction project management unit in Vietnam: Lessons learned and organizational changes. *Engineering Journal*, *25*(7), 177-192. https://doi.org/10.4186/ej.2021.25.7.177

European Commission. (2021). *Calculating costs and benefits for the use of Building Information Modelling in public tenders: Methodology handbook*.

Gharaibeh, L., Eriksson, K., & Lantz, B. (2024). Quantifying BIM investment value: A systematic review. *Journal of Engineering, Design and Technology*, 23 (5), 1384–1403. https://doi.org/10.1108/JEDT-06-2023-0259

Government of Vietnam. (2021). *Decree No. 10/2021/ND-CP on construction investment cost management*. Hanoi, Vietnam. https://vanban.chinhphu.vn/?pageid=27160&docid=202663

Government of Vietnam. (2024). *Decree No. 175/2024/ND-CP on Detailed Provisions and Measures for the Implementation of the Law on Construction Regarding the Management of Construction Activities*. Hanoi, Vietnam. https://vanban.chinhphu.vn/?pageid=27160&docid=212166

Hardin, B., & McCool, D. (2015). *BIM and construction management: proven tools, methods, and workflows*. John Wiley & Sons.

Kumar, B. (2015). *A practical guide to adopting BIM in construction projects*. Whittles Publishing.

Lu, W., Fung, A., Peng, Y., Liang, C., & Rowlinson, S. (2014). Cost-benefit analysis of building information modeling implementation in building projects through demystification of time-effort distribution curves. *Building and Environment*, *82*, 317-327. https://doi.org/10.1016/j.buildenv.2014.08.030

Mai, B. N., Tran, Q. P., & Nguyen, M. D. (2025). Experimental application of BIM in the appraisal of design cost estimates for publicly funded civil building projects. *Journal of Materials and Construction, Ministry of Construction*, *15*(1), 102-111. https://doi.org/10.54772/jomc.01.2025.834

Ministry of Construction. (2021). *Circular No. 11/2021/TT-BXD Guidelines on Certain Aspects of Construction Investment Cost Determination and Management*. Hanoi, Vietnam. https://congbao.chinhphu.vn/van-ban/thong-tu-so-11-2021-tt-bxd-34379.htm

Ministry of Construction. (2024). *Circular No. 09/2024/TT-BXD amending and supplementing several construction cost norms*. Hanoi, Vietnam. https://chinhphu.vn/?pageid=27160&docid=211221

Mitchell, A., Williges, C., Henly-Thomas, S., & Messner, J. (2023). *Lifecycle BIM for Infrastructure: A Business Case for Project Delivery and Asset Management*. National Academies of Sciences, Engineering, and Medicine.

Ngo, T. T., Truyen, D. M., & Tin, H. X. (2020). BIM application for bridge, highway and infrastructure projects in Vietnam. *Transport and Communications Science Journal*, *71*(7), 760-774.

Nguyen, M., Nguyen, T.-Q., Nguyen, Q.T., Vu, N.N., & Thieu, T.T.T. (2021). BIM adoption as a perceived source of competitive advantages and competitive strategies for construction consultancy SMEs: evidence from Vietnam. *AIP Conference Proceedings*, Volume 2428, Issue 1, 060005. AIP Publishing https://doi.org/10.1063/5.0070739

Nguyen, T.-Q., Thieu, T.T.T., & Vu, N.N. (2021). BIM-based competitive advantages and competitive strategies for construction consultancy SMEs: A case study in Vietnam. *International Journal of*

*Sustainable Construction Engineering and Technology*, *12*(3), 1-11. https://doi.org/10.30880/ijscet.2021.12.03.001

Nguyen, T. H. (2024). Determining the cost of BIM implementation in construction investment projects. *Science and Technology, University of Communication and Transport*, *740*, 180-183.

Pham, V. D., Ta, V. P., Nguyen, M. N., Nguyen, V. V., & Mai, V. (2024). The important roles of BIM in the construction industry in Vietnam: A multi-approach analysis. *International Journal of Sustainable Construction Engineering and Technology*, *15*(4), 176-187. https://doi.org/10.30880/ijscet.2024.15.04.013

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. John Wiley & Sons.

Yin, K. R. (2018). *Case study research and applications design and methods* (6th ed.). Sage Publications, Inc.

Nissanka, N.L.A., De Silva, G.H.S.P. and Ahila, R., 2026. Building resilience: Navigating the barriers of innovation in construction SMES of Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 349-363. DOI: https://doi.org/10.31705/WCS.2026.26. Available from: https://ciobwcs.com/papers/

# BUILDING RESILIENCE: NAVIGATING THE BARRIERS OF INNOVATION IN CONSTRUCTION SMES OF SRI LANKA

**N.L.A. Nissanka[1], G.H.S.P. De Silva[2] and R. Ahila[3]**

## *ABSTRACT*

*Small and Medium Enterprises (SMEs) are recognised as a crucial sector responsible for the growth and social development of Sri Lanka. However, compared with global trends, many sectors of Sri Lanka's SMEs are far behind in embracing innovation. The Sri Lankan construction sector is no exception, as it continues to face various barriers in implementing innovation day by day. The primary reasons are some barriers that negatively affect the project's performance. This study aims to investigate these specific barriers, with a particular focus on construction SMEs in Sri Lanka, and to address a gap in the existing literature. The study adopted a mixed approach following a comprehensive literature review. Data were collected through semi-structured interviews conducted with 8 construction SME owners/managers. To assess the impact of barriers on innovation adoption, a 5-point Likert scale was included in the interview guideline. The collected data were then analysed using both code-based content analysis and descriptive statistical tools such as percentages, means, and weighted averages. The author identified several barriers with high impacts: high costs of obtaining external capital and lack of access to finance were identified as barriers with very high impact, lack of or insufficient access to knowledge, lack of skilled workers, lack of government support, low level of innovation on the market, and no infrastructure available on the market. The study proposes a set of strategies to enhance awareness of innovation within the construction sector. It concludes that improving the innovative performance of Sri Lankan SMEs and enabling them to compete globally requires reducing or eliminating the identified barriers. The study suggests promoting industry-wide collaboration by establishing innovation hubs and events that showcase innovation and foster knowledge exchange among organisations. The study may help industry practitioners identify barriers and take proactive measures to overcome them.*

***Keywords:*** *Barriers; External; Innovation; Internal; SMEs.*

## 1. INTRODUCTION

While long-standing evidence indicates slower progress and notable resistance to innovation in construction (Sayyed et al., 2023; Wei & Lam, 2014), the construction industry is criticised for being conservative and non-innovative, in both developed and developing countries. However, globalisation, economic changes, technological advancements, and increased competition have necessitated adopting innovations in

[1] Lecturer, Department of Civil Engineering and Construction, Scot Campus, Sri Lanka, achikanissanka@gmail.com
[2] Senior Lecturer, Department QS, SLIIT, Sri Lanka, priyanwada.d@sliit.lk
[3] Student, Liverpool John Moores University, UK, ahila19970225@gmail.com

organisational structures, process technologies, and culture to establish a competitive advantage (Lasanthika & Pavithra, 2025).

For construction organisations, adopting innovation is essential for improved outcomes in the design-construction process and for many other reasons, such as leading projects to success and creating opportunities for competitive advantage and organisational survival. Innovation encompasses concepts like novelty, modifications, opportunities, creative ideas, organisational adoption, and value creation (Koffi et al., 2021). However, from a construction industry perspective, innovation is a structured strategy of organisational functioning, comprising aspects such as goals, environmental barriers/drivers, strategies, and organisational factors, performing as a prototype for bringing systematic change to the construction industry (Qi et al., 2023). When innovation brings long-term benefits to the business and users by creating value and uniqueness in the product or service (Mohammed, 2019), the level and quality of innovation depend on several factors. Among these factors are employees' expertise, operational quality, and the ability to adapt to continuous changes in the business environment (Nguyen, 2023), to name a few. By nature, the construction industry is complex and faces tension due to high competition driven by technological advances and modern construction techniques (Egwunatum & Oboreh, 2022). As a result, alongside market competitiveness, barriers to innovation are rapidly growing, slowing or preventing novel ideas from moving forward and hindering business development and the ability to remain competitive in the market (Beyer, 2022). Despite this situation, many countries and businesses are now making strong efforts to implement innovation within their organisational environments to survive in the highly competitive construction landscape (Mohammed, 2019).

However, this situation is not common across all construction environments. While construction sector organisations in some countries are successfully innovating, those in developing countries often face critical barriers in implementing innovation, with a key barrier being a lack of expertise and knowledge (Sayyed et al., 2023). Most of the construction businesses in both developed and developing countries are SMEs. These SMEs play a special role in driving the diffusion of entrepreneurial skills, innovation, and employment in modern economies (Egwunatum & Oboreh, 2022). SMEs lack an accepted definition, as criteria vary across countries and regions based on factors such as employment size, investment, and turnover. In the Sri Lankan construction sector, SMEs are identified using the ICTAD grading system, with firms having an annual turnover below Rs. 40 million also classified as small-scale enterprises. In today's dynamic business environment, construction SMEs must prioritise gaining a competitive advantage and expanding their market share. In the context of innovation, there is an opportunity for them to improve their business performance and gain a competitive advantage (Koffi et al., 2021). As competition intensifies, traditional methods available become less effective; therefore, these organisations must adopt innovative methods to differentiate themselves from competitors and increase their market share. According to Modranský et al. (2020), these innovative approaches involve adapting to new technologies, changing market conditions, and evolving customer needs.

Despite being the backbone of the economy and bridging supply gaps, SMEs in the construction industry face unique competitive risks and numerous barriers in incorporating innovation into their operations and business processes (Owolabi et al., 2019). Therefore, exploring context-specific barriers faced by construction SMEs in

adopting innovation is of contemporary relevance to the current economic recovery of the Sri Lankan construction sector. Existing research highlights the importance of innovation (Madhavika et.al., 2024; Lasanthika & Pavithra, 2025), but the research on construction SMEs in developing countries like Sri Lanka has received limited attention. There is insufficient understanding of context-specific barriers and their impact on innovation adoption and performance in the construction industry (Madhavika et.al., 2024). Since SMEs are crucial for economic growth (Madhavika et al., 2024; Lasanthika & Pavithra, 2025), but face barriers in adopting innovation, especially in the construction industry, it is essential to identify and examine the impact of these barriers on performance and competitiveness in the industry. Therefore, the following four objectives were set in this research,

*1: Review* the barriers to implementing innovation and its impact on the performance of construction organizations, *2:* Investigate the barriers to implementing innovation in construction SMEs in Sri Lanka, *3:* Examine the impacts of barriers to implementing innovation on the performance of construction SMEs in Sri Lanka and *4: Propose* strategies for overcoming innovation barriers in Sri Lankan construction SMEs

# 2. LITERATURE REVIEW

## 2.1 THE CONCEPT OF INNOVATION

The term "innovation" is not limited to economics but also encompasses sociology, political science, and science (Beyer, 2022). Innovation involves adopting "new ideas or behaviours, whether in systems, policies, programs, devices, processes, products, or services, that were not previously familiar to the adopting organisation (Nguyen, 2023). It is also seen as the application of new or upgraded products, processes, marketing methods, or organisational practices (Bolosha et al., 2022).

## 2.2 BARRIERS TO IMPLEMENTING INNOVATION IN THE CONSTRUCTION INDUSTRY

Barriers to implementing innovation are mainly classified as external or internal (Larenwaju Nassar & Olaleye Faloye, 2015). Internal barriers can be further sub-classified into financial resources, human resources, and organisational barriers, whereas external barriers include government, infrastructure, and other factors (Banu, 2020).

### 2.2.1 Internal Barriers

Internal barriers related to barriers stem within the business and can be further classified into organisational, human resources, and economic subgroups (Nguyen, 2023). These barriers usually include resistance to change, limited access to knowledge, and ineffective communication with external stakeholders, as identified by Beyer (2022). ***Organisational Barriers****:* internal policies and performance measures hinder innovation within organisations (Nguyen, 2023). Researchers highlight various management barriers that impede innovation. Among them are enterprise rigidity, which hinders the implementation of innovative ideas; inadequate access to knowledge and a lack of awareness of the importance of implementing innovations pose (Beyer, 2022), lack of an innovation-friendly culture within organisations which further hampers progress (Wei & Lam, 2014) a limited understanding of the benefits of innovation, which reduces motivation for innovation efforts (Owolabi et al., 2019), to name a few. ***Human Resource***

***Barriers:*** Human resource barriers in organisations contain several complications related to human factors. In the construction industry, labour costs can represent a significant portion (30–50%) of the total project budget (Nguyen, 2023). Barriers within human resources include a lack of skilled workers and a refusal to develop employees' skills due to fear and resistance to change (Beyer, 2022). Skills shortages, particularly in science, technology, and soft skills for collaboration and intercultural competence, pose significant barriers to innovation (Modranský et al., 2020). These human resources barriers, including organisational policies, management barriers, communication barriers, short-term orientation, cultural barriers, and a lack of understanding of innovation benefits, hinder progress (Nguyen, 2023; Beyer, 2022; Modranský et al., 2020; Owolabi et al., 2019; Wei & Lam, 2014). ***Financial Barriers***: These barriers include insufficient funds and the high costs of securing external capital. For construction organisations, the pursuit of short-term profits and the need for immediate capital outlay are critical due to funding gaps and substantial initial investments. Another side of financial barriers is the challenging access to external financing sources and the high capital associated with innovation (Beyer, 2022). Moreover, barriers such as funding shortages, inadequate salaries, and a lack of job security significantly affect innovation in this sector. Construction companies' culture of risk and fear of failure further impedes innovation, as it increases the perceived risk and uncertainty associated with exploring innovative alternatives and experimenting with new ideas (Nguyen, 2023).

### 2.2.2 External Barriers

External barriers to innovation stem from the external environment (Nguyen, 2023). According to Modranský et al. (2020), significant barriers to adopting an innovative culture include regulations, bureaucracy, societal norms, acquiring skilled employees, accessing knowledge, securing funding, and navigating the external environment. External barriers can be classified into the following areas:

***Government Barriers:*** The construction industry faces barriers in achieving a positive innovation cycle since the government fail to support innovation (Nguyen, 2023). Beyond regulatory issues that play a crucial role in applying innovation (Wei & Lam, 2014), avoiding and limiting legal regulations are identified as the primary barriers, ranking first and second, respectively, mainly impacting innovation motivation and adherence to innovative solutions (Wei & Lam, 2014). ***Legal Barriers:*** Legal barriers related to ecological policy, the lack of state policy on innovation, and restrictions on intellectual property rights (Beyer, 2022) lead to external barriers to innovation. Market barriers, such as intense competition, limited innovation, and inadequate market infrastructure (Beyer, 2022), further impede innovation. ***Other Barriers:*** Adequate funding for research and development, along with active research activities, is essential for fostering innovation (Owolabi et al., 2019).

## 2.3 THE IMPACT OF BARRIERS TO IMPLEMENTING INNOVATION IN CONSTRUCTION SMEs.

According to Nguyen (2023), certain factors impede innovation in construction organisations. *Client influence* plays a specific role in innovation. However, clients can motivate innovation by improving collaboration and identifying new desires; their limited ability to clearly articulate requirements may act as a barrier to innovation performance. Additionally, *the low education level of construction workers* often leads to a closed mindset; making them less willing to question traditional practices. Employees may also

dislike the implementation of innovation due to issues about high workload and job security. Furthermore, the *lack of internal training opportunities* reduces employees' concern and participation in innovation activities. Economic barriers such as high inflation, expensive loans, and limited tax benefits also restrict innovation efforts, particularly in SMEs in developing countries. Modranský et al. (2020) identified several organisational and market-related barriers to innovation. *A poor innovation culture within organisations*, characterised by *inadequate resource allocation, bureaucratic decision-making,* and *risk-averse attitudes*, can negatively affect creativity and innovation. Additionally, when firms undertake innovation projects together, the high costs and time required to identify the most commercially viable options pose a challenge. Paying attention to a few strategically selected projects can improve resource utilisation and efficiency. Furthermore, lengthy product development and market launch processes may lead to missed opportunities, allowing competitors to introduce innovations more quickly.

## 3. METHODOLOGY

Following a comprehensive literature review primarily based on journal articles and conference proceedings, the barriers to innovation in construction organisations were identified. In light of the Literature findings, and the selected qualitative approach, the author conducted a series of semi-structured interviews with owners and/or top managers of SMEs to identify the barriers to innovation and their impact on construction SMEs in Sri Lanka. The rationale behind selecting each SME as a suitable candidate for the semi-structured interview is that they hold significant decision-making authority within their respective SMEs.

This study adopts Individual In-Depth Interviews (IDI) as its primary research approach. IDI focuses on building trust, empathy, and effective communication between the researcher and participant to obtain detailed insights. It is well-suited for in-depth exploration and has long been a widely used, practical qualitative data collection method (Boyce & Neale, 2006; Kvale & Brinkmann, 2009). To ensure the effectiveness of the semi-structured interview approach, the author conducted a pilot interview prior to the main study. Two individuals with extensive experience in the construction industry (each with over 10 of experience) participated in the pilot interview. Based on the insights gained from the pilot interviews, the semi-structured interviews were conducted in accordance with the refined guidelines. The semi-structured interview consisted of 12 open-ended questions. A list of innovation barriers was presented to respondents, who ranked their level of impact using a five-point Likert scale below, where "1" denoted "very low " and "5" denoted "very high" as shown in Table 1 below.

*Table 1: Likert scale for the level of the impact of innovation barriers*

| Scale | Interpretation | Range |
|---|---|---|
| 1 | Very low | 1.00 – 1.80 |
| 2 | Low | 1.81 – 2.60 |
| 3 | Moderate | 2.61 – 3.40 |
| 4 | High | 3.41 – 4.20 |
| 5 | Very high | 4.21 – 5.00 |

Although the study is basically qualitative, a five-point Likert scale was used to capture respondents' perceptions of the impact of innovation barriers. The Likert-scale responses were used descriptively to identify general patterns and support comparison across key themes derived from the qualitative findings. According to Frels & Onwuegbuzie (2013), including rating-scale questions alongside open-ended discussion allows researchers to obtain both numerical assessments and detailed explanations, thereby enhancing the robustness of the findings. Accordingly, the study adopts a predominantly qualitative design with a limited quantitative component rather than a fully balanced mixed-methods approach.

Purposive sampling was used to select participants with relevant experience in the construction industry. The study targeted practitioners with 5–20 years of experience in SME building and infrastructure projects, mainly recruited through LinkedIn. Owners, managers, and industry experts were selected because they possess decision-making authority and valuable insights, making them suitable for semi-structured interviews. The participants included Quantity Surveyors (QS), Engineers, and Project Managers (PM). Although the study initially planned to conduct 10 interviews, only 8 were completed due to practical constraints, including participant unavailability and lack of responsiveness. Despite this, the achieved sample size was considered sufficient, as data saturation was reached and no new significant insights emerged from additional interviews. Therefore, the 8 interviews provided adequate depth and richness of data to address the research objectives. The study employed inductive thematic analysis with manual coding to analyse qualitative data, providing flexibility to explore participants' perceptions and experiences. The process involved familiarisation, coding, theme development, and refinement. Initial coding was conducted using NVivo by the lead researcher, followed by team review to ensure consistency and accuracy. An iterative approach, involving repeated engagement with the data, was used to refine themes and enhance the depth and reliability of the findings.

# 4. RESULTS AND DISCUSSION

## 4.1 DEMOGRAPHIC FINDINGS

The below Table 2 presents below the professions and the industry experience of the participants.

*Table 2: Composition of participants*

| Respondent | Profession | Industry experience |
|---|---|---|
| R1 | Project Manager | More than 15 |
| R2 | Project Manager | More than 6 |
| R3 | Project Manager | More than 20 |
| R4 | Senior Quantity surveyor | More than 24 |
| R5 | Senior Quantity surveyor | More than 10 |
| R6 | Chatted Quantity surveyor | More than 20 |
| R7 | Civil Engineer | More than 15 |
| R8 | Civil Engineer | More than 8 |

Participants in Sri Lankan building-construction SMEs report their years of experience. According to the data received, 75% of the population claimed more than 10 years of experience in construction SMEs.

## 4.2 INNOVATION FROM THE EYE OF CONSTRUCTION INDUSTRY

The expert responses collectively suggest that construction innovation consists of the introduction and application of new ideas, technologies, and practices to improve project performance. The built environment recognised innovation as *"Successful introduction of new technologies or procedures into the construction industry" (*$R_1$). However, the responses also indicated that practitioners tend to prioritise technological and practical improvements, while giving less attention to organisational, institutional, and systemic aspects of innovation. $R_4$ argued that *"Innovation means trying out methods not commonly adopted in the industry as well as testing unique and novel methods*". At the same time, $R_3$ claimed "*innovation in construction means using new ideas, methods, technologies, or processes to make building projects better, safer, and more sustainable*". The novelty includes advances in materials, tools, hardware, and machinery, leading to improvements across various aspects of construction projects. Another opinion was that the concept of innovativeness must be a better, safer, and more sustainable approach to creating a *better built environment* that addresses society's evolving needs. At the same time, another respondent shared the opinion that *"innovation in construction means using new ideas, methods, technologies, or processes to make building projects better, safer, and more sustainable" (*$R_3$).

This analysis shows the need for a more holistic understanding of construction innovation, one that integrates technological, managerial, and organisational factors to capture the complexity of innovation within the construction industry.

## 4.3 BARRIERS FACED BY SMES IN IMPLEMENTING INNOVATION IN SRI LANKA

The results revealed a clear divergence of opinion among experts. While 43% of respondents believed that SMEs could implement innovation without major barriers, the majority 57% argued that these enterprises encounter significant barriers. The findings suggest that the innovation capacity of SMEs within the Sri Lankan construction context is context-dependent, shaped by organisational capabilities, access to resources, and external support mechanisms. Table 3 below presents the interview insights on barriers to innovation.

*Table 3: Interview insights on barriers to innovation in Sri Lankan SMEs*

| Respondent | Opinion | Justification for their statement |
|---|---|---|
| R1 | Yes | "SMEs in Sri Lanka can now leverage the same information and technology as larger companies to stay updated on innovations and implement them". |
| R2 | No | (SMEs) may face barriers in obtaining the necessary funding to invest in innovative projects. |
| R3 | No | SMEs may struggle to find skilled labour for new technology implementation and maintenance. |

| Respondent | Opinion | Justification for their statement |
|---|---|---|
| R4 | Yes | Sri Lankan SMEs are known for their creativity and willingness to try new things. |
| R5 | No | SMEs may be unaware of construction industry innovations and their benefits. |
| R6 | Yes | Several organizations in Sri Lanka support SMEs with resources for growth and innovation. |
| R7 | No | There exist some initial costs and a lack of competence |

The opinions show a slight negativity toward SME innovation in Sri Lanka. Some respondents believe that SMEs can adopt innovation due to access to technology, creativity, and institutional support; others highlight barriers such as limited funding (R2), lack of skilled labour ($R_3$), low awareness ($R_6$), and high initial costs. However, the barriers outweigh the advantages. The reason can be that prevailing economic uncertainty encourages firms to prioritise operational continuity over long-term innovation investments, resulting in perceived barriers exerting a stronger influence than available opportunities.

### 4.3.1 Pathways for Enhancing Innovation Adoption in Sri Lankan SMEs

Furthermore, respondents highlighted several factors that facilitate innovation among local construction SMEs. They are: *Access to Information and Technology:* Respondents highlighted that, today, as with large organisations, SMEs can also fully access information and technological resources through digital platforms, online sources, and affordable technologies. It has reduced the industry gap between large-scale and SMEs. Therefore, SMEs can stay up to date with innovations and industry developments. *Entrepreneurial Culture and Creativity:* the willingness and the creativity of SMEs to explore novel ideas. By nature, SMEs are flexible and adaptable, and they make quick decisions, unlike larger organisations, which makes them more responsive to innovative opportunities. *Institutional support:* Another highlighted opinion was that the support they receive from government agencies, industry associations, and development programs for SME development and innovation, includes training opportunities, funding mechanisms, and knowledge-sharing platforms that help overcome barriers to innovation. In contrast to the enabling factors, some respondents pointed out a few barriers to innovation in the Sri Lankan context.

### 4.3.2 Fundamental Systemic Barriers to Innovation Adoption in Sri Lankan Construction SMEs

*Financial Constraints*: Limited access to funding facilities is one of the major barriers identified by $R_2$. The respondent further elaborated that, innovation requires investment in technology and research and development. Many SMEs struggle with training and infrastructure, as well as with limited financial capacity and difficulty accessing external financing. In Beyer's (2022) research on enterprises in the West Pomeranian region of Poland, limited access to external financing and high innovation related capital cost were identified as significant barriers. Similarly, the study's interview findings revealed that SMEs in Sri Lanka's construction industry face difficulties obtaining the necessary funding to invest in innovative projects.

*Shortage of skilled labour*: Respondents claimed that implementing and maintaining new technology requires skilled labour; however, the construction industry often suffers from

shortages of specialised skilled labour in digital technologies, automation, and advanced construction methods. SMEs may struggle to find skilled labour to implement and maintain new technologies. Similarly, Beyer (2022) identified a shortage of skilled workers and reluctance to develop employees' skills, driven by fear and resistance to change, as significant human resource barriers to innovation. These findings are consistent with the interview results of the present study, which revealed that construction SMEs in Sri Lanka face barriers in accessing and developing the skilled workforce required to support innovation.

*Lack of awareness*: Respondents noted that limited awareness of innovations and their benefits is another reason SMEs struggle to implement them within organisations. Since SMEs get exposed to novel technologies, best practices, and case studies, they are reluctant to adopt innovation. A lack of understanding of the benefits of innovation further reinforces these human resource barriers. Similarly, Nguyen (2023) found that SMEs are often unaware of innovations available in the construction industry and the benefits they offer. This finding is consistent with the interview results, which revealed that limited awareness and understanding of innovation hinder its adoption among construction SMEs.

*Limited Competence and Initial Costs*: Even though these SMEs realise the value of innovation, the lack of expertise within the organisations and the financial risks associated with early adoption discourage them from implementing innovative practices, as identified by Nguyen (2023) in the Vietnamese engineering industry.

According to the data, Sri Lankan construction SMEs face several key barriers to innovation, primarily driven by limited financial capacity: firms operate on tight margins, face cash flow constraints, and have restricted access to credit due to high borrowing risks. The industry's traditionally risk-averse nature further discourages innovation, as firms prefer established methods and perceive little need for change. Additionally, limited awareness of emerging technologies and global practices leads to a poor understanding and communication of innovation within organisations. A skills gap in the workforce, particularly in digital and advanced construction methods, further constrains innovation. At the same time, low investment in training and development reflects a focus on short-term survival over long-term growth. Together, these factors significantly hinder the adoption of innovation in SMEs.

## 4.4 THE BARRIERS AND THE RATINGS PROVIDED BY THE INTERVIEWEES FOR EACH LEVEL OF BARRIERS

According to respondents, the identified barriers are at least partially significant in hindering innovation within construction SMEs in Sri Lanka. It implies that there are no negligible barriers to innovation; every identified barrier poses a challenge that requires immediate actions to foster a more innovative environment. Table 4 below summarises the barriers to implementing innovation experienced by SMEs in Sri Lanka and the level of impact of each barrier.

*Table 4: Barriers of implementing innovation experienced SMEs in Sri Lanka*

| Type | Barrier | Finding | Level |
|---|---|---|---|
| Internal | Financial Barriers | Lack of own funds | High |
| | | High costs of obtaining external capital | Very high |
| | | Lack of access to finance | Very high |
| | | High-interest rates on loans | High |
| | Organisational Barriers | Fear of taking risks | High |
| | | The firmness of the enterprise is unfavourable for introducing innovation | Moderate |
| | | Lack of a sense of the need to implement innovations. | Moderate |
| | | Lack of understandable messages about the need for innovation | High |
| | | Management barriers | Moderate |
| | | Lack or insufficient access to knowledge. | Very high |
| | Human resources Barriers | Limited allocation of funds for employee training | High |
| | | Lack of knowledge to analyse the durability and profitability of the innovation | High |
| | | High labour turnover | High |
| | | Lack of skilled workers | Very high |
| | | Lack of willingness to improve employees' competencies. | Low |
| | | Barriers resulting from the employees' fear and reluctance to implement changes. | Low |
| External | Legal Barriers | High taxes and other regulatory fees | Moderate |
| | | Poor innovation policy | High |
| | | Restrictions on intellectual property rights | Moderate |
| | Government Barriers | Difficulty in obtaining government grants | High |
| | | Political instability | Moderate |
| | | Lack of government support | Very high |
| | Market Barriers | Difficulty in accessing international markets | Moderate |
| | | Low level of innovation on the market | Very high |
| | | No infrastructure available on the market | Very high |
| | Other Barriers | Economic crisis | High |
| | | High import traffic | Moderate |

| Type | Barrier | Finding | Level |
|---|---|---|---|
| | | Lack of opportunities for research development | High |
| | | Poor funding for research and developments | High |
| | | Poor industry cooperation | High |
| | | Lack of customer responsiveness | High |

The highlighted barriers above, with very high impact, reflect the realities of the construction industry, especially in developing countries like Sri Lanka, where the sector is capital based, fragile, and highly risk sensitive (Madhavika et.al., 2024). SMEs face critical financial issues such as limited access to funding, high borrowing costs, and lack of internal capital, which strongly hinder the adoption of innovation (Pallegedara, 2017). Furthermore, human resource barriers such as shortages of skilled labour, low investment in training, and high employee turnover limit SMEs' ability to implement new technologies and innovative practices (Lasanthika & Pavithra, 2025; Loosemore, 2015). External factors such as weak government support, poor innovation ecosystems, and limited industry engagement also magnify these difficulties, as construction innovation heavily depends on institutional and policy support (Gann, 2000; Manley, 2008). Overall, these combined financial, organisational, and external constraints explain why the barriers are rated very high compared to those in more developed construction environments.

## 4.5 IMPACT OF INNOVATION BARRIERS ON CONSTRUCTION SME PERFORMANCE IN SRI LANKA

Barriers to implementing innovation in construction SMEs can be categorised into financial, organisational, management, human resource, and external barriers, all of which influence sales growth and profitability. *"Many firms face limitations on their ability to invest in innovation due to a lack of internal funding, high costs associated with obtaining external capital, and restricted access to finance. These barriers impede their capacity to develop new products, enhance processes, or expand into new markets, thereby reducing their competitiveness, market share, profitability, and sales growth."* ($R_1$-$R_8$).

*Financial barriers*, such as limited internal funds and high costs of external financing, **restrict** SMEs' ability to invest in research and development, new technologies, and innovative processes ($R_2$ & $R_7$). *Organisational barriers*, including rigid structures and a lack of awareness of the importance of innovation, **reduce** firms' ability to adapt to changing market demands, potentially leading to stagnant or declining sales and profits ($R_7$ & $R_3$). *Management barriers*, particularly ineffective leadership, further **limit** SMEs' ability to pursue innovative opportunities and expand revenue streams ($R_7$ & $R_3$). *Human resource barriers*, such as limited access to knowledge, a shortage of skilled workers, and inadequate employee training, **hinder** the adoption of new technologies and processes, affecting productivity and competitiveness ($R_3$, $R_5$ & $R_7$). *External barriers* also significantly influence innovation activities. Factors such as weak innovation policies, limited government support, intellectual property restrictions, lack of infrastructure, insufficient Research and Development (R&D) funding, low market innovation, and poor customer responsiveness create an **unfavourable** environment for innovation ($R_4$ & $R_5$).

These barriers collectively **reduce** SMEs' capacity to innovate, ultimately affecting their sales growth, competitiveness, and profitability ($R_1$, $R_2$, $R_3$ & $R_5$).

## 4.6 STRATEGIES FOR OVERCOMING INNOVATION BARRIERS IN SRI LANKAN CONSTRUCTION SMES

The experts suggested several strategies to overcome innovation barriers faced by SMEs in Sri Lanka. Among these suggestions, *"There is a growing awareness of the need for innovation in the industry"* ($R_1$ & $R_5$). growing awareness of innovation: by promoting innovation among construction organisations and educating these organisational professionals about the importance of innovation to sustain competitiveness and long-term success, was identified as one of the main tasks. Emerging culture of change: The construction industry has now recognised the importance of change and is gradually shifting towards an open-minded approach, overcoming its inherent resistance to it. Increased focus on employee development: SMEs must provide training opportunities to help employees upskill and embrace new ideas and technologies ($R_4$). *"If we can identify the key barriers, we can focus our efforts on overcoming them and creating an environment that better supports innovation"* ($R_3$) - This recognises opportunity for targeted interventions: Exploring these barriers may offer opportunities to implement targeted interventions that further reduce the impact and encourage an innovation-conducive setting.

Furthermore, the respondents showed the importance of continuous improvement, highlighting that any barrier cannot be treated as minor, as it may escalate to a much more critical level. Reforming innovation policies can also make a big impact on promoting innovation among SMEs in Sri Lanka. The respondents also pointed out, *"The government must review and revise existing innovation policies to create a more supportive environment for innovation" (*$R_1$). The policymaker's responsibility is to review and revise current innovation policies to create a more supportive environment for innovation by providing incentives for research and development, tax breaks for innovative firms, and streamlined regulations. Strengthening government support: from the Government's perspective, respondents stated that to promote innovation, the Government must introduce various schemes, such as grants, subsidies, and technology transfer programs, to assist and encourage construction firms - *"the government could collaborate with educational institutions or industry associations" (*$R_1$, $R_3$, $R_4$ & $R_5$). Respondents suggested that *"there is a greater need for industry associations and leading construction firms to promote collaboration and knowledge sharing through forums, workshops, and partnerships"* ($R_4$, $R_5$ & $R_6$) to nurture the innovation ecosystem. The best step is to promote industry-wide collaboration by establishing innovation hubs and hosting events that showcase innovation and foster knowledge exchange among organisations.

# 5. CONCLUSIONS AND FUTURE DIRECTIONS

## 5.1 REVIEW THE BARRIERS THAT HINDER THE IMPLEMENTATION OF INNOVATION IN CONSTRUCTION ORGANISATIONS

A comprehensive literature review was conducted using academic databases, industry journals, and relevant books to identify barriers to innovation in construction organisations. In light of findings from previous studies, the author developed a comprehensive list of barriers. These barriers were categorised as internal and external barriers. Internal barriers include organisational, financial, and human resource factors, while external barriers include legal, government, market, and other external factors. Key studies such as Nguyen (2023), Beyer (2022), Modranský et al. (2020), Owolabi et al. (2019) and Wei & Lam (2014) were reviewed to identify and analyse these barriers.

## 5.2 THE BARRIERS TO IMPLEMENTING INNOVATION IN CONSTRUCTION SMES IN SRI LANKA

The findings show that a combination of internal and external barriers has been severely distracting the implementation of innovation in Sri Lankan construction SMEs. Internal barriers include financial constraints, organisational resistance to change, lack of innovation awareness, limited knowledge and skills, and inadequate employee development, while external barriers are regulatory barriers, insufficient government support, political instability, market limitations, economic uncertainties, and weak industry collaboration. Among these, financial limitations and the lack of skilled human resources come as the most significant barriers, restricting SMEs' ability to invest in innovative practices. These findings are supported by the existing literature, confirming that innovation barriers faced by Sri Lankan construction SMEs are same as the ones that are experienced globally. Therefore, addressing these barriers needs greater financial support, capacity building, policy improvements, and stronger collaboration among industry stakeholders to promote a more innovation friendly environment within the construction industry.

## 5.3 THE IMPACTS OF BARRIERS TO INNOVATION IMPLEMENTATION ON THE PERFORMANCE OF CONSTRUCTION SMES IN SRI LANKA

The findings of this objective show that barriers to innovation have a crucial overall impact on the performance of construction SMEs in Sri Lanka, with financial constraints, lack of finance, shortage of skilled labour, weak infrastructure, and limited market innovation identified as having a very high impact. Other factors such as poor government support, high implementation costs, limited R&D opportunities, and weak industry collaboration also show a high impact, while organisational and regulatory issues have a moderate effect. Only the employees' hesitation to adopt change and improve skills was found to have a low impact. Overall, the results confirm that financial and resource related barriers are the most critical factors affecting innovation performance, which aligns with existing literature.

## 5.4 RECOMMENDATIONS

The study identifies opportunities for innovation in the construction sector while highlighting existing barriers and their impacts. It emphasises the need for further

research to develop effective strategies to overcome these barriers, especially in light of the new barriers posed by the pandemic to construction SMEs in Sri Lanka.

### 5.5 LIMITATIONS

The study depends on a small purposive sample, which limits the generalisability of the findings. In addition, the Likert-scale analysis only acted as a supplementary tool to support the qualitative findings rather than to provide statistically generalisable results. It provides a descriptive indication of respondents' perceived level of impact of innovation barriers. Therefore, the study is better positioned as a qualitative dominant design with a supplementary quantitative component rather than a fully structured mixed-methods approach.

### 5.6 FUTURE RESEARCH STUDIES

Based on an analysis of the existing literature, a conceptual framework can be developed to guide more in-depth research on innovation in the construction sector, focusing on the opportunities it creates the advantages it delivers, and the barriers to its adoption. It may also help structure future studies by connecting internal factors such as financial, organisational, and human resource barriers with external influences, including market conditions, regulatory requirements, and government support. Further research is needed to gain a deeper understanding of the crucial barriers construction SMEs face in implementing innovative solutions in practice, as well as to examine how these barriers vary across firm types, project contexts, and economic environments. In addition, comparative studies across regions or countries would be important for providing a more comprehensive understanding of barriers to innovation and for developing more effective strategies to promote innovation in the construction industry. Moreover, future research could use a larger sample and a fully quantitative or mixed-methods approach to improve generalisability and enable more robust statistical analysis of innovation barriers among Sri Lankan SMEs.

## 6. ACKNOWLEDGEMENTS

The researcher would like to extend sincere appreciation to the Sri Lanka Institute of Information Technology and Liverpool John Moores University (LJMU) for their continuous support and for providing the institutional resources required to conduct this research successfully.

## 7. REFERENCES

Banu, S. (2020). Barriers to Innovation in SMEs: A Context of Bangladesh. *Bangladesh Journal of MIS, 8*(1), 1-25.

Beyer, K. (2022). Barriers to innovative activity of enterprises in the sustain development in times of crisis. *Procedia Computer Science, 207,* 3140–3148. https://doi.org/10.1016/j.procs.2022.09.372

Bolosha, A., Sinyolo, S., & Ramoroka, K. H. (2022). Factors influencing innovation among small, micro and medium enterprises (SMMEs) in marginalized settings: evidence from South Africa. *Innovation and Development, 13*(3), 583–601. https://doi.org/10.1080/2157930x.2022.2092681

Boyce, C., & Neale, P. (2006). *Conducting in-depth interviews: A guide for designing and conducting in-depth interviews for evaluation input* (Vol. 2), Pathfinder international.

Egwunatum, S. I., & Oboreh, J. C. (2022). Factors Limiting Knowledge Management among Construction Small and Medium Enterprises. *Journal of Engineering, Project, and Production Management, 12*(1), 25–38. https://doi.org/10.32738/JEPPM-2022-0003

Frels, R.K. & Onwuegbuzie, A.J. (2013) Administering Quantitative Instruments with Qualitative Interviews: A Mixed Research Approach. *Journal of Counseling & Development, 91,* 184-194. https://doi.org/10.1002/j.1556-6676.2013.00085.x

Gann, D. M. (2000). *Building innovation: Complex constructs in a changing world.* Thomas Telford Publishing.

Koffi, A. L., Hongbo, L., & Seinfeldian, S. (2021). Examining the impact of innovation types on Ivorian Small and Medium-sized Enterprises (SMEs) performance and competitiveness. *International Journal of Academic Research in Accounting, Finance and Management Sciences, 11*(1). https://doi.org/10.6007/ijarafms/v11-i1/9223

Kvale, S., & Brinkmann, S. (2009). *Interviews: Learning the craft of qualitative research interviewing.* Sage.

Nassar, M., & Faloye, D. O. (2015). Barrier to innovation in developing countries' firms: evidence from Nigerian small and medium scale enterprises. *European Scientific Journal, 11*(19).

Lasanthika, W.J.A.J.M. & Pavithra, H.D. (2025), Technological Adoption and Organizational Performance of SMEs in Sri Lanka. *Sri Lankan Journal of Entrepreneurship, 4*(1), pp. 48–71. https://doi.org/10.31357/sje.v4i01.8640

Loosemore, M. (2015). *Innovation, strategy and risk in construction*. Routledge.

Madhavika, N., Bandara, M., Manchanayake, M., Perera, C., Bandara, W., Jayasinghe, P., & Ehalapitiya, S. (2024). Navigating economic crisis: Factors shaping resilience in Sri Lankan construction SME supply chains. *International Journal of Construction Management, 25*(11), 1324–1336. https://doi.org/10.1080/15623599.2024.2415158

Manley, K. (2008). Against the odds: Small firms in Australia's construction industry. *Journal of Construction Engineering and Management, 134*(12), 1121–1129. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:12(1121)

Modranský, R., Jakabová, S., & Oláh, A. (2020). Innovation management and barriers – creating space for innovation and organisational change. *Emerging Science Journal, 4*(5), 345–364. https://doi.org/10.28991/esj-2020-01236

Mohammed, D.A. (2019). Barriers and Enablers of Innovation in United Arab Emirates (UAE) Small and Medium Enterprises (SMEs) Sector. *International Journal of Entrepreneurship, 23*(3).

Owolabi, J. D., Faleye, D., Eshofonie, E. E., Tunji-Olayeni, P. F., & Afolabi, A. O. (2019). Barriers and drivers of innovation in the Nigerian construction industry. *International Journal of Mechanical Engineering and Technology, 10*(2), 334–339.

Pallegedara, A. (2017). Factors affecting SMEs' access to bank finance: An evidence from Sri Lanka. *International Journal of Economics and Business Research, 13*(1), 30–42. https://doi.org/10.1504/IJEBR.2017.10002650

Nguyen, M. V. (2023). Barriers to innovation in construction organizations of different sizes: a case study in Vietnam. *Engineering Construction & Architectural Management, 31*(11), 4209–4235. https://doi.org/10.1108/ecam-07-2022-0701

Qi, L., Wong, P. S. P., & Holdsworth, S. (2023). Towards understanding the impact of the perceptions about construction innovation on advanced technology adoption. *International Journal of Construction Management, 24*(14), 1521–1529. https://doi.org/10.1080/15623599.2023.2220519

Sayyed, Y., Hatamleh, M. T., & Alaya, A. (2023). Investigating the influence of procurement management in construction projects on the innovation level and the overall project performance in developing countries. *International Journal of Construction Management, 23*(3), 462–471. https://doi.org/10.1080/15623599.2021.1889088

Wei, Y., & Lam, P. T. I. (2014). Innovation Barriers at the Project Level: Study of a UK Construction Firm. *International Journal of Architecture, Engineering and Construction, 3*(3), 182–194. https://doi.org/10.7492/ijaec.2014.015

Nadeetharu, M., Udawatta, N., Costin, G.P. and Karunasean, G., 2026. Circular economy knowledge management initiatives in the Australian construction and demolition waste management sector. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 364-376. DOI: https://doi.org/10.31705/WCS.2026.27. Available from: https://ciobwcs.com/papers/

# CIRCULAR ECONOMY KNOWLEDGE MANAGEMENT INITIATIVES IN THE AUSTRALIAN CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT SECTOR

**M. Nadeetharu[1], N. Udawatta[2], G.P. Costin[3] and Gayani Karunasena[4]**

## *ABSTRACT*

*Circular Economy (CE) implementation has been identified as a key solution in addressing the issue of Construction and Demolition (C&D) waste generation. However, the lack of CE knowledge among designers in the construction industry impedes CE uptake for C&D waste management. Although existing studies emphasise the importance of CE Knowledge Management (KM) as a key enabler to equip designers with CE knowledge to manage C&D waste, there remains limited research outlining the specific KM practices needed to achieve this in practice. Therefore, this study investigates the current CE KM initiatives in the Australian C&D waste management sector to understand the landscape of CE KM of designers. Nineteen semi-structured expert interviews were conducted with designers and were analysed using reflexive thematic analysis. The findings indicate current CE KM initiatives to be fragmented and mainly focused on KM activities supporting knowledge sharing: primarily delivered through professional association courses, seminars, and workshops. This exposed a notable misalignment between knowledge sharing and knowledge acquisition, revealing low knowledge acquisition by designers. The need for knowledge creation, evaluation, and documentation initiatives to support designers in the CE application is thus identified, whilst demonstrating that current initiatives are primarily reactive – generally emerging in response to regulatory requirements. These findings assist designers and policymakers in targeting improvements in the CE KM practices, addressing gaps, and leading to enhanced implementation of C&D waste management practices. By framing the CE KM landscape for Australian designers, this study contributes to Sustainable Development Goals (SDGs) 04 and 08.*

***Keywords:*** *Circular Economy; Construction and Demolition Waste; Designers; Knowledge Management; Waste Management.*

[1] Doctoral Researcher, School of Architecture and Built Environment, Deakin University, Australia, m.buddhakoralage@deakin.edu.au
[2] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, nilupa.udawatta@deakin.edu.au
[3] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, g.costin@deakin.edu.au
[4] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, gayani.karunasena@deakin.edu.au

# 1. INTRODUCTION

Waste is defined as any material that the holder discards, as it no longer serves a functional purpose in production, transformation, or consumption processes (Circle Economy, 2025). C&D waste denotes the subset of such waste generated in the construction processes. The construction industry is responsible for around 2-3 billion tons of construction and demolition (C&D) waste generated annually, contributing to around 25-30% of global waste generation (Sakthibala et al., 2025). When it comes to the Australian context, the construction industry generates approximately 29 Mt of waste materials annually, accounting for around 39% of the nation's waste generation (Coreo, 2025). At present, a large portion of C&D waste ends up in landfills, creating severe environmental and social challenges (Purchase et al., 2022), ratifying the need for improved C&D waste management approaches. Waste management refers to the practices of avoiding, reducing, reusing, recycling, recovery, treatment and disposing of waste using a high-to-low priority order known as the waste management hierarchy (NSW Environment Protection Authority, 2022). Despite the existence of numerous measures aimed at managing C&D waste, it remains inadequately managed in both global (Petrović & Thomas, 2024) and Australian contexts (Coreo, 2025).

Circular Economy (CE) has gained attention in the construction industry as a promising solution to reducing the environmental impacts of construction activities (Sun et al., 2025). It is an economic system designed to minimise waste and pollution, enhance effective resource consumption and regenerate the natural environment (Ellen MacArthur Foundation, 2016). Therefore, as conveyed in the definition above, it extends beyond the existing waste management hierarchy, intending for the regeneration of the natural environment. As a solution to managing C&D waste, CE provides a variety of benefits (Mahpour, 2018) including: natural resources protection, minimising illegal disposal, landfill diversion, and maximising financial benefits through material reuse (Swarnakar et al., 2025). However, the adoption of CE for C&D waste management remains limited within the construction industry. For example, (Circle Economy, 2025) states that globally, only 22% of C&D-generated waste is diverted from landfill. Further, despite potential for diversion to high-value streams, most of the C&D waste is used for low-value applications such as backfilling (Circle Economy, 2025). Similarly, in Australia, there is a notable misalignment between reported and actual landfill diversion rates in C&D waste. While some projects claim diversion rates exceeding 90%, outcomes in certain cases are found to be as low as 14% of waste recovery (Coreo, 2025).

This limited adoption of CE for C&D waste management derives from a range of barriers, including environmental, economic, cultural, organisational, technical, regulatory constraints and knowledge (Gherman et al., 2023; Wuni, 2023). Lack of CE knowledge is identified among the top three barriers for the Australian construction industry (Shooshtarian et al., 2023), which exerts influence on all the aforementioned barriers, narrowing perceived options, limiting stakeholder engagement, and constraining effective implementation of CE practices for C&D waste management (Koralage et al., 2024). Further, Wuni (2023) promotes knowledge as the topmost driver for construction industry CE adoption. Existing studies reflect this position, highlighting the importance of CE Knowledge Management (KM) in improving industry C&D waste management practices (Koralage et al., 2024; Oluleye et al., 2022). Borrowing from Koralage et al. (2024) and Evans et al. (1993), this study considers KM as a cyclical process encompassing the activities of knowledge creation, acquisition, documentation

(organising and storing), application, evaluation and sharing. In investigating CE KM, design team professionals were considered as prominent stakeholders due to their ability to influence material selection decisions that affect waste generation and management (De Marchi & Di Maria, 2020). Further to the authors, their role in advancing CE KM is significant, particularly during a project's preliminary phases, where such contributions can help mitigate end-of-life environmental impacts (De Marchi & Di Maria, 2020). However, Adams et al. (2017) revealed that designers, whilst one of the most influential construction project practitioners, were frequently the least informed on CE implementation.

Existing studies frequently mentioned the importance of CE knowledge and KM for enhancing C&D waste management practices. Further, there are very limited studies that initiated efforts in CE KM in Australia. For example, Sun et al. (2025) identified information-sharing barriers for CE adoption in construction projects and provided factors limiting information sharing, derived from a case study. While this study provides insights regarding factors hindering knowledge sharing, it does not explore knowledge sharing and KM practices to be enabled in detail. Nadeetharu et al. (2026) identified CE knowledge requirements for designers to effectively manage C&D waste; its scope is limited to specifying what knowledge is necessary, rather than explaining how that knowledge can be managed in practice. Moreover, the Department of Climate Change (2024) conveyed collaboration as a necessary step to enable knowledge exchange; however, it is also limited in its scope to convey the CE KM landscape of the Australian C&D waste management sector. Thus, there is a dearth of studies that investigated the current landscape of CE KM initiatives in the Australian construction context whilst covering the KM cycle's multiple dimensions.

This study, therefore, aims to investigate such CE KM initiatives- focusing upon the Australian C&D waste management sector- seeking to depict and interpret the landscape of CE KM of designers. The scope of this study is limited to commercial building projects in Australia, where CE adoption is marginal, and with awareness that expert availability is currently limited outside of this sector. According to (Coreo, 2025) commercial construction projects in Australia generate an average of 128 kg/m$^2$ of waste materials, being one of the topmost project types that need to be circular. Further, a study by Nadeetharu et al. (2026), also articulated that most of the current CE efforts are centred on commercial settings, allowing the feasibility of data collection. The upcoming section describes the adopted methodology, followed by chapters covering the findings, discussions, and a summary of our conclusions.

## 2. RESEARCH METHODOLOGY

This study employs a qualitative research methodology. Widely acknowledged as the most appropriate approach for exploring individuals' subjective experiences, it enables the capture of perspectives and beliefs generally missed by quantitative approaches (Sun et al., 2025). Semi-structured expert interviews were developed for data collection due to their potential for obtaining rich and detailed information through the researcher's interactive participation (Ahlin, 2019). The interview questions were designed to unveil multiple perspectives on current circular economy (CE) knowledge management (KM) initiatives covering different steps of the KM cycle. Nineteen such interviews were conducted with CE experts in the Australian construction industry. Data saturation was reached after 16 interviews, as no new themes emerged at that stage. Nevertheless, three

additional interviews were undertaken to validate and confirm the point of saturation. Interviewees were selected based on the criteria of holding a minimum of five years of industry experience and at least two years of CE or construction and demolition (C&D) waste management experience. In selecting interviewees, consideration was also given to ensuring the multiple professions within a design team were covered. Design team role definitions followed those of the Building Designers Association of Australia (Building Designers Association of Australia (BDAA), 2024) with the chosen expert profiles offered in Figure 1. Potential participants aligning with the above criteria were identified from publicly available company websites, LinkedIn profiles and CE groups, and initially contacted with a plain language statement describing the research project, consent from and withdrawal of consent form. Judgmental sampling was used in data collection as it is considered ideal for exploratory research design, low cost and less time-consuming (Taherdoost, 2016). To ensure anonymity, respondents were allocated a unique code (R-01 to R-19).

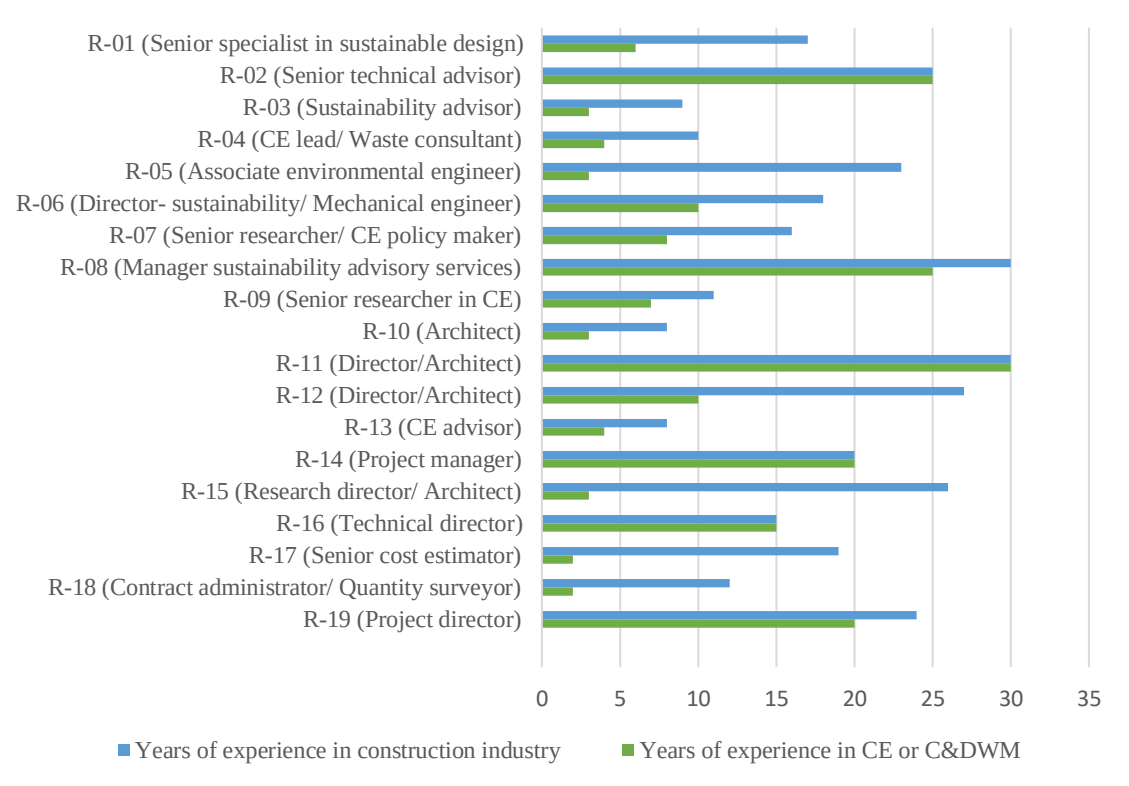



*Figure 1: Profile of experts participated in the semi-structured interviews*

Ultimately, all respondents exceeded the selection criteria with more than eight years of construction industry experience and two years of CE or C&D waste management experience. Interviews were conducted and recorded using Zoom with the written consent of interviewees. The resultant auto-generated Zoom transcripts were then manually reviewed and verified to ensure accuracy. Data was considered acceptably saturated after 16 interviews; however, three additional interviews were conducted for surety. This study received ethical approval from Deakin University (Approval Nr.: 2024/HE000532).

Reflexive thematic analysis, as outlined in Byrne (2022), was chosen as the most appropriate means of deciphering the obtained data. Consisting of six steps, this approach covers the following: 1. Data familiarisation and note-taking; 2. Systematic coding of

data; 3. Identifying initial themes; 4. Reviewing and expanding themes; 5. Refining, defining and naming themes, and 6. Writing (Byrne, 2022). Following this method, the raw transcripts were thoroughly reviewed initially to familiarise, and appropriate phrases were coded to the six steps of the KM cycle (creation, acquisition, documentation, application, evaluation and sharing). The identified phrases were revisited to identify initial themes and iteratively cross-verified with transcripts to expand and identify final themes. This method is allowed for and appropriately exposes the researcher's active role in data interpretation. NVivo 15 was also deployed as a coding interface, enabling researchers to handle large amounts of data and identify and organise patterns (Castleberry & Nolen, 2018).

## 3. RESEARCH FINDINGS

This study identifies circular economy (CE) knowledge management (KM) initiatives following the steps in the KM cycle, as shown in Figure 2.

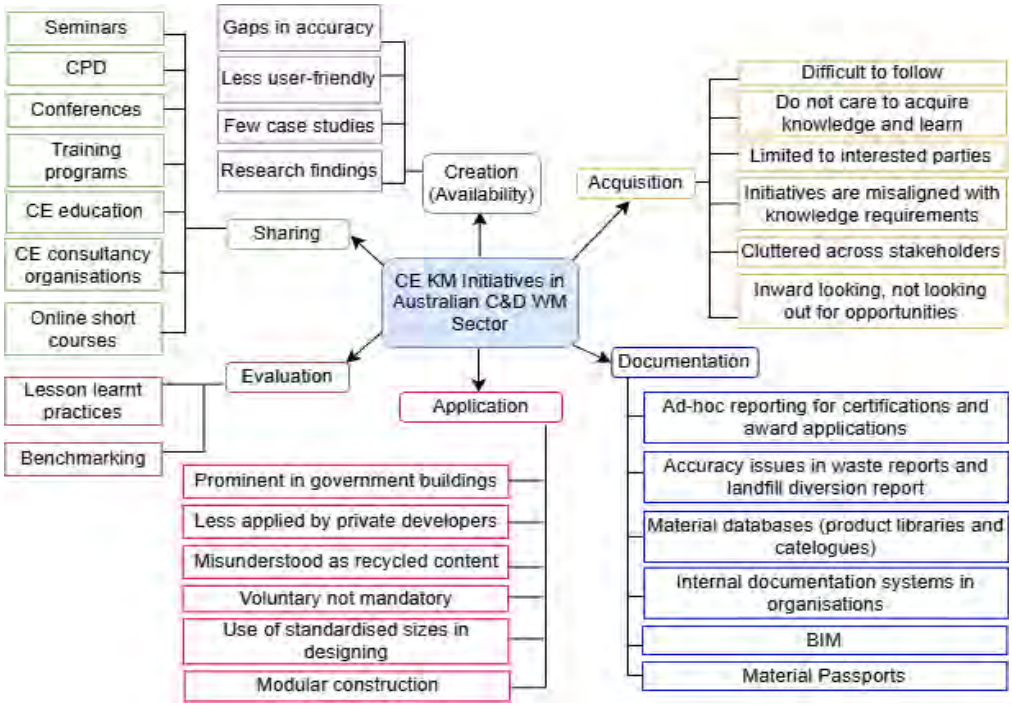



*Figure 2: Current circular economy knowledge management initiatives in the Australian construction and demolition waste management sector*

Notably, respondents unanimously acknowledged the need for CE KM initiatives. In itself, this highlights a significant CE knowledge deficiency amongst Australian construction industry design professionals (R-01: R-19). However, respondents emphasised that there are plans to advance CE KM in Australian construction and demolition (C&D) waste management through innovative research projects (R-15) and CE frameworks (R-14). The following sections discuss these initiatives, as presented in Figure 2, in more depth.

## 3.1 AVAILABILITY OF CIRCULAR ECONOMY KNOWLEDGE

Contradictory views were expressed by respondents regarding circular economy (CE) information availability for designers to plan construction and demolition (C&D) waste management into their projects. Three out of 19 respondents claimed there is plentiful CE information adaptable and relevant to the Australian construction industry. Conversely, two of the respondents suggested a significant dearth of suitable CE information and knowledge. This left the majority (10 out of 19) of respondents reporting an intermediate view, suggesting information gaps, particularly in relevant formats (R-05, R-10), accuracy (R-03, R-04), and user-friendliness (R-09, R-13). This lack of user-friendliness, expressed in Figure 2, was reported as resulting in substantial time consumption when referring to documents and so inhibiting adoption of existing knowledge (P-11). More user-friendly formats of available knowledge were thus being called for. In addition, respondents were uncertain of where to find information and the trustworthiness of CE knowledge sources (R-01). Furthermore, the substantial cost of the information resources, often behind association paywalls, discourages designer engagement despite availability (R-01). Thus, there is a necessity for improved databases easily and freely accessible to practitioners in the design fields. Notably, participants (R-03 and R-04) highlighted the importance of access to relevant case-based, real-world information rather than abstract theory, something significantly lacking in the construction industry.

## 3.2 CE KNOWLEDGE SHARING INITIATIVES

All the respondents agreed on the availability of initiatives for CE knowledge sharing in the Australian construction industry. For example, R-02 disclosed, *"I am surprised how most of the industry is kind of happy to share that (CE) information. It is quite interesting"*. Seminars and conferences are two popular initiatives to share CE knowledge in the construction industry. In addition to knowledge sharing initiatives focused on a wider range of professionals, there are knowledge sharing initiatives focused internally on the employee level at organisations (R-01, R-04). However, attendance to these initiatives is generally limited to the design professionals how are already interested in CE (R-08), providing limited accessibility to knowledge. CE education for entry-level professionals and CE-focused Continuing Professional Development (CPD) programs for existing professionals in the industry are considered two formal approaches for knowledge acquisition and dissemination of CE knowledge. However, CPDs focused on CE are limited in the present construction industry (R-06), which is unevenly target on different professionals comprising the design team (R-18). This is potentially due to the absence of robust regulatory frameworks mandating compliance with CE practices in construction and demolition (C&D) waste management. As CE principles are typically adopted in response to regulatory requirements (R-03), the lack of mandatory regulations can diminish the need for CE-trained professionals.

CE education (refer to Figure 2) is positively attributing in the Australian construction industry as an initiative for the dissemination of knowledge, as there are a few Australian universities recently started CE courses (R-06). However, R-15 claimed that it is embedded only as a part of the learning outcome, not as a core unit. Further CE educational programs should expand to prioritise targeting different professionals, like waste contractors, who are physically dealing with waste (R-03). In addition, it needs to expand CE education beyond university level, as there are few initiatives for that at present (R-07, R-15). Seven out of 19 comment on CE consultation, presented in Figure

2 as a current supportive initiative to disseminate CE knowledge to industry professionals to apply CE to manage C&D waste. R-08 appreciates the current consultation and also emphasised the importance of commenting on the financial benefits of waste management, as the industry is driven by profits instead of prioritising environmental considerations. However, the cost associated with hiring a CE consultant hinders the effective use of their knowledge in construction projects to manage C&D waste (R-10).

### 3.3 INITIATIVES FOR CIRCULAR ECONOMY KNOWLEDGE ACQUISITION

Despite the availability of circular economy (CE) knowledge and knowledge sharing, eight out of 19 respondents claimed that the acquisition of CE knowledge by design team professionals was quite low. Lack of interest, as presented in Figure 2, is one of the reasons impeding knowledge acquisition. For example, R-13 explains that "*it's not hard that knowledge is out there (...). So, if somebody gave literally the tiniest (effort), they could Google it and find out (a) bunch of stuff today"*, conveying that professionals do not care to learn about CE. This limited interest in professionals causes limited connectivity with others interested in CE, which is referred to as "an echo chamber" (R-08). Therefore, stakeholder networking needs to be further expanded, especially to contractors (R-07) and clients (R-05), encouraging more knowledge sharing among those stakeholders.

Another reason for the lack of knowledge acquisition is the less emphasis on formal qualifications placed in the Australian construction industry, provided that the required tasks are completed satisfactorily (R-18). This lack of momentum from the industry might be a reason for the indifference in knowledge acquisition, compared to knowledge availability and sharing. Financial constraints are also a reason for the lack of knowledge acquisition of design professionals, as there is limited freely available, trustworthy knowledge. R-01 claimed that the accuracy of freely available knowledge is difficult to verify, which limits professionals from acquiring new information. Another reason for limited acquisition is the misalignment of available knowledge with the specific needs of the design team professionals (R-04) (refer to Figure 2). Further to R-04, design professionals in the Australian construction sector place greater value on experiences, including real-world best practices and pitfalls, which are currently insufficiently available. Nevertheless, there are adequate CE information sources available, and this abundance creates challenges in determining appropriate entry points and identifying relevant and credible sources (R-13).

### 3.4 INITIATIVES FOR APPLICATION OF CIRCULAR ECONOMY KNOWLEDGE

Modular construction (R-16), relocatable stages and temporary housing arrangements in festivals (R-13), use of standardised sizes of materials when designing (R-14), reusing construction and demolition (C&D) waste in its exact form (metal lift cables used as an elephant enclosure in the Zoo) (R-08), and use technologies like Virtual Reality (VR) and 3D printing in the building survey stages to determine potential waste (R-19) are mentioned as current circular economy (CE) application initiatives in Australian construction industry suggesting positive trend towards CE application. However, 10 out of 19 respondents claimed that most of the CE applications in the current context are merely to achieve "Green star", or to "protect heritage listed site". Further, this application sometimes leads to "greenwashing" (R-12) with limited disclosure and highlights the need for an internally driven application with a purpose. Despite architects

and design teams taking efforts to reuse existing building materials in new developments and extension projects as an initiative for CE implementation (R-17), CE is still commonly misunderstood by clients as being limited to the "use of recycled content" (R-06), as stated in Figure 2. This misunderstanding contributes to its restricted adoption, as clients often express concerns regarding the quality of recycled materials. Additionally, the application of CE in construction projects remains limited among private developers, as they perceive such initiatives are associated with a heightened level of risk and consider them to be a "guinea pig". In contrast, as stated in Figure 2, government-funded buildings, including university projects, are taking the initial steps and undertaking the associated risks, which is essential for creating success stories that can encourage CE adoption among private investors (R-04).

## 3.5 INITIATIVES FOR DOCUMENTATION OF CIRCULAR ECONOMY KNOWLEDGE

Although few initiatives for the documentation of circular economy (CE) practices exist, the majority of respondents characterised these efforts as inadequate and largely ad hoc, as stated in Figure 2. External drivers, including awards, have been identified as a key reason for documenting CE practices in current construction projects (R-03, R-15). Consequent to this responsive nature to external mandatory requirements, regulations have been identified as the most prominent way to enable documentation of CE practices regarding construction and demolition (C&D) waste management in construction projects (R-18). Another documentation approach that needs to be improved in construction projects is the material libraries (R-13) (Figure 2), as the validity of current directories remains difficult to verify (R-02). This validity needs to be improved via an independent third-party, as according to R-08, "*it (material directory) cannot come from the government because they are not allowed to show preferences to any commercial people*". The role of digital technologies in improving documentation of CE practices was also highlighted as an important documentation initiative. As stated in Figure 2, Building Information Modelling (BIM) software is a current initiative to identify "*where the wastage is"* (R-10). It has a limited adoption in the construction industry (R-02). One of the potential reasons for this is the sophisticated nature of the software (R-11), which suggests the need for more education regarding software use. "Material passports" (R-05) and "building passports" (R-02, R-13) were two other initiatives that need to be expanded, incorporating all products and services data into a centralised system.

## 3.6 INITIATIVES FOR EVALUATION OF CIRCULAR ECONOMY KNOWLEDGE

Current initiatives for evaluating circular economy (CE) knowledge of designer professionals are considered very limited in the Australian construction industry, irrespective of the profession (R-07). As stated in Figure 2, lesson learnt practices (R-19) and benchmarking (R-15) have been identified as two initiatives for evaluating CE knowledge, which still need to be expanded. Although the capturing of lessons learned has long been a recognised practice within the construction industry, its uptake remains limited due to time constraints (R-02, R-06). R-08 supported this view explaining that "*as an industry, everything novates so fast, then they (project team members) get to the end of a project, and they don't capture, or they might capture lessons learned, but they don't bring it back to the start of the next project, because they've already rushed off to another project*". Establishing a work ethic to prioritise the importance of applying lessons learned can help mitigate these time-related barriers (R-19).

Lack of benchmarked guidelines or criteria to evaluate current knowledge for design professionals in the construction industry is identified as a limitation of current knowledge evaluation initiatives, which impedes designers from tracking knowledge (R-05). Therefore, there is a need for a consistent set of criteria for professionals to measure their CE practices (R-01). Furthermore, R-07 explained that this lack of evaluation impedes the practical application of CE for construction and demolition (C&D) waste management, as professionals in the construction industry, despite possessing distinct skill sets, tend to operate within isolated perspectives, as there are limited opportunities for collective analysis and the effective integration of knowledge on shared grounds. Similar to documentation, evaluation of lessons learnt in CE applications is also happening on an ad-hoc basis only if it is essential in the immediate project (R-02). In addition, due to the fragmented and complex nature of the construction industry, there is no designated custodian responsible for the evaluation and protection of CE data (R-06). This absence represents a pressing issue that requires urgent attention.

# 4. DISCUSSION

The Australian construction industry has few of the circular economy (CE) guidance plans, which can also be used by designers to contribute to managing C&D waste (Barner et al., 2024; Department of Climate Change, 2024). Despite the positive growth in CE knowledge management (KM) initiatives in the Australian construction and demolition (C&D) waste management sector, the findings of this study reveal the requirements for extensive revisions, updates and a structured approach to ensure their effectiveness, covering multifaceted areas of KM. This includes increasing adoption of documentation of CE practices, evaluation and purposeful dissemination of CE knowledge, in addition to the mere sharing of knowledge, which is the current practice.

CE knowledge sharing is increasing in the Australian construction industry, which contributes to closing the data sharing gaps for CE highlighted by (Adams et al., 2017; Mahpour, 2018; Sun et al., 2025). However, the findings of this study conveyed that current knowledge-sharing initiatives are identified as misaligned with the knowledge requirements of design professionals, limited only to interested parties, cluttered and difficult to follow. This can be due to a lack of in-depth understanding of knowledge requirements targeting different design professionals at the industry and at different education levels. Therefore, CE knowledge assessment tools are required to be utilised by universities, professional accreditation bodies, industry organisations and policymakers to gain a detailed understanding of knowledge areas, targeting sharing. Share with a purpose (structured dissemination of knowledge) also needs to be empowered as a vision of CE knowledge sharing, rather than mere transfer of information, by ensuring recipients clearly understand the rationale and significance underlying the knowledge being communicated.

Insufficient information on materials and methods related to CE implementation has identified as a needed area for improvement, which aligns with the findings of Gherman et al. (2023) who conveyed a lack of information as a barrier hindering CE adoption for C&D waste management. Therefore, enhancing the engagement of supply chains with CE reporting is required to enhance the reliability of material information. The findings suggest a positive attitude of design professionals to real-life examples in contrast to theoretical knowledge, with increased sharing of tools and techniques, best practices and lessons learned practices. Oluleye et al. (2022) similarly highlighted this knowledge

requirement in their study, unveiling the necessity for a CE best practices framework incorporating tools, guidance and standards for C&D waste management. However, the empirical findings expand this requirement by emphasising the importance of making such best practices frameworks accessible through case studies and real-life examples. Therefore, the government could lead in implementing CE demonstration projects for the wider construction industry, especially conveying lessons learned practices.

Existing studies of Gherman et al. (2023) and Purchase et al. (2022) revealed a lack of education opportunities for construction professionals on CE. However, empirical findings in contrast convey that there is positive progress towards CE education in the Australian context, which is also similarly conveyed by Barner et al. (2024). Yet, this study conveys that these available initiatives are more focused on sustainability than CE, limited to a few design professions like architects and are primarily at the university level. Instead, these initiatives should be expanded towards the vocational education and training (VET) sector (TAFE and private registered training organisations [RTOs]) and should focus on a wide range of professions (eg: cost management, contract administration, procurement and engineering). Cost being a key barrier for CE uptake in the Australian construction industry Feldman et al. (2024), focus on CE education and career development of cost managers and quantity surveyors, should be considered a priority. While CE consultation is being initiated in Australia, it should be expanded specifically to the construction industry and communicate the financial benefits of C&D waste management to motivate clients to adopt CE practices. Australia's Waste[d] Opportunity report (Coreo, 2025) initiated a similar initiative, and there is a need for more trustworthy initiatives in the future. Cost managers and quantity surveyors need to take priority in this regard; therefore, enhancing their CE knowledge is vital. This sharing of financial benefits will contribute to addressing one of the topmost barriers identified by Mahpour (2018) which is an inadequate understanding of the benefits of CE in C&D waste management.

Despite the availability of industry bodies focusing on CE, including the Green Building Council of Australia and Sustainability Victoria, empirical findings reveal the need for structured CPDs from professional accreditation bodies covering all professions, which is lacking in the current context. Even though Australia's CE framework (Department of Climate Change, 2024) conveys the credibility of building codes to incorporate circularity, the experts, in contrast, claim that CE has not been adequately incorporated into the National Code of Construction (NCC). This can be an important background initiative to enable designing for C&D waste management using CE, as current voluntary requirements for CE are not effective. Elaborating on the view of Swarnakar et al. (2025), who conveyed digital technologies as a key driving factor for CE implementation for C&D waste management, empirical findings confirmed the positive role of digital technology in CE KM in addition to the application of CE practices. This study further confirmed that documentation feasibility as an additional benefit of digital technologies. As the respondents highlighted the role of digital technologies in documentation and explained the sophistication of available software, software developers can work on introducing more CE-friendly document management systems to centralise all building data. Concurrently, enhancing the technological knowledge of construction professionals is required to prepare them to adopt and utilise software effectively.

## 5. CONCLUSIONS, LIMITATIONS AND FURTHER RESEARCH DIRECTIONS

This study focused on identifying current circular economy (CE) knowledge management (KM) initiatives to enhance CE knowledge of designers to manage construction and demolition (C&D) waste in the Australian construction industry. The results indicated the limited availability of initiatives and a cluttered KM approach mainly focused on knowledge sharing. The gap is noted in organisational and independent professional knowledge acquisition compared to knowledge availability and sharing. The application of CE knowledge needs expanding as it currently occurs on an ad-hoc basis, mainly limited to government-funded large-scale projects, with a few voluntarily led C&D waste minimisation initiatives. Thus, there is a need for more structured initiatives to systematically create, evaluate and document CE knowledge; it being shown that existing efforts are generally reactive, primarily driven by regulatory compliance requirements associated with certifications or awards. The study's findings also serve as guidelines for policy makers, enabling policy formulation addressing multiple perspectives of KM, design organisations and professionals. Through this, opportunities are afforded for new CE KM initiatives, business opportunities, expanded educational curricula, and professional accreditation body Continuing Professional Development (CPD) programs. The findings also serve Sustainable Development Goals (SDGs) 04: advancing education and SDG 08: green economic growth by contributing to enhancing CE knowledge of design professionals, thereby implementing CE practices and reducing C&D waste.

As with all research, there are a few limitations to this study. The first lies in its focus on the Australian context. However, this is also a key strength in that it allows for the generation of context-specific insights. These findings not only contribute uniquely to the Australian C&D waste sector but also serve as a reference for other countries, supporting comparative investigations and assisting in the identification of potential challenges during the early stages of similar initiatives. Secondly, there can be a response bias based on the experts selected, despite the measures followed to minimise it, like data saturation. Thirdly, this is a cross-sectional study of CE KM initiatives; however, knowledge is a temporal domain that benefits from longitudinal studies to explore CE KM behaviour over time. This study will be expanded in the future to identify potential causes for gaps in CE KM initiatives and propose strategies to overcome them. Future studies can focus on a stakeholder analysis to identify powerful and influential stakeholders to address the limitations of current CE KM initiatives, investigate perspectives of other professionals in the construction industry, and rank the effectiveness of current CE KM initiatives based on larger industry populations.

## 6. REFERENCES

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Waste and Resource Management*, *170*(WR1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Ahlin, E. M. (2019). Semi-structured interviews with expert practitioners: Their validity and significant contribution to translational research. In *SAGE Research Methods Cases Part 2*. SAGE Publications. https://doi.org/10.4135/9781526466037

Barner, L., Herbst, J., Toth-Peter, A., Chu, T., & Pakdel, A. (2024). *48 Scoping study for building the future - Circular economy* (Final Report). Building 4.0 CRC. https://building4pointzero.org/wp-content/uploads/2024/11/48-Scoping-Study-for-Building-the-Future-%E2%80%93-Circular-Economy_Final.pdf

Building Designers Association of Australia (BDAA). (2024). *Who is Building Designers Association of Australia*. https://bdaa.com.au/about-us/

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality and Quantity*, *56*(3), 1391–1412. https://doi.org/10.1007/s11135-021-01182-y

Castleberry, A., & Nolen, A. (2018). Thematic analysis of qualitative research data: Is it as easy as it sounds? *Currents in Pharmacy Teaching and Learning*, *10*(6), 807–815. https://doi.org/10.1016/j.cptl.2018.03.019

Coreo. (2025). *Australia's Waste[d] Opportunity*. https://www.coreo.com.au/construction-materials-benchmarking-report

De Marchi, V., & Di Maria, E. (2020). Achieving circular economy via the adoption of industry 4.0 technologies: A knowledge management perspective. In *Knowledge Management and Organizational Learning* (Vol. 9, pp. 163–178). Springer. https://doi.org/10.1007/978-3-030-43589-9_7

Department of Climate Change, E. the E. and W. (DCCEEW). (2024). *Australia's Circular Economy Framework*. HarperCollins Publishers. https://www.dcceew.gov.au/environment/protection/circular-economy/framework

Ellen MacArthur Foundation. (2016). *What is a circular economy*. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Evans, M. M., Dalkir, K., & Bidian, C. (1993). A holistic view of the knowledge life cycle: The knowledge management cycle (KMC) model. *The Electronic Journal of Knowledge Management*, *12*(2), 85–97. www.ejkm.com

Feldman, J., Seligmann, H., King, S., Flynn, M., Shelley, T., Helwig, A., & Burey, P. (Polly). (2024). Circular economy barriers in Australia: How to translate theory into practice? *Sustainable Production and Consumption*, *45*(2024), 582–597. https://doi.org/10.1016/j.spc.2024.02.001

Gherman, I. E., Lakatos, E. S., Clinci, S. D., Lungu, F., Constandoiu, V. V., Cioca, L. I., & Rada, E. C. (2023). Circularity outlines in the construction and demolition waste management: A literature review. *Recycling*, *8*(5). https://doi.org/10.3390/recycling8050069

Koralage, M. B., Udawatta, N., & Karunasena, G. (2024). A conceptual framework to manage circular economy knowledge in construction projects. *World Construction Symposium*, 27–38. https://doi.org/10.31705/WCS.2024.3

Mahpour, A. (2018). Prioritizing barriers to adopt circular economy in construction and demolition waste management. *Resources, Conservation and Recycling*, *134*, 216–227. https://doi.org/10.1016/j.resconrec.2018.01.026

Nadeetharu, M., Udawatta, N., Karunasena, G., & Costin, G. P. (2026). Unlocking circular economy potential: knowledge requirements of design teams in Australian construction and demolition waste management. *Engineering, Construction and Architectural Management*, 1–16. https://doi.org/10.1108/ECAM-05-2025-0891

NSW Environment Protection Authority. (2022, October 20). *The Waste Hierarchy*. https://www.epa.nsw.gov.au/Your-environment/Recycling-and-reuse/warr-strategy/The-waste-hierarchy

Oluleye, B. I., Chan, D. W. M., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. In *Journal of Cleaner Production* (Vol. 357). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2022.131927

Petrović, E. K., & Thomas, C. A. (2024). Global patterns in construction and demolition Waste (C&DW) research: A bibliometric analysis using VOSviewer. *Sustainability (Switzerland)*, *16*(4). https://doi.org/10.3390/su16041561

Purchase, C. K., Al Zulayq, D. M., O'brien, B. T., Kowalewski, M. J., Berenjian, A., Tarighaleslami, A. H., & Seifan, M. (2022). Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials*, *15*(76). https://doi.org/10.3390/ma15010076

Sakthibala, R. K., Vasanthi, P., Hariharasudhan, C., & Partheeban, P. (2025). A critical review on recycling and reuse of construction and demolition waste materials. In *Cleaner Waste Systems* (Vol. 12). Elsevier B.V. https://doi.org/10.1016/j.clwas.2025.100375

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T., & T. Garofano, N. (2023). Circular economy in the Australian AEC industry: investigation of barriers and enablers. *Building Research and Information*, *51*(1), 56–68. https://doi.org/10.1080/09613218.2022.2099788

Sun, Y., Rameezdeen, R., Chow, C. W. K., & Gao, J. (2025). Information sharing barriers of construction projects toward circular economy: Review and framework development. *Buildings*, *15*(15). https://doi.org/10.3390/buildings15152744

Swarnakar, V., Eltoukhy, A. E. E., Omar, M., Acquaye, A., Alawadi, K., & Khalfan, M. (2025). Unlocking circular economy potential in construction and demolition: an empirical analysis of success factors, failure drivers, benefits, and emerging technologies. *Smart and Sustainable Built Environment*, 1–21. https://doi.org/10.1108/SASBE-01-2025-0044

Taherdoost, H. (2016). Sampling methods in research methodology: How to choose a sampling technique for research. *International Journal of Academic Research in Management*, *5*(2), 18–27.

Circle Economy. (2025). *The circularity gap report 2025*. https://www.circle-economy.com/resources/the-circularity-gap-report-2025

Wuni, I. Y. (2023). Drivers of circular economy adoption in the construction industry: a systematic review and conceptual model. *Building Research and Information*, *51*(7), 816–833. https://doi.org/10.1080/09613218.2023.2211689

Karunarathna, E.H.K.K., Perera, B.L.S.H. and Kalugala, C.S., 2026. Circular economy policy framework for promoting sustainable construction practices in Sri Lankan construction industry: Stakeholder perception. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 377-390. DOI: https://doi.org/10.31705/WCS.2026.28. Available from: https://ciobwcs.com/papers/

# CIRCULAR ECONOMY POLICY FRAMEWORK FOR PROMOTING SUSTAINABLE CONSTRUCTION PRACTICES IN SRI LANKAN CONSTRUCTION INDUSTRY: STAKEHOLDER PERCEPTION

**E.H.K.K. Karunarathna[1], B.L.S.H. Perera[2] and C.S. Kalugala[3]**

## *ABSTRACT*

*Circular economy has emerged as a promising strategy to mitigate environmental impacts and foster sustainable development. Although Sri Lanka has implemented several regulations and policies aimed at promoting sustainability in construction, actual progress remains limited. This research mainly investigates stakeholder perceptions regarding developing a circular economy policy framework tailored specifically for the Sri Lankan construction industry. Furthermore, the study reviews global CE policy frameworks, assessing both top-down and bottom-up approaches, and evaluates the current state of CE practices in Sri Lanka. Moreover, it identifies key barriers influencing the adoption of CE policies within the sector. Adopting a mixed-method approach, the research gathers qualitative data through a comprehensive literature review and semi-structured interviews, while quantitative data is collected from Likert-scale questionnaires distributed to industry stakeholders. Analytical techniques include the Relative Importance Index (RII), thematic analysis, and content analysis. Findings indicate that CE adoption in Sri Lanka is currently minimal, primarily due to the absence of effective regulations and policy enforcement. However, stakeholder responses suggest a moderately positive perception towards the development of a CE policy framework. The study highlights the necessity of introducing mandatory regulations and tailored policies to enable effective CE implementation. Key recommendations include establishing design guidelines for dismantlable and reusable buildings, developing a CE certification system similar to the Green Rating System, promoting multi-use building designs, implementing green financing options, restricting landfill disposal of reusable materials, and offering tax incentives to companies that comply with CE requirements. These context-specific strategies aim to advance sustainable construction practices in Sri Lanka.*

***Keywords:*** *Circular Economy; Construction Industry; Policy Framework; Stakeholder Perception; Sustainable Construction.*

[1] Lecturer, Civil & Construction Department, SCOT campus, SCOT campus, kasunyakarunarathna@gmail.com
[2] PhD Scholar, College of Science, Massey University, New Zealand, samindi3d@gmail.com
[3] Lecturer, Civil & Construction Department, SCOT campus, Sri Lanka, cskalugala@gmail.com

# 1. INTRODUCTION

As the human population expands and income increases, the consumption of material resources is intensified, which leads to more scarcity, elevated costs, and significant potential loss of these resources to future generations' use (Adams et al., 2017). To address the optimization of resource consumption, energy use minimization, and reduction of greenhouse gas emissions caused by construction practices, both government and construction organizations need to seek sustainable solutions as the building stock grows (Illankoon & Vithanage, 2023).

In the current era, the circular economy appears as a promising solution to establish environmental sustainability to create economic and industrial structures that are less resource-consuming and with better waste management (Teerikangas et al., 2021). The CE concept is gaining recognition in the construction industry as an alternative strategy to move away from the basic linear module, which consists of extracting, landfilling & reusing, and developing sustainability in a systematic manner (Rahla et al., 2021). Slowing, narrowing, and closing material loops using circular strategies (like reuse, repair, refurbish, recycle, and recover) has raised interest in the circular economy concept to accommodate minimizing problematic challenges emerging from the construction context (Eberhardt et al., 2020). Transitioning towards circularity will provide the ability to resolve emerging issues in the industry by reducing the use of primary materials, protecting material resources, and reducing the carbon footprint (Adams et al., 2017).

Since built structures vary from other short life-cycle goods produced in a more controlled environment, it is a challenge to transit towards circularity via regular policies due to the shortage of clear regulations to adopt CE goals and corruptions among official policies, regulatory frameworks, and traditional industrial practices on the way towards a circular economy related built environment (Yu et al., 2022). According to Ghufran et al. (2022), developing countries need to initiate further research on the implementation of CE for the construction industry.

According to Fernando et al. (2022), to ensure resource efficiency and enhance sustainability in the Sri Lankan construction industry, both the government and the industry stakeholders need to take the necessary actions in promoting and implementing the 6R concept consist of reduce, reuse, recycle, rethink, refuse, and repair, alongside other circular strategies. Therefore, there appears to be a significant need to understand stakeholder perceptions when developing a practical policy framework that transitions the Sri Lankan construction industry from linear to circular practices to achieve sustainability.

This study is required to bridge the existing gap in identifying the stakeholder perception of an effective policy framework to promote the circular economy in the Sri Lankan construction industry by reviewing the circular economic principles and policy frameworks found globally in the domain of sustainable construction, examining the circular economy practices adopted in the Sri Lankan construction industry to promote a circular economy, determining the key drivers and barriers in adopting the circular economy-related frameworks and investigating the Stakeholder perception of having a CE framework within the Sri Lankan construction industry.

# 2. LITERATURE SURVEY

The circular economy in the construction sector can be identified as a promising concept that will provide long-lasting structures while ensuring the proper value of construction materials (Torgautov et al., 2021). Implementing CE principles to drive toward sustainable development by connecting stakeholders has become a priority in construction projects (Senaratne et al., 2023).

## 2.1 CIRCULAR ECONOMY POLICY FRAMEWORKS PRACTICED IN GLOBAL CONTEXT

The circular economy in the construction sector in the current era can be identified as a promising concept that will provide long-lasting structures while ensuring the proper value of construction materials (Torgautov et al., 2021). According to van Buren et al. (2016) developing a circular related economy will require effective changes in consumer behavior, government policies, and industrial practices as well as the simultaneous renewal of sectors such as energy, logistics, and finance. In 2015, CE was adopted as a guiding principle in the policies of many countries, and they implemented it mainly in two ways. While China is adopting top top-down national policy approach, other countries are implementing a bottom-up policy approach for implementation.

According to (Fitch-Roy et al., 2021) explained that circular economy regulatory policy packages are more recent adaptation form in CE policies, while in earlier CE policy-making contexts China has developed CE policies under the Circular Economy Promotion Law 2008 and since then many national governments have implemented strategic policy measures based upon circular economy principles including South Korea's Framework Act on Resource Circulation 2016. China, as a country, considers the future sustainability of the economy and social welfare, attracted by CE and has made various attempts to implement the CE concept considering micro, meso, and macro levels one at a time (Mohajan, 2021). Furthermore, Mohajan (2021) states that in 2008, the CE policy of China was established through the "Circular Economy Promotion Law", that was to guide China's economic development in ways that save energy, water, and materials and defend the environment, creating a closed loop of all materials in every stage of production, distribution, and consumption process.

Although it originated in Europe, the circular economy (CE) levels of European policymaking, with the European Commission (EC) addressing concerns about high commodity prices through its leading initiative on resource optimization, first implemented through the Roadmap to a Resource Efficient Europe and then developed into the Circular Economy Package of policy measures (De Melo et al., 2022). Furthermore, for the construction phase of the work, the Ellen MacArthur Foundation (EMF) indicates adaptation of technology as an important aspect in the implementation of CE principles (Hentges et al., 2022). While the EU follows bottom-up policies, the government of China (GoC) has provided a clear view of top-down national policies to transition towards CE for a sustainable economic structure, and they have accepted the economic structure since 2002 (Mohajan, 2021).

The circular concept is also implemented in countries such as Denmark, Netherlands, Scotland, Sweden, Japan, and Germany, while in some countries, it has been planning to

be implemented including England, Austria, and Finland (Ogunmakinde, 2019). The comparison of the national CE policy frameworks presented in Denmark, Finland, Norway, and Sweden showed that the policy landscapes of countries are quite similar with unified goals and objectives, and it is prominently featured in their CE policy documents (Zu Castell-Rüdenhausen et al., 2021).

## 2.2 CURRENT ADOPTION STATES OF CIRCULAR ECONOMY PRACTICES IN SRI LANKAN CONSTRUCTION INDUSTRY

Standard CE practices in the construction industry can be listed as carbon embodied materials reduction, lighter materials used in construction, use of cement alternatives like pulverized fuel ash and ground granulated blast furnace slag, re-utilization of mixed used buildings, reuse of wooden materials and façade from demolition waste, adopting modular construction principles by reusing steel from old buildings, and use of solar panels, use of local resourced biomaterials and use of recycled materials such as 100% recycled PVC from perused electric cable covers, pipes, and hoses. Additionally, CE practices extend to building on contaminated land, using greywater systems to recycle water from baths and showers, and constructing new buildings with blocks that can be easily disassembled and reused once the building reaches the end of its life (Torgautov et al., 2021).

Despite the long-term benefits and high environmental degradation of the circular method, most industries in Sri Lanka still accommodate linear or take-make-and-dispose economic models (Aluthge & Mendis, 2023). Furthermore, Fernando et al. (2022) highlighted that due to the newness and unpopularity of the circular economy concept in the Sri Lankan context, the applicability of the principles of circular economy is still in the initial stage. Even though the circular economy model presents a sustainable alternative to the traditional linear economic model, it also consists of barriers, and one of them is the high initial investment required to change towards the circular model from a linear model (Aluthge & Mendis, 2023).

But CE adoption in the Sri Lankan construction context is still in its infant stages, and the 3R principles of reduction, reuse, and recycling act as 3 major processes in successfully contributing to the reduction of global resource supply demand, supporting sustainability in construction projects (Fernando et al., 2022). As the growing trend of obtaining the GREEN SL rating system in Sri Lanka is expected to provide different marketing perspectives, Weerakoon and Thayaparan (2023) suggested introducing mandatory checkpoints within the GREEN SL system as it can enhance the value of rating system as well, and it will also help with the CE implementation.

According to (Wanaguru et al., 2022) material wastage generated in construction is around 25% sand, 20%of lime, 14% cement, 14% bricks, 10% ceramic tiles, 10% timber (formwork), 7% rubble, 7% reinforcement (steel), 6% cement block, 5% of paint, and 3% of asbestos sheets due to in approximately 38% of Sri Lankan construction firms are lack of clear policies on waste management alongside with the lack of recycling contractors in Sri Lanka. According to Fernando et al. (2022), current conditions and practices in the construction sector prove that CE can be used to achieve the industry's sustainability. Current trends along with practices in the construction industry explain that implementing Circular Economy (CE) concepts can help the sector become more sustainable, as CE provides ways to minimize the environmental degradation from construction activities.

### 2.3 BARRIERS TO ADOPTING CIRCULAR ECONOMY RELATED POLICY FRAMEWORKS

Circular Economy as an emerging concept for construction, there are concerns that conceptual confusion might be a barrier to its widespread adoption (O'Leary et al., 2024). Furthermore, the Sri Lankan construction industry faces a key barrier in the lack of awareness about potential CE practices, which are implemented in each stage of a construction project while implementing CE in construction (Ishan et al., 2023). Meanwhile, the lack of supportive regulatory frameworks to encourage CE transition is defined as a critical challenge that accompanies CE policymaking. (Yu et al., 2022) identified that a lack of relevant environmental regulations and laws was driving the rest of the barriers to a CE in this industry.

Lack of interest and knowledge, companies' reluctance due to limited technical and financial resources, incompatible corporate strategies, and a regulatory framework that restricts the development of circular models are the main barriers to the adoption of a circular economy in Sri Lankan industries (Aluthge & Mendis, 2023). Moreover, (Weerakoon & Thayaparan, 2023) state that due to corruption taking place at various levels by the officers, Sri Lanka does not have a proper system to implement the circular policies.

Furthermore, lack of awareness of sustainable concepts like circular economy and willingness to follow the traditional project management practices by construction professionals, regarding only the initial cost of a project despite the life cycle cost of a project, are the barriers in the Sri Lankan context that were highlighted at the (Fernando et al., 2022).

Existing literature consistently emphasizes that overcoming these barriers requires a collaborative and integrated framework involving policymakers, regulatory authorities, professional institutions, and industry stakeholders. Suggested strategies include increasing stakeholder awareness, promoting education and training programs, strengthening technical innovation, developing clear regulatory standards, encouraging partnerships, and introducing effective policy mechanisms to support CE implementation (Ishan et al., 2023; Munaro & Tavares, 2023). Furthermore, Weerakoon and Thayaparan (2023) highlighted the importance of introducing unified guidelines and policy frameworks for CE implementation in Sri Lanka through the collective involvement of academic and industry experts.

## 3. METHODOLOGY

This study accommodates both qualitative and quantitative data through data collection using a questionnaire and semi-structured interviews with practical aspects from industry stakeholders. Using a mixed approach is a thoughtful strategy for exploring complex topics like the circular economy's role in achieving sustainable goals in the construction sector, particularly in Sri Lanka.

### 3.1 QUESTIONNAIRE SURVEY

The questionnaire survey was conducted to examine the level of awareness of the circular economy (CE), relevant sustainability policies, and the key drivers, barriers, and gaps affecting CE adoption in the Sri Lankan construction industry. A simple random sampling

approach was employed to provide each member of the target population, comprising project managers, engineers, architects, quantity surveyors, designers, and other construction professionals with sustainability-related experience, an equal chance of selection. A total of 50 respondents participated in the survey. The sample size was considered adequate based on methodological recommendations for similar construction and CE studies that have successfully utilized sample sizes ranging from 40–60 respondents to obtain reliable findings (Golzar & Noor, 2022; O'Leary et al, 2024; Wanaguru et al, 2022). The questionnaire consisted of three sections covering respondent demographics, awareness and perceptions of CE policies and practices, and views on the drivers, barriers, and gaps related to CE adoption. Data were collected through Google Forms, email, and hard-copy questionnaires and analysed using the Relative Importance Index (RII) analysis. Analysis.

*Table 1: Respondent profile of questionnaire survey*

| Designation | Number of Respondents | % |
|---|---|---|
| Quantity Surveyor | 20 | 40% |
| Engineer | 17 | 34% |
| Architect | 7 | 14% |
| Project Manager | 2 | 4% |
| Sustainability consultant | 2 | 4% |
| Environmental process Operative | 1 | 2% |
| Surveyor | 1 | 2% |

## 3.2 SEMI -STRUCTURED INTERVIEWS

Semi-structured interviews were selected to obtain expert insights on the circular economy. Purposive sampling was used to select participants with specialized knowledge and experience in sustainable construction and construction policy-making. Accordingly, six industry professionals were interviewed using semi-structured questions with predefined inquiries and opportunities for open-ended discussions. The interview sample was justified through data saturation, as no new themes or insights emerged beyond the sixth interview. The interviews were audio-recorded, transcribed, and analysed using thematic analysis to identify recurring themes and perspectives. This process aimed to explore current practices, drivers, barriers, and gaps in the transition towards circularity, as well as perceptions on developing a policy framework for the Sri Lankan construction sector.

*Table 2: Respondent's profile of interviews*

| Code | Profession | Experience |
|---|---|---|
| RE | CIDA Representative (Engineer) | 30 years |
| CS | CIDA Representative (Surveyor) | 20 years |
| SE | Senior Engineer | 18 years |
| SQ | Sustainability consultant (Quantity surveyor) | 8 years |
| EP | Environmental process operative (Green Building Council of Sri Lanka) | 6 years |

| Code | Profession | Experience |
|---|---|---|
| SC | Sustainability consultant (Engineer) | 6 years |

# 4. ANALYSIS AND DISCUSSION

## 4.1 THE FAMILIARITY OF THE CIRCULAR ECONOMY CONCEPT IN THE SRI LANKAN CONSTRUCTION INDUSTRY

The findings indicate that most respondents possess a moderate level of familiarity with the circular economy (CE) concept, suggesting that stakeholders have a basic understanding of its principles and applications. Only a small number of respondents reported being unfamiliar or very unfamiliar with the concept, indicating that awareness of CE exists within the Sri Lankan construction industry to some extent. However, the interview findings provide a deeper perspective, as all interviewees emphasized that stakeholder awareness remains insufficient for the effective implementation of CE practices. As highlighted by RE, "all of the stakeholders should have a clear idea about the circular economy before creating sustainability via circular economy practices in any kind of construction project." This finding suggests that basic awareness alone is inadequate for successful CE adoption. Since the implementation of circular practices requires the active involvement and coordination of key project stakeholders, including clients, consultants, and contractors, a comprehensive understanding of CE principles is essential to ensure informed decision-making and effective collaboration. Therefore, enhancing stakeholder knowledge through awareness programmes, training initiatives, and industry guidance is a critical prerequisite for advancing sustainability through circular economy practices in the Sri Lankan construction sector.

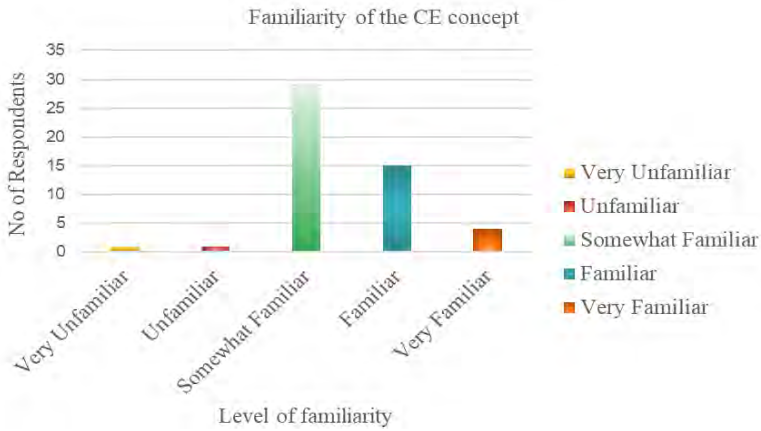



*Figure 1: Familiarity of circular economy concept among Sri Lankan construction stakeholders*

## 4.2 FAMILIARITY OF THE CIRCULAR ECONOMY PRACTICES IN SRI LANKAN CONSTRUCTION CONTEXT

According to Table 3, the CE practices identified by Torgautov et al. (2021) were ranked based on stakeholders' agreement regarding their influence on CE adoption in the Sri Lankan construction sector. Reuse of building materials (PR01) emerged as the most influential practice with the highest RII value of 0.756, reflecting its direct cost-saving benefits. This was followed by the use of eco-friendly concrete alternatives, such as hempcrete, fly ash, and slag-based cement (PR06), with an RII value of 0.696,

highlighting stakeholder recognition of sustainable material solutions. Adoption of modular and prefabricated construction methods (PR13), limiting landfill disposal of construction and demolition waste (PR07), construction on containment land (PR14), and demolition waste harvesting (PR08) jointly ranked third with an RII value of 0.684, although their implementation is constrained by higher investment and technical requirements.

In contrast, the least influential practices were the reduction of carbon-embedded materials, cradle-to-cradle design, and 3D printing with recycled materials. Among these, 3D printing with recycled materials received the lowest RII value (0.480), mainly due to its high technical complexity, substantial initial investment, and limited stakeholder awareness. Similarly, cradle-to-cradle design recorded a relatively low RII value of 0.564, reflecting challenges associated with recycling infrastructure and waste management capabilities within the Sri Lankan construction industry.

*Table 3: RII ranking table for familiarity of circular economy practices in Sri Lankan construction context.*

| Code | Circular practice | RII Value | Rank | Importance level |
|---|---|---|---|---|
| **PR01** | Reuse of Building Materials | 0.756 | 1 | High -Medium |
| **PR02** | Recycling construction waste | 0.640 | 11 | High - Medium |
| **PR03** | Use of eco-friendly materials | 0.680 | 7 | High - Medium |
| **PR04** | Optimizing the supply chain focusing on the just-in-time (JIT) delivery and minimizing surplus materials. | 0.672 | 10 | High-Medium |
| **PR05** | Reduction of the use of carbon-embedded materials. | 0.588 | 16 | Medium(M) |
| **PR06** | Using eco-friendly concrete alternatives such as Hempcrete and low-carbon cement alternatives like fly ash or slag | 0.696 | 2 | High - Medium |
| **PR07** | Limiting the landfill from the disposal of construction and demolition waste. | 0.684 | 3 | High -Medium |
| **PR 08** | Demolition waste harvesting | 0.684 | 3 | High - Medium |
| **PR 09** | Employment of gray water recovered from bath and shower systems. | 0.608 | 12 | High - Medium |
| **PR10** | Cradle-to-Cradle Design (fully recyclable or compostable material usage) | 0.564 | 17 | Medium(M) |
| **PR 11** | 3D printing with recycled materials | 0.480 | 18 | Medium(M) |
| **PR12** | Design structures that can be easily disassembled with materials that can be reused, repaired, or repurposed. | 0.569 | 13 | Medium(M) |
| **PR13** | Adopt modular and pre-fabrication construction methods. | 0.684 | 3 | High-Medium |

| Code | Circular practice | RII Value | Rank | Importance level |
|---|---|---|---|---|
| **PR14** | Construction on containment land. | 0.684 | 3 | High-Medium |
| **PR15** | Reutilizing several small buildings into one large building | 0.676 | 9 | High- Medium |
| **PR16** | Applying new eco-friendly renewable technologies. | 0.680 | 7 | High - Medium |
| **PR17** | Consider up to 6R or 10R strategies in construction instead of the commonly used 3R strategies. | 0.592 | 15 | Medium |
| **PR18** | Integration of green financing options for sustainable projects. | 0.596 | 13 | Medium |

## 4.3 KEY BARRIERS IN ADOPTING THE CIRCULAR ECONOMY-RELATED FRAMEWORKS

Literature review has identified 09 main barriers from the literature from the similar studies done in global context, which can be evaluated considering their identification as a barrier among stakeholders to emphasize their appearance rate in the Sri Lankan construction industry. The RII calculation will provide the ranking in order of agreeability with the key barriers identified by the stakeholders in the Sri Lankan construction industry, highlighting which has the most impact on the current Sri Lankan industry.

*Table 4: RII ranking table for barriers in adopting CE related policy framework in Sri Lanka.*

| Code | Key Barrier | RII value | Rate | Importance level |
|---|---|---|---|---|
| **BR01** | Lack of knowledge and awareness (Ishan et al., 2023). | 0.7875 | 6 | High-Medium |
| **BR02** | High initial cost of implementation (Fernando et al., 2022). | 0.820 | 4 | High |
| **BR03** | Lack of government support (Yu et al., 2022) | 0.804 | 5 | High |
| **BR04** | Absence of clear regulations and policies (Yu et al., 2022) | 0.824 | 3 | High |
| **BR05** | Resistance to change to new technologies (Fernando et al., 2022). | 0.836 | 1 | High |
| **BR06** | Lack of expertise (Aluthge & Mendis, 2023). | 0.832 | 2 | High |
| **BR07** | No guarantee of economic benefits (Fernando et al., 2022). | 0.748 | 8 | High-Medium |
| **BR08** | Limited stakeholder collaboration (Fernando et al., 2022). | 0.728 | 9 | High-Medium |
| **BR09** | Lack of a supportive market to facilitate reuse or recycling (Aluthge & Mendis, 2023). | 0.756 | 7 | High-Medium |

The findings indicate that the barriers to circular economy (CE) adoption in the Sri Lankan construction industry largely align with those identified in both local and international literature, although their relative importance varies within the local context. Previous studies have highlighted inadequate awareness, lack of expertise, weak regulatory support, financial constraints, and resistance to change as key challenges to CE implementation (Fernando et al., 2022; Ishan et al., 2023; Aluthge & Mendis, 2023; O'Leary et al., 2024). The RII analysis revealed that resistance to change towards new technologies is the most significant barrier (RII = 0.836), followed closely by lack of expertise (RII = 0.832), suggesting that behavioural and capacity-related factors have a greater influence on CE adoption than policy-related issues. These findings are consistent with studies from other developing countries, where limited technical knowledge and reluctance to adopt innovative practices hinder the transition to circular construction (Yu et al., 2022; Munaro & Tavares, 2023). In contrast, limited stakeholder collaboration recorded the lowest RII value (0.728), indicating that stakeholders perceive knowledge and skill gaps as more critical barriers. Therefore, alongside developing supportive CE policies and regulatory frameworks, policymakers and industry stakeholders should prioritize awareness programs, professional training, and knowledge-sharing initiatives to enhance industry readiness and facilitate the effective implementation of CE practices in Sri Lanka.

## 4.4 STAKEHOLDER PERCEPTION OF HAVING A CE FRAMEWORK WITHIN THE SRI LANKAN CONSTRUCTION INDUSTRY.

So, according to the questionnaire survey, the importance of adopting circular economy policies to enhance sustainability in the Sri Lankan construction industry is emphasized in the chart below. The majority of the respondents have chosen that it is very important to adopt circular economic principles to enhance sustainability. While 30 respondents chose the very important level, 15 respondents chose that it is important to adopt CE-related policies to enhance sustainability. The least number of respondents have chosen a neutral level of importance towards adopting CE-related policies, while none of them chose an unimportant or very unimportant level.

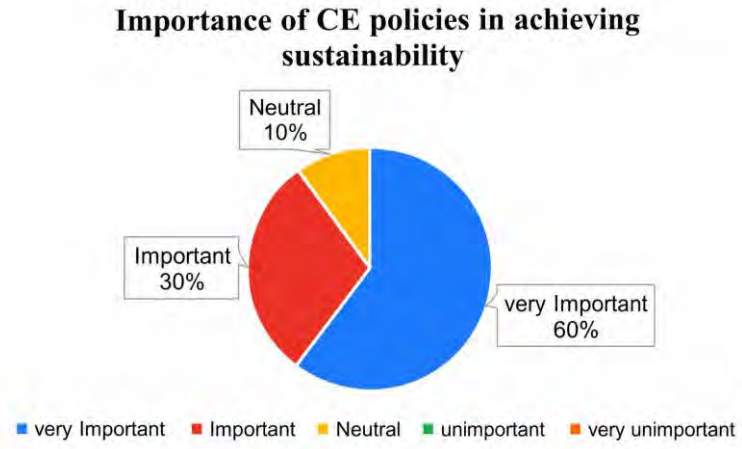



*Figure 2: Importance level in adopting CE-related policies to enhance sustainability*

Then, RII analysis was carried out to prioritize the recommendations found through literature for developing a circular economy policy framework that enhances

sustainability in the construction industry based on their perceived importance according to the respondent's ratings.

*Table 5: RII ranking table for practical recommendations in adopting CE related policy framework in Sri Lanka.*

| Code | Recommendations | RII value | Rate | Importance level |
|---|---|---|---|---|
| **R01** | Provide tax breaks and subsidies for companies that meet CE requirements. | 0.64 | 7 | High-Medium |
| **R02** | Develop green financing schemes specifically for sustainable construction projects. | 0.713 | 4 | High-Medium |
| **R03** | Create guidelines for designing buildings that can be easily dismantled and reused. | 0.76 | 1 | High-Medium |
| **R04** | Fund the development of localized recycling facilities in each district to process construction waste and reduce transport emissions. | 0.7 | 6 | High-Medium |
| **R05** | Promote multi-use building designs (storefront buildings with apartments on the upper floors) | 0.72 | 3 | High-Medium |
| **R06** | Develop a certification system for the circular economy, such as the green rating system in Sri Lanka. | 0.7278 | 2 | High-Medium |
| **R07** | Restrict landfill disposal of recyclable or reusable construction and demolition materials. | 0.713 | 4 | High-Medium |

The findings support existing literature, which emphasizes that overcoming CE implementation barriers requires collaborative efforts among policymakers, regulatory authorities, professional institutions, and industry stakeholders (Ishan et al., 2023; Munaro & Tavares, 2023). Consistent with these recommendations, the most highly rated policy measure by stakeholders was the development of guidelines for designing buildings that can be easily dismantled and reused (RII = 0.760), reflecting the industry's need to reduce demolition and material recovery costs. The second-ranked recommendation was the introduction of a CE-focused certification system similar to the existing Green Building Council Sri Lanka (GBCSL) rating system (RII = 0.728), indicating stakeholder confidence in certification-based approaches to encourage sustainable practices. Promoting multi-use and adaptable building designs was ranked third (RII = 0.720), highlighting the importance of maximizing resource efficiency throughout a building's lifecycle. These findings reinforce the argument of Weerakoon and Thayaparan (2023) that Sri Lanka requires clear CE guidelines and policy frameworks developed through collaboration between industry and academic experts. Therefore, policymakers should prioritize practical design standards, certification mechanisms, and adaptable building approaches to accelerate the transition towards a circular construction industry.

## 4.5 DISCUSSION ON INTERVIEW FINDINGS

Interviews with key stakeholders indicate that while awareness of circular economy concepts in Sri Lanka’s construction industry is at a moderate level, their actual implementation remains minimal. RE and CS consistently highlighted that the industry is still in an early transition phase, largely due to the absence of mandatory regulations,

limited stakeholder support, high initial costs, and insufficient awareness. Circular practices are mainly confined to basic activities such as recycling and the use of locally sourced materials, with only a few large or foreign-funded projects adopting more advanced approaches due to external requirements. Additionally, SQ stated resistance to change from traditional construction methods and reliance on unsustainable waste disposal practices further hinder progress. Overall, majority of respondents stated that, the lack of a strong regulatory framework and enforcement mechanisms has resulted in low adoption of circular practices across the industry.

Despite these challenges, several key drivers for advancing circular economic practices were identified by SE, EP and CS, including regulatory enforcement, resource scarcity, increasing public awareness, and the need for improved sustainability. Stakeholders emphasized that government commitment and policy support are essential to drive widespread adoption, with regulatory bodies expected to lead through clear policies, compliance requirements, and monitoring systems. Additionally, RE and EP mentioned that organizations such as CIDA and GBCSL were recognized for their complementary roles in enforcing regulations and promoting awareness, certifications, and training programs.

Additionally, thematic analysis of the open-ended questions from questionnaire supported by interview responses from RE, CS and EP identified the responsibilities of regulatory bodies such as CIDA and GBCSL. Respondents highlighted that CIDA should focus on policies, regulations, and compliance related to circular economy principles, while GBCSL can promote certification systems, awareness programs, and training initiatives to encourage circular practices. Together, these organizations can also provide financial incentives, technical support, and guidance for the industry's transition towards circularity.

Furthermore, responses emphasized the role of professional bodies such as SLIA, IESL, and IQSSL in developing a suitable policy framework for sustainable construction in Sri Lanka. Respondents noted that these bodies can collaborate with regulatory authorities and industry stakeholders to create awareness through training programs, educational initiatives, industry standards, localized recycling support, and certification systems. They can also contribute significantly to changing stakeholder mindsets towards adopting circular economy practices.

## 5. CONCLUSIONS

This study addresses a key research gap by identifying stakeholder perceptions on developing a circular economy (CE) based policy framework to enhance sustainability in the Sri Lankan construction industry, revealing generally moderately positive attitudes toward such policies. Based on the findings, the study recommends several context-specific measures, including developing design guidelines for buildings that can be easily dismantled and reused to reduce demolition waste, introducing a CE-focused certification system similar to the existing GBCSL green rating scheme, promoting multi-use and adaptable building designs to optimize resource use and extend building life cycles, and establishing green financing mechanisms such as low-interest loans to improve the economic feasibility of circular practices. Additional recommendations through the survey and interview findings include restricting landfill disposal of recyclable construction and demolition waste, funding localized district-level recycling facilities to

reduce transport emissions and strengthen closed-loop systems and providing tax incentives and subsidies for companies complying with CE requirements. Furthermore, future research could be done through detailed case studies in Sri Lanka, comparative analyses with other developing Asian countries, and long-term post-implementation and life cycle assessments, while acknowledging limitations related to sample size and varying levels of stakeholder expertise, which may affect the generalizability of the findings.

# 6. REFERENCES

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Aluthge, C., & Mendis, M. (2023). Feasibility of the circular economy model for Sri Lankan industries: A conceptual approach. *Colombo Economic Journal, 1*(2), 91-116. https://arts.cmb.ac.lk/wp-content/uploads/2024/02/Manuskript-6_28.12.23.pdf

Buren , M., Khan, K. I. A., Ullah, F., Nasir, A. R., Al Alahmadi, A. A., Alzaed, A. N., & Alwetaishi, M. (2022). Circular economy in the construction industry: A step towards sustainable development. *Buildings*, *12*(7), 1004. https://doi.org/10.3390/buildings12071004

De Melo, T. A. C., De Oliveira, M. A., De Sousa, S. R. G., Vieira, R. K., & Amaral, T. S. (2022). Circular economy public policies: A systematic literature review. *Procedia Computer Science*, *204*, 652–662. https://doi.org/10.1016/j.procs.2022.08.079

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2020*).* Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *18*(2), 93–113. https://doi.org/10.1080/17452007.2020.1781588

Fernando, W. M. K. H., Rupasinghe, A. R., & Jayasuriya, D. M. S. (2022, September*). Implementing 6R principles of the circular economy concept in Sri Lankan construction industry.* International Research Conference Articles (KDU IRC). http://ir.kdu.ac.lk/handle/345/6152

Fitch-Roy, O., Benson, D., & Monciardini, D. (2021). All around the world: Assessing optimality in comparative circular economy policy packages. *Journal of Cleaner Production*, *286*, 125493. https://doi.org/10.1016/j.jclepro.2020.125493

Golzar, J., & Noor, S. (2022). Simple random sampling. *International Journal of Education & Language Studies*, *1*(2), 78-82. https://doi.org/10.22034/ijels.2022.162982

Hentges, T. I., Machado da Motta, E. A., Valentin de Lima Fantin, T., Moraes, D., Fretta, M. A., Pinto, M. F., & Spiering Böes, J. (2022). Circular economy in Brazilian construction industry: Current scenario, challenges and opportunities. *Waste Management and Research*, *40*(6), 642–653. https://doi.org/10.1177/0734242X211045014

Illankoon, C., & Vithanage, S. C. (2023). Closing the loop in the construction industry: A systematic literature review on the development of circular economy. *Journal of Building Engineering*, *76*, 107362. https://doi.org/10.1016/j.jobe.2023.107362

Ishan, M., Gamage, I., & Lingasabesan, V. (2023). Highly effective circular economic practices for the life cycle of a construction project. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra, & K.A.T.O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023. (pp. 532–544). CIOB. https://doi.org/10.31705/WCS.2023.44

Mohajan, H. K. (2021). Circular economy in China: Towards the progress. *International Journal of Economics and Business Administration*, *12*(3), 89-96. https://www.researchgate.net/publication/354034877_Circular_Economy_in_China_Towards_the_Progress

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy*:* The construction sector perspective. *Cleaner and Responsible Consumption*, *8*, 100107. https://doi.org/10.1016/j.clrc.2023.100107

O'Leary, M. J., Osmani, M., & Goodier, C. (2024). Circular economy implementation strategies, barriers and enablers for UK rail infrastructure projects. *Resources, Conservation and Recycling Advances*, *21*, 200195. https://doi.org/10.1016/j.rcradv.2023.200195

Ogunmakinde, O. E. (2019). A review of circular economy development models in China, Germany and Japan. *Recycling*, *4*(3), 27. https://doi.org/10.3390/recycling4030027

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings: From theory to practice. *Applied System Innovation*, *4*(2), 26. https://doi.org/10.3390/asi4020026

Senaratne, S., Rodrigo, N., Almeida, L. M. M. C. E., Perera, S., & Jin, X. (2023). Systematic review on stakeholder collaboration for a circular built environment: Current research trends, gaps and future directions. *Resources, Conservation and Recycling Advances*, *19*, 200169. https://doi.org/10.1016/j.rcradv.2023.200169

Teerikangas, S., Onkila, T., Koistinen, K., & Makela, M. (2021). *Research handbook of sustainability agency*. Edward Elgar Publishing. https://www.e-elgar.com/shop/gbp/research-handbook-of-sustainability-agency-9781803922546.html?srsltid=AfmBOopAUbrQCVt6_ZTI-RwXMlvPyB2JYccxmBtwXOHEFDTiDVkYlbDy

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, *11*(11), 501. https://doi.org/10.3390/buildings11110501

van Buren, N., Demmers, M., van der Heijden, R., & Witlox, F. (2016). Towards a circular economy: The role of Dutch logistics industries and governments. *Sustainability*, *8*(7), 647. https://doi.org/10.3390/su8070647

Wanaguru, K., Mallawaarachchi, H., & Vijerathne, D. (2022). Circular economy (CE) based material selection: development of a CE-based '10R' evaluation framework for building construction projects in Sri Lanka. In Y.G. Sandanayake, S. Gunatilake, & K.G.A.S. Waidyasekara (Eds.), *Proceedings of the 10th World Construction Symposium*, 24-26 June 2022. (pp. 208–219). CIOB. https://doi.org/10.31705/WCS.2022.18

Weerakoon, P., & Thayaparan, M. (2023). Analysis of barriers towards implementing circular economy in Sri Lankan built environment. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra, & K.A.T.O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023. (pp. 162–173). CIOB. https://doi.org/10.31705/WCS.2023.14

Yu, Y., Junjan, V., Yazan, D. M., & Iacob, M. E. (2022). A systematic literature review on circular economy implementation in the construction industry: A policy-making perspective. *Resources, Conservation and Recycling*, *183*, 106359. https://doi.org/10.1016/j.resconrec.2022.106359

Zu Castell-Rüdenhausen, M., Wahlström, M., Fruergaard Astrup, T., Jensen, C., Oberender, A., Johansson, P., & Waerner, E. R. (2021). Policies as drivers for circular economy in the construction sector in the Nordics. *Sustainability*, *13*(16), 9350. https://doi.org/10.3390/su13169350

Balapitiya, L.P. and Perera, N.G.R., 2026. Cognitive framework for lighting design: Perceptions from contemporary Sri Lankan architects. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 391-404. DOI: https://doi.org/10.31705/WCS.2026.29. Available from: https://ciobwcs.com/papers/

# COGNITIVE FRAMEWORK FOR LIGHTING DESIGN: PERCEPTIONS FROM CONTEMPORARY SRI LANKAN ARCHITECTS

**L.P. Balapitiya[1] and N.G.R. Perera[2]**

## *ABSTRACT*

*This paper is an investigation of Architects' perceptions of light effects and how they integrate them into the architectural design process. It is an exploration of the position that Architects rarely just illuminate a space; rather, they consciously or subconsciously build a composition using light. Drawing on Skarlatou's cognitive framework of luminous composition, the research examines the stages at which lighting considerations emerge and how cognitive lighting principles are applied. Through qualitative and interpretive inquiry, the study involved five Colombo-based Architects utilising in-depth, semi-structured interviews and retrospective protocol analysis. The data were analysed using thematic coding to identify patterns in the deployment of lighting principles across different design stages. The findings indicate that Skarlatou's principles remain relevant within the Sri Lankan context; however, their application is significantly influenced by the tropical climatic environment. The study reveals a consistent temporal sequence in lighting-related decision-making, beginning with abstract and metaphorical intentions, progressing to strategies of light positioning and distribution, and culminating in the detailed resolution of material–light relationships and technical specifications. The results further demonstrate the central role of experiential knowledge, intuition, and mental visualisation in guiding design decisions, with architects relying less on quantitative simulation tools during the early stages of design. This work contributes by demonstrating the significant influence of the tropical climatic context on the cognitive design process and a framework for understanding lighting design thinking.*

***Keywords:*** *Architectural Cognition; Design Process; Lighting Design; Luminous Composition; Tropical Architecture.*

## 1. INTRODUCTION

The profound connection between architecture, cognition, emotions, and general well-being is now widely recognised and extensively studied [(Abbas et al., 2024; Djebbara et al., 2019, 2021; Eberhard, 2009a, 2009b; Pallasmaa, 2015) as cited in Possati, 2026]. Within an interdisciplinary discourse, lighting emerges as a critical mediator between built form and human experience, influencing affective response, spatial comprehension, and behavioural orientation (Boyce, 2014).

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, premeshbalapitiya@gmail.com
[2] Professor, Department of Architecture, University of Moratuwa, Sri lanka, nareinperera@uom.lk

In architectural practice, considering the meaning of light within the design process leads to more sustainable solutions with an optimisation beyond the widely discussed economic and performance factors like efficiency or visibility (Schielke, 2019). Natural and artificial light jointly shape spatial legibility and emotional tone, often determining how architecture is perceived and experienced over time (Boyce, 2014). Despite this, lighting design is frequently treated as a secondary technical concern rather than an integral component of architectural conception, particularly during early design stages (Steane, 2011). Designers often oscillate between poetic, metaphorical descriptions of light and highly technical specifications relating to illuminance levels, luminance ratios, and material reflectance values. This discontinuity contributes to a misalignment between design intent and built outcome, a concern widely recognised in design cognition literature (Lawson, 2006; Cross, 2001; Schön, 2017).

To address this gap, the present study draws upon Skarlatou's framework of luminous composition (Skarlatou, 2011), which identifies five cognitive principles underpinning how designers perceive and manipulate lighting effects. While this framework provides a valuable foundation for understanding perceptual and compositional aspects of lighting, it does not explicitly account for how these principles unfold temporally during the design process, nor how they may be influenced by differing climatic contexts.

The primary research question guiding this study is:

At what stages do architects consider lighting effects during the design process, and how are Skarlatou's cognitive principles deployed in tropical architectural practice?

To address this question, the study explores two interrelated sub-questions:

1. How are Skarlatou's principles applied across different stages of the design process?
2. In what ways do climate and cultural context influence lighting cognition in tropical architecture?

The primary aim is to decode the cognitive processes through which architects in Sri Lanka develop lighting strategies by mapping Skarlatou's principles onto architectural design stages. In doing so, the study seeks to identify when, how, and why specific lighting principles are activated throughout the design process.

The research contributes to design cognition theory and climate-responsive architectural discourse by presenting a stage-oriented cognitive framework that positions lighting not as a late-stage technical consideration, but as an early-stage generative design driver. Methodologically, the study adopts a qualitative interpretivist approach supported by retrospective protocol analysis (Ericsson & Simon, 1993) and reflective practice theory (Schön, 2017), enabling reconstruction of tacit design cognition from completed architectural works.

# 2. BACKGROUND

## 2.1 LIGHT, PERCEPTION, AND ARCHITECTURAL EXPERIENCE

Light is widely recognised as one of the primary generators of architectural experience. Architectural theorists have consistently argued that spatial experience is inseparable from the qualities of illumination through which space is revealed and interpreted.

According to Pallasmaa (2024), architecture is fundamentally experienced through embodied perception, where light contributes to the multisensory understanding of space. Similarly, Zumthor (2006) identifies atmosphere as a central architectural quality produced through the interaction of light, materiality, temperature, sound, and memory.

Earlier phenomenological work by Norberg-Schulz (1980) similarly positioned light as a critical component of place-making, arguing that environmental character emerges through the interaction between natural phenomena and built form.

Research in environmental psychology further demonstrates that lighting conditions influence behaviour, cognition, and emotional well-being. Flynn (1977) established that variations in brightness, uniformity, and distribution significantly affect users' perceptions of spaciousness, clarity, privacy, and comfort. Subsequent studies have shown that daylight exposure influences productivity, mood, circadian regulation, cognitive performance, and overall health (Figueiro, 2017). Consequently, lighting design operates simultaneously within physiological, psychological, and experiential domains.

## 2.2 DESIGN COGNITION AND ARCHITECTURAL THINKING

The study of design cognition seeks to understand the mental processes through which designers generate, evaluate, and refine design solutions. Unlike analytical problem-solving models, architectural design involves ambiguity, uncertainty, and the simultaneous evolution of problems and solutions.

According to Cross (2001), designers possess unique forms of knowledge that differ from scientific and artistic modes of thinking. Design cognition involves solution-focused reasoning, abductive thinking, and iterative exploration. Rather than discovering predefined answers, designers construct possible futures through continuous reframing of design situations.

Similarly, Schön (2017) conceptualises design as a reflective conversation with materials and situations. Through reflection-in-action, architects continuously test design moves and reinterpret emerging consequences. This framework is particularly relevant to lighting design because many lighting effects cannot be fully predicted through abstract reasoning alone and must be explored through iterative visualisation.

Research by Lawson (2006) further demonstrates that architects move repeatedly between analysis, synthesis, and evaluation. Lighting considerations may emerge at multiple stages of this cycle, influencing spatial organisation, material selection, and environmental performance simultaneously.

Recent studies in design cognition increasingly acknowledge the role of tacit knowledge, intuition, and expertise. Experienced architects frequently rely upon accumulated mental schemas developed through repeated exposure to environmental and spatial conditions. These observations align with Schön's notion of knowing-in-action and suggest that lighting design may depend heavily upon experiential pattern recognition rather than explicit calculation alone (Schön, 2017).

## 2.3 COGNITIVE FRAMEWORKS OF LIGHTING DESIGN

Within lighting research, technical performance has historically dominated scholarly discourse. Metrics such as illuminance, luminance, daylight factors, glare indices, and

energy efficiency have frequently overshadowed investigations into how designers conceptualise luminous experiences.

A significant contribution to addressing this imbalance was made by Skarlatou (2011), whose doctoral research examined designers' perceptions of light effects within architectural practice. Drawing upon interviews and protocol analysis, Skarlatou identified five principles that structure designers' understanding of luminous composition:

1. Direction and position of the light source.
2. Geometry of light distribution.
3. Illumination perspective.
4. Abstraction in luminous composition.
5. Syntactic relationships between surfaces and light sources.

(Skarlatou, 2011)

Importantly, the framework demonstrated that designers frequently think in perceptual rather than quantitative terms. This insight aligns with broader theories of architectural representation, which suggest that design concepts often emerge as abstract mental constructs before becoming materially defined. However, Skarlatou's framework leaves several questions unresolved. Most notably, it does not explain how these principles are temporally deployed throughout the design process or how environmental conditions influence their prioritisation.

# 3. METHOD

## 3.1 RESEARCH PARADIGM AND METHODOLOGICAL APPROACH

This study adopts a qualitative interpretivist research paradigm to investigate how architects conceptualise and integrate lighting within the architectural design process. The interpretivist approach is particularly appropriate because architectural design is fundamentally a cognitive and experiential activity in which knowledge is constructed through perception, reflection, and professional practice (Creswell & Poth, 2018; Denzin et al., 2023).

Given that many design decisions occur internally and are not directly observable, a qualitative methodology was considered most suitable for accessing the tacit knowledge, experiential reasoning, and reflective judgement that characterise professional design practice (Cross, 2006; Schön, 2017).

To investigate these processes, the study employs a multiple-case study strategy. Case study research enables the exploration of complex phenomena within real-world contexts and is particularly valuable when examining professional decision-making processes (Yin, 2018). By analysing multiple architectural practices, the research identifies recurring patterns while also recognising individual variations in design thinking.

A principal methodological tool adopted in this research is Retrospective Protocol Analysis (RPA) (Ericsson & Simon, 1993). The use of retrospective protocols was especially appropriate because the research sought to understand design decisions embedded within completed architectural projects. Asking architects to reflect upon built

works enabled access to decision-making processes that evolved across multiple stages of design development and could not be observed directly in real time.

## 3.2 CASE SELECTION AND SAMPLING STRATEGY

A multiple-case study approach was adopted to capture a diverse range of professional experiences while maintaining a consistent architectural context. The study focused on residential and boutique-scale projects, as these project types typically allow architects greater control over experiential and lighting-related design decisions than larger commercial developments.

Participants were selected using purposive expert sampling. Purposive sampling is particularly appropriate when the objective is to obtain rich, information-intensive data from individuals possessing specialised knowledge and extensive professional experience (Creswell & Poth, 2018). The selection process, therefore, prioritised Architects recognised for their design quality and demonstrated sensitivity to lighting and spatial experience.

Five architects based in Colombo were selected. The sample intentionally represented different generations of professional practice to explore potential differences in design thinking associated with experience and technological change. Although the sample size is relatively small, it is consistent with qualitative design cognition studies that prioritise depth of understanding over statistical representation.

## 3.3 DATA COLLECTION PROCEDURES

Data collection was undertaken through in-depth semi-structured interviews supported by project documentation reviews. Interviews were organised according to the major stages of the architectural design process, enabling participants to reconstruct their decision-making chronologically from project inception to post-occupancy evaluation. This stage-based structure was specifically designed to investigate the temporal deployment of lighting principles throughout the design process.

Each interview lasted between 90 and 120 minutes and was audio-recorded with participant consent. Discussions focused on completed projects selected by the architects themselves, allowing participants to draw upon detailed memories of design decisions and project development. To enhance the richness and reliability of the data, verbal accounts were cross-referenced against project documentation, including sketches, drawings, photographs, renderings, and construction details. Such triangulation is recommended in qualitative research to strengthen interpretive validity and contextual understanding (Denzin et al., 2023).

## 3.4 DATA ANALYSIS

All interviews were transcribed verbatim and imported into NVivo qualitative data analysis software for systematic coding and analysis. A hybrid thematic analysis approach was adopted, combining deductive and inductive coding procedures.

The deductive coding framework was derived directly from Skarlatou's principles (P) of luminous composition:

P1: Direction and position of the light source.

P2: Geometry of light distribution.

P3: Illumination perspective.

P4: Abstraction in luminous composition.

P5: Syntactic relationships between surfaces and light sources.

These predefined categories provided the analytical structure through which existing theory could be examined within the Sri Lankan context.

Simultaneously, inductive coding was employed to identify themes that emerged directly from participants' accounts without being constrained by the original framework.

Through iterative analysis, two significant tropical-specific themes (T) were identified:

T1: Light Reduction and Solar Moderation.

T2: Heat–Light Decoupling Strategies.

Following initial coding, pattern coding was conducted to identify relationships between themes, design stages, and cognitive processes. The resulting data were organised into a stage–principle matrix, enabling systematic examination of how different lighting principles were deployed throughout the architectural design process.

# 4. RESULTS

The cross-case analysis of the five architectural practices revealed consistent patterns in the ways lighting principles were conceptualised, prioritised, and translated into built form. Analysis of interview transcripts, project documentation, and visual material demonstrated that lighting considerations emerged throughout the design process rather than being confined to technical detailing stages. While all five participants exhibited evidence of Skarlatou's principles, their deployment followed a discernible sequence that moved from abstract conceptual intentions towards increasingly spatial, material, and technical resolutions.

The findings are organised according to the principal themes identified through thematic analysis: (1) abstraction and metaphorical frameworks, (2) direction, position, and geometry of distribution, and (3) illumination perspective, and syntactic relationship of surface and source.

## 4.1 PRINCIPLE 4: ABSTRACTION AND METAPHORICAL FRAMEWORKS

The analysis revealed that abstraction constituted the primary cognitive entry point through which architects conceptualised lighting. Across all five cases, lighting decisions were initially framed not through quantitative criteria but through experiential aspirations, emotional narratives, and metaphorical constructs. Within the coding structure, P4 generated the highest concentration of references during the conceptual design stage, indicating its foundational role in lighting-related decision-making.

Rather than beginning with considerations of illuminance levels, fixture types, or daylight performance, participants consistently described desired atmospheres, emotions, and sensory experiences. These abstract intentions subsequently guided more concrete spatial and technical decisions.

Architect A repeatedly referred to the concept of a "womb" or "cave" as the governing metaphor for a residential project. The desired atmosphere was characterised by enclosure, mystery, refuge, and intimacy. Consequently, lighting strategies focused on

controlling and suppressing illumination rather than maximising it. Darkness was treated as an active design material, with selective openings and carefully controlled light penetration reinforcing the intended spatial experience.

Similarly, Architect B described aspirations of "cosiness" and "drama," employing lighting contrasts to create emotionally charged interior environments. Rather than seeking uniformly illuminated spaces, the architect intentionally developed zones of brightness and shadow to establish visual hierarchy and atmospheric depth.

Architect C framed lighting objectives through concepts of "silence," "stillness," and "monastic calm." In this case, shadow was not regarded as a deficiency of light but as a critical architectural device. Light reduction strategies were employed to create cool, contemplative environments that encouraged reflection and sensory awareness.

Architect D drew inspiration from culturally embedded experiences, particularly the visual qualities associated with the annual Perahera (Buddhist procession). Warm focal illumination, reflective surfaces, and controlled highlights were employed to recreate qualities of festivity, ceremony, and collective memory within contemporary architectural settings.

Across all cases, metaphors functioned as more than descriptive language. They operated as cognitive frameworks that informed decisions regarding orientation, aperture placement, material selection, and lighting distribution. These findings suggest that abstraction serves as a generative mechanism through which lighting intentions are translated into architectural form.

## 4.2 PRINCIPLES 1 & 2: DIRECTION, POSITION, AND GEOMETRY OF DISTRIBUTION

Following the establishment of conceptual intentions, architects consistently shifted their attention towards the spatial organisation of light. This phase corresponded closely with P1 and P2, involving decisions concerning the positioning of light sources and the distribution of illumination within space.

A recurring pattern observed across all projects was the deliberate avoidance of direct exposure to intense tropical sunlight. Unlike temperate-climate approaches that often prioritise maximising direct daylight penetration, participants consistently emphasised the importance of filtering, redirecting, and moderating incoming light.

Three primary positioning strategies were identified;

First, high-level light admission was frequently employed through clerestory openings, roof monitors, and elevated apertures. These devices enabled daylight to wash walls and ceilings indirectly while reducing visual discomfort caused by direct solar exposure.

Second, peripheral positioning strategies were commonly observed. Courtyards, verandas, transitional zones, and buffer spaces acted as intermediate layers that moderated daylight before it entered occupied spaces. Rather than functioning solely as spatial organisers, these elements served as environmental filters that softened light intensity and improved visual comfort.

Third, reflected-light strategies were consistently employed. Participants described the use of ceilings, walls, water surfaces, and reflective planes to redistribute daylight

indirectly throughout interiors. Such approaches reduced glare while maintaining visual brightness.

The geometry of light distribution emerged as an equally significant concern. All participants rejected the notion of uniformly illuminated environments. Instead, variation, contrast, and gradation were regarded as essential qualities of successful architectural lighting.

Architect B intentionally introduced areas of reduced brightness, arguing that occupants appreciate light more fully when it is experienced in contrast with shadow. This perspective reflects a broader preference for spatial diversity rather than visual uniformity.

Architect C frequently employed timber screens, perforated walls, concrete fins, and lattice elements to fragment incoming sunlight. These devices generated textured and dynamic lighting conditions characterised by shifting patterns of illumination. Participants often compared these effects to sunlight filtered through vegetation, indicating the importance of natural precedents in informing design decisions.

The findings demonstrate that distribution strategies in tropical architecture are primarily concerned with moderation rather than maximisation. Light is actively shaped, filtered, and transformed before reaching occupied spaces.

### 4.3 PRINCIPLES 3 & 5: ILLUMINATION PERSPECTIVE, AND SYNTACTIC RELATIONSHIP OF SURFACE AND SOURCE

The final group of findings relates to P3 and P5, which became increasingly prominent during design development and technical resolution stages.

P3 was frequently employed as a means of guiding movement, directing attention, and structuring spatial sequences. Participants consistently described lighting as a tool for choreographing user experience rather than merely providing visibility.

Several architects intentionally utilised contrasts between darker transitional spaces and brighter destination spaces to create anticipation and visual progression. Corridors, thresholds, and circulation routes were often maintained at lower illumination levels, while key spaces received concentrated daylight or artificial lighting emphasis. This strategy generated a sense of movement and discovery, encouraging users to navigate spaces according to carefully orchestrated visual cues.

The relationship between lighting and materiality emerged as another significant theme. Participants consistently emphasised that lighting effects could not be considered independently from the surfaces upon which they were projected. Material properties were therefore treated as integral components of luminous composition.

Architect C highlighted how natural weathering processes alter the interaction between light and material over time. Rough concrete, exposed brick, and untreated timber were selected not only for their tactile qualities but also for their capacity to reveal changing patterns of illumination and ageing. Light was understood as a mechanism through which material transformation becomes visible.

Similarly, Architect A described the strategic use of textured rubble walls to capture and diffuse light while simultaneously employing dark ceiling treatments to absorb

illumination. The resulting contrast reinforced the project's overarching conceptual framework of enclosure and refuge.

Across all cases, decisions regarding material selection were closely intertwined with lighting intentions. Surface texture, colour, reflectance, and ageing characteristics were repeatedly identified as critical factors influencing the perception of light within architectural space.

Collectively, these findings indicate that P3 and P5 are typically resolved during later design stages when conceptual aspirations are translated into detailed material and technical strategies. Nevertheless, their effectiveness remains dependent upon the abstract intentions and spatial decisions established earlier in the design process.

### 4.4 EMERGENCE OF TROPICAL-SPECIFIC PRINCIPLES (T1 AND T2)

The findings extend existing theories of design cognition by suggesting that environmental conditions influence not only architectural outcomes but also the underlying cognitive processes that generate them.

Two climate-specific principles emerged consistently across the data:

T1: Light Reduction and Solar Moderation

Unlike temperate frameworks that prioritise daylight acquisition, tropical lighting cognition prioritises the reduction, filtration, and modulation of excessive solar intensity. Architects repeatedly described strategies for “breaking,” “softening,” or “filtering” sunlight before it entered occupied spaces.

T2: Thermal-Luminous Decoupling

Participants consistently attempted to separate the beneficial qualities of daylight from its undesirable thermal effects. Courtyards, screened openings, indirect daylighting systems, reflective surfaces, and shaded transitional spaces were employed to maximise visual comfort while minimising heat gain.

Together, these principles suggest that tropical lighting design involves a preliminary stage of environmental moderation that precedes conventional compositional concerns. Consequently, climate-specific adaptations appear necessary when applying Skarlatou’s framework within tropical contexts.

## 5. DISCUSSION

### 5.1 THE TEMPORAL SEQUENCE OF LIGHTING DESIGN COGNITION

The principal theoretical contribution of this study lies in extending Skarlatou’s framework beyond a descriptive taxonomy of lighting principles to a temporally structured model of lighting cognition. While Skarlatou identified the perceptual and compositional principles through which designers understand lighting effects, the present study demonstrates that these principles are not deployed simultaneously. Instead, they emerge sequentially throughout the architectural design process. (see Table 1)

The cross-case analysis revealed a remarkably consistent progression across all participants, irrespective of age, professional experience, or stylistic orientation. Lighting design thinking began with abstraction and metaphorical framing (P4), progressed towards decisions concerning the positioning and distribution of light (P1 and P2), and

culminated in considerations of illumination perspective and material interaction (P3 and P5) (see Table 1). This sequence suggests that lighting cognition evolves from conceptual intentions towards increasingly spatial, material, and technical forms of resolution. This finding supports broader theories of design cognition (Dorst & Cross, 2001; Lawson, 2006).

*Table 1: Stage-principal matrix with tropical adaptations*

| Typical Design Stage | Primary Principles | Key Questions | Tropical Strategies |
|---|---|---|---|
| Concept | P4: Abstraction<br>T1: Light Reduction | What is the feeling or atmosphere I want to create?<br>How do I manage excess light, or where does the light come from? | Define metaphor<br>Identify "breaking" strategy.<br>Reference vernacular wisdom |
| Schematic | T1: Light Reduction<br>P1: Position<br>P2: Distribution<br>T2: Heat-Light | How do you filter light before entry?<br>Where does light come from?<br>How does it spread?<br>How to separate light from heat? | Eaves/overhangs depth<br>Courtyard placement<br>Screen/buffer zones<br>Vertical vs. horizontal entry<br>Ventilation integration |
| Development | P2: Distribution<br>P3: Perspective<br>P5: Surface-Source | How do you refine the spread?<br>How does light guide movement?<br>Which materials for interaction? | Patching, diffusing, or dappled effects<br>Brightness contrast for wayfinding<br>Material sampling for texture syntax<br>Weathering consideration and ageing |
| Detailing | P1: Position<br>P5: Surface-Source | Will the exact fixture locations correlate with the abstraction?<br>What are the technical specifications?<br>Material-light details experimentation? | Hidden source detailing<br>Colour temperature (2700-3000K) (feeling)<br>Colour temperature (5000k-6500K) (Task)<br>Recessing/reflection details<br>CRI value is key in choosing luminaries. |
| Post-occupancy | All principles | What worked and what didn't?<br>What to do differently next time? | Build an experiential library (archive).<br>Document lessons learned.<br>Refine mental imagery. |

*(Source – Author)*

The results also reinforce Schön's (2017) conception of reflective practice. Architects did not begin by calculating illuminance levels or selecting luminaires; rather, they first imagined desired experiences and atmospheres before progressively translating these intentions into architectural form.

The proposed temporal model (see Figure 1), therefore, transforms Skarlatou's framework from a static set of principles into a dynamic process-oriented theory capable of explaining how lighting-related decisions emerge and evolve throughout architectural design.

| | |
|---|---|
| Concept Stage | This stage is universally dominated by *P4* and the emergent *T1*. Architects set lighting goals metaphorically before any spatial drawing occurs |
| Schematic Stage | The focus systematically shifts to *P1* and *P2*.<br>Abstract goals are used to inform the physical placement of apertures and the general spread of light. |
| Design Development | The process involves *P3* for choreographing user movement.<br>It also involves *P5* as they integrate specific material textures. |
| Detailing | *All principles* are translated into precise, quantifiable technical specifications. |

*Figure 1: Temporal sequence of lighting design cognition (Source – Author)*

## 5.2 CLIMATE AS A COGNITIVE MEDIATOR: BEYOND TEMPERATE MODELS OF LIGHTING DESIGN

A second and arguably more significant contribution of the study concerns the role of climate in shaping design cognition. Although Skarlatou's framework provides a valuable account of how architects conceptualise lighting effects, it was developed within a temperate context where daylight is frequently regarded as a scarce resource requiring maximisation.

The findings demonstrate that this assumption does not hold within the tropical conditions of Sri Lanka. Across all cases, architects consistently approached light not as a scarce commodity to be captured but as an abundant environmental force requiring moderation, filtration, and control. The predominance of terms associated with reduction, filtering, shielding, and breaking light suggests a fundamentally different cognitive orientation towards daylight. (see Figure 2)

| | |
|---|---|
| Tropical Principle T1 | Light Reduction (Breaking Light). Before tropical architects ask, "Where should light come from?" (P1), they explicitly ask, "How do we reduce or filter this overwhelming light?" |
| Tropical Principle T2 | Thermally Decoupled Illumination. The research highlighted the phenomenon of "light-heat inseparability." Because every additional lux of direct natural light brings thermal energy, distribution strategies must simultaneously manage heat. |

*Figure 2: Tropical-specific findings: the emergence of light control (Source – Author)*

This observation aligns with broader literature and traditional tropical design strategies - including verandas, courtyards, screens, deep overhangs, and vegetation buffers - that are fundamentally concerned with transforming intense sunlight into visually comfortable and thermally manageable conditions.

The study, therefore, proposes that climate functions as a cognitive mediator. (see Figure 2) Rather than merely influencing the physical performance of buildings, climatic conditions shape the very way architects conceptualise design problems and formulate solutions.

### 5.3 EXPERIENTIAL KNOWLEDGE, MENTAL VISUALISATION, AND REFLECTIVE PRACTICE

One unexpected finding concerns the relatively limited reliance on quantitative simulation tools during the early stages of design. Four of the five participating architects reported that lighting decisions were primarily guided by mental visualisation, accumulated experience, and intuitive judgement rather than by lux calculations or daylight simulation software.

This finding provides strong empirical support for Schön's (2017) concept of knowing-in-action. The senior architects in this study demonstrated particularly strong reliance on experiential reasoning. Rather than modelling lighting performance digitally at the conceptual stage, they described mentally simulating spatial experiences based on previously encountered projects, environmental observations, and accumulated design knowledge.

The predictability of the tropical climate partially explains this phenomenon. Unlike temperate regions characterised by significant seasonal variation, Sri Lanka experiences relatively stable solar conditions throughout the year. As a result, architects can draw upon a consistent experiential archive of environmental observations that remains transferable across projects.

Importantly, the findings do not suggest that digital tools are irrelevant. Rather, simulation technologies appear to function primarily as validation instruments during later stages of design development rather than as generators of initial design ideas. This distinction highlights the continued importance of intuition, imagination, and experiential knowledge within contemporary architectural practice despite increasing technological sophistication.

### 5.4 GENERATIONAL SHIFTS AND THE PERSISTENCE OF VERNACULAR KNOWLEDGE

The study also identified notable generational differences in cognitive approaches to lighting design. Senior practitioners tended to operate primarily as visual thinkers and verbal conceptualisers, relying heavily on metaphorical reasoning, memory, and intuitive judgement. In contrast, younger practitioners frequently utilised digital modelling platforms and real-time rendering software as extensions of their design thinking processes. However, the findings indicate that digital technologies supplement rather than replace conceptual reasoning. Even among younger practitioners, atmospheric intentions and experiential goals continued to precede technical modelling activities.

Equally significant is the persistence of vernacular environmental knowledge. Participants rarely reproduced traditional architectural forms directly. Instead, they abstracted underlying environmental principles and reinterpreted them through contemporary design solutions. Traditional courtyards evolved into deep light wells, lattice screens became timber trellises, and shaded transitional spaces were reconfigured through modern materials and construction techniques. The findings suggest that vernacular precedents remain influential not because of their aesthetic characteristics but because they embody generations of environmental adaptation and climatic intelligence.

## 6. CONCLUSIONS

This study demonstrates that Skarlatou's five principles of luminous composition provide a robust cognitive framework for understanding how architects conceptualise and deploy lighting within architectural design practice. However, the findings also indicate that the application of this framework is not universal in its original form. Rather, it is fundamentally shaped by climatic context, which influences both the cognitive entry points and the sequential development of lighting decisions.

A key theoretical contribution of this research is the transformation of Skarlatou's static typology into a dynamic, process-oriented model of lighting cognition. The identification of a consistent temporal deployment sequence - moving from abstraction (P4), through spatial organisation (P1 and P2), and culminating in material and syntactic resolution (P3 and P5) - reframes lighting not as a set of isolated perceptual categories, but as an evolving cognitive process embedded within architectural design thinking. (see Table 1)

In addition, the study identifies two climate-specific extensions to the original framework: Light Reduction (T1) and Thermal-Luminous Decoupling (T2). These findings demonstrate that temperate-based lighting theories cannot be directly transposed onto tropical contexts without conceptual adaptation. The resulting stage-principle matrix (see Table 1) therefore functions not only as an analytical framework but also as a practical design instrument for integrating lighting as a generative design force rather than a late-stage technical concern.

From a pedagogical perspective, the study suggests the need for a reorientation in the teaching of architectural lighting within tropical regions. Instead of privileging primarily quantitative approaches to daylight analysis, architectural education should place greater emphasis on experiential learning, environmental observation, and physical modelling. Developing students' capacity for mental visualisation and their ability to abstract design principles from vernacular and climatic precedents can strengthen their ability to respond effectively to complex environmental conditions. Furthermore, cultivating an awareness of how expert designers structure and translate lighting intentions across design stages may contribute to a more reflective and cognitively informed design pedagogy.

Overall, this research contributes to architectural knowledge by linking climate, cognition, and design process within a unified framework. It demonstrates that lighting design is not solely a matter of technical optimisation or aesthetic composition, but a situated cognitive activity shaped by environmental conditions, experiential knowledge, and culturally embedded design practices.

## 7. ACKNOWLEDGEMENT

The authors extend sincere gratitude to the five Colombo-based architects who participated in this study and generously shared their time and professional insights during the in-depth interviews. Their reflective contributions were essential to the empirical foundation of this research.

## 8. REFERENCES

Boyce, P. R. (2014). *Human factors in lighting* (3rd ed.). CRC Press. https://doi.org/10.1201/b16707

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). SAGE Publications.

Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. In C. M. Eastman, W. M. McCracken, & W. C. Newstetter (Eds.), Design knowing and learning: Cognition in design education (pp. 79–103). Elsevier. https://doi.org/10.1016/B978-008043868-9/50005-X

Cross, N. (2006). *Designerly ways of knowing*. Springer.

Denzin, N. K., Lincoln, Y. S., Giardina, M. D., & Cannella, G. S. (Eds.). (2023). *The SAGE handbook of qualitative research* (6th ed.). SAGE Publications.

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/s0142-694x(01)00009-6

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis: Verbal reports as data*. The MIT Press. https://doi.org/10.7551/mitpress/5657.001.0001

Figueiro, M. G. (2017). Disruption of circadian rhythms by light during day and night. *Current Sleep Medicine Reports*, *3*(2), 76–84. https://doi.org/10.1007/s40675-017-0069-0

Flynn, J. E. (1977). A study of subjective responses to low-energy and nonuniform lighting systems. *Lighting Design & Application*, *7*(2), 6–15. https://doi.org/10.1177/036063257700700204

Lawson, B. (2006). *How designers think: The design process demystified* (4th ed.). Routledge. https://doi.org/10.4324/9780080454979

Norberg-Schulz, C. (1980). *Genius loci: Towards a phenomenology of architecture*. Rizzoli.

Pallasmaa, J. (2024). *The eyes of the skin: Architecture and the senses* (4th ed.). John Wiley & Sons.

Possati, L. M. (2026). *How light reshapes the mind: An active inference framework for the cognitive and emotional effects of indoor lighting* (arXiv:2605.01290). arXiv. https://arxiv.org/abs/2605.01290

Schielke, T. (2019). The language of lighting: Applying semiotics in the evaluation of lighting design. *LEUKOS*, *15*(2–3), 227–248. https://doi.org/10.1080/15502724.2018.1518715

Schön, D. A. (2017). *The reflective practitioner: How professionals think in action*. Routledge. https://doi.org/10.4324/9781315237473

Skarlatou, A.-Z. (2011). *Light effects in the design process: A theoretical investigation of designers' perceptions of light effects and an empirical study of how they use them in architectural lighting design* [Doctoral dissertation, University College London]. UCL Discovery. https://discovery.ucl.ac.uk/id/eprint/1211391/

Steane, M. A. (2011). *The architecture of light: Recent approaches to designing with natural light*. Routledge. https://doi.org/10.4324/9780203715505

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE Publications.

Zumthor, P. (2006). *Atmospheres: Architectural environments, surrounding objects*. Birkhäuser.

Rathuge, L.R., Hewage, I.S., Mendis, M.S. and Halwatura, R. U., 2026. Comparative field performance of organic and commercial preservatives against blue stain fungi in pinewood. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 405-418. DOI: https://doi.org/10.31705/WCS.2026.30. Available from: https://ciobwcs.com/papers/

# COMPARATIVE FIELD PERFORMANCE OF ORGANIC AND COMMERCIAL PRESERVATIVES AGAINST BLUE STAIN FUNGI IN PINEWOOD

**L.R. Rathuge[1], I.S. Hewage[2], M.S. Mendis[3] and R.U. Halwatura[4]**

## *ABSTRACT*

*The occurrence of blue stain fungi is one of the severe problems in the pinewood industry. This significantly reduces the market value of pinewood due to visible discoloration. This study evaluated the field performance of two plant extract based organic preservatives against boron-based inorganic preservatives for reducing the blue stain fungi development in pinewood. The organic preservatives are locally developed final solution with mud and final solution without mud and inorganic preservatives are commercially available Anti-blue and Anti-boron. The study used freshly cut pinewood specimens exposed for six months at three geographical regions in Sri Lanka i.e. (i) Bandarawela, (ii) Ratnapura, and (iii) Colombo. The effects of location, exposure condition, treatment type, and treatment timing were considered. Specimens were placed under sheltered and non-sheltered conditions, while preservative treatment was applied as early treatment and delayed treatment after cutting. Visible blue stain affected surface area was quantified using an image processing method applied to photographs taken of wood specimens. Untreated non-sheltered specimens in Bandarawela showed the highest visible blue stain development and were therefore used for detailed preservative performance comparison. Sheltered storage reduced visible discoloration compared with non-sheltered exposure. All preservative treatments reduced visible blue stain affected surface area compared with untreated specimens. Final solution with mud performed comparably with the tested commercial preservatives, while final solution without mud was effective but less protective. The findings indicate that early preservative treatment combined with sheltered storage is a practical approach for reducing visible blue stain development in freshly cut pinewood.*

***Keywords:*** *Blue Stain Fungi; Organic Preservatives; Pinewood; Sustainable Materials; Visible Discoloration.*

[1] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, rathugelr.19@uom.lk
[2] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, iresharesearch1@gmail.com
[3] Senior Lecturer, Department of Design Studies, NSBM Green University, Sri Lanka, malsha.m@nsbm.ac.lk
[4] Senior Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangika@uom.lk

# 1. INTRODUCTION

Timber has remained an important construction and industrial material for centuries because of its renewable nature, workability, and suitable for a wide range of structural and non-structural applications. Among commonly used softwoods, pinewood is used in furniture, interior finishing, packaging, temporary works, and other light construction applications because it is workable, relatively lightweight, and commercially accessible. In Sri Lanka, pinewood is also used in timber related applications where efficient post-harvest handling and storage are important.

Freshly cut pinewood is vulnerable to discoloration when environmental conditions favour fungal development. Blue stain fungi are a major cause of such discoloration in pinewood and other softwoods. They colonise sapwood and produce visible blue, grey, or dark staining on the wood (Jankowiak et al., 2021). Although blue stain does not always cause severe structural strength loss, it can reduce the visual quality and market acceptance of timber products (Humar et al., 2008). This is particularly important for appearance sensitive applications, where surface colour and visual uniformity affect product value. Therefore, controlling blue stain development is important for maintaining the commercial value of pinewood between felling, treatment, storage, and processing.

In practice, blue stain development can be reduced through preservative treatment and improved storage conditions. Fungal development on wood is strongly influenced by environmental conditions such as moisture availability, temperature, relative humidity, and drying periods (Hukka & Viitanen, 1999; Ringman et al., 2019). Inorganic commercial preservatives are commonly used to control staining and bio deterioration in timber. However, plant-based organic preservatives have drawn the attention because of concerns associated with some conventional wood protection chemicals. These plant-based preservatives have many natural compounds show antifungal or wood protective potential (Broda, 2020; Singh & Singh, 2012).

Two locally developed organic preservatives in Sri Lanka, Final Solution with Mud (FSWM) and Final Solution Without Mud (FSWOM), have shown potential for timber treatment applications and require further field-based evaluation and comparison against the currently used preservatives in the industry. Previous work has examined preservative uptake of plant extract based organic formulations using dipping diffusion methods, supporting the practical relevance of such treatment approaches (Hewage et al., 2024).

Although previous studies have examined wood preservatives and blue stain fungi separately, limited field-based evidence is available on the comparative performance of locally developed organic preservatives and commercial preservatives under Sri Lankan exposure conditions. The combined influence of geographical location, exposure condition, and treatment timing on blue stain development in freshly cut pinewood remains insufficiently studied.

Therefore, this study evaluates the field performance of FSWM and FSWOM in comparison with two commercially available preservatives, Anti-blue and Anti-boron. The study considers three different Sri Lankan geographical regions, sheltered and non-sheltered exposure conditions, and early and delayed treatment application. The findings are expected to support practical decision making on pinewood preservation and storage.

# 2. LITERATURE REVIEW

## 2.1 BLUE STAIN FUNGI IN PINEWOOD

Blue stain fungi are staining fungi that colonise wood, particularly the sapwood of softwoods, and produce blue, grey, or dark discoloration. In pinewood, staining is commonly associated with freshly felled timber, where exposed sapwood surfaces and high moisture levels provide favourable conditions for fungal colonisation (Jankowiak et al., 2021). Therefore the risk of visible staining is closely connected with post felling handling, storage, and treatment practices.

The major concern associated with blue stain is the deterioration of visual quality rather than direct structural failure. Humar et al. (2008) reported that blue stained wood may retain many of its basic material properties, but its appearance and commercial acceptability are reduced. This finding is important because blue stain becomes a practical quality problem even when the wood remains mechanically usable. For furniture, interior finishing, and other appearance sensitive applications, visible discoloration can reduce product value and market acceptance. Therefore, visible blue stain affected surface area is a relevant indicator for assessing timber quality and preservative performance in practical use conditions.

Freshly cut pinewood is especially vulnerable because cutting exposes sapwood surfaces before drying, processing, or preservative treatment (Brischke & Alfredsen, 2023). Jankowiak et al. (2021) showed that blue stain fungi can be isolated from freshly felled Scots pine logs, indicating the importance of post felling management in controlling staining. This supports the need to examine both preservative treatment and the timing of treatment application when evaluating methods for reducing visible blue stain development.

## 2.2 ENVIRONMENTAL FACTORS INFLUENCING BLUE STAIN DEVELOPMENT

The development of blue stain discoloration is strongly influenced by environmental conditions. Moisture availability is one of the most important factors because fungal activity generally requires sufficient water within the wood or on the wood surface. Ringman et al. (2019) emphasised that moisture critically affect for fungal development although the response may vary depending on wood species, treatment type, and exposure condition, Under field conditions, moisture availability is influenced not only by average relative humidity but also by rainfall, surface wetting, drying periods, and degree of exposure.

Temperature affects fungal development. Hukka and Viitanen (1999) demonstrated that mould growth on wooden materials is governed by the combined effects of temperature, relative humidity, and exposure duration. Therefore, differences in visible staining between locations should not be interpreted using relative humidity alone. Instead, temperature, wetting and drying cycles, duration of favourable conditions, and surface exposure should be considered together.

Storage condition is important because sheltering reduces direct rainfall exposure, thereby altering surface wetting and drying behaviour. Since the blue stain discoloration develops on exposed surfaces, reducing direct wetting may help limit staining severity. Therefore, the comparison between sheltered and non-sheltered exposure conditions is practically relevant for timber handling and storage.

## 2.3 WOOD PRESERVATIVES AND THE NEED FOR SAFER ALTERNATIVES

Wood preservatives are used to reduce biological deterioration, staining, and decay by limiting the ability of fungi and insects to colonise wood (Ayanleye et al., 2022). Inorganic commercial preservatives are widely used because of their effectiveness and market availability. However, concerns regarding environmental impact, leaching behaviour, and toxicity of some wood protection chemicals have encouraged the search for safer alternatives (Xing et al., 2020).

Boron based preservatives are commonly used in wood protection because Boron compounds show biological activity against fungi and insects. Lloyd et al. (2020) discussed the role of borate treatments in improving wood performance, particularly when used in systems designed to enhance protection. However, Boron based preservatives can be vulnerable to leaching under wet exposure conditions, which is an important consideration for outdoor, field-exposed timber applications. Hence, even though commercial preservatives remain important in timber protection, alternative formulations need to be evaluated under realistic exposure conditions.

The effectiveness of any preservative depends not only on antifungal activity yet on its ability to remain available on or within the wood under exposure conditions. This is particularly important where treated timber is exposed to rainfall, surface wetting, and drying cycles (Obanda et al., 2008). Therefore, the preservative performance should be evaluated under conditions that represent practical storage or field exposure rather than only under controlled laboratory settings.

## 2.4 PLANT BASED ORGANIC PRESERVATIVES AND TREATMENT METHODS

Plant based organic preservatives have gained increasing attention as potential alternatives to conventional wood protection chemicals. Natural compounds such as extractives, essential oils, tannins, alkaloids, and other plant derived substances show antifungal or insecticidal activity, depending on their chemical composition and target organism (Broda, 2020; Singh & Singh, 2012). These compounds are of interest because they may provide wood protection benefits while reducing reliance on more hazardous conventional chemicals.

Research on naturally durable heartwood has shown that wood extractives can contribute to biological resistance through both biocidal and non-biocidal mechanisms. Binbuga et al. (2008) noted that understanding the protective role of extractives can support the development of environmentally friendly wood preservatives. This is relevant to plant extract based preservative development because the performance of organic formulations may depend not only on direct antifungal toxicity but also on retention, surface coverage, and resistance to leaching.

However, bio-based preservatives require careful evaluation. López et al. (2021) showed that bio-based wood preservatives can be effective, yet their performance should be considered together with leaching behaviour and eco-toxicity. This is important for field exposed timber because rainfall and surface wetting may reduce preservative effectiveness if active compounds are not sufficiently retained. Therefore, field based comparisons with commercial preservatives are necessary before plant based formulations can be recommended for practical use.

Previous work on plant extract based organic preservatives has examined preservative uptake using dipping diffusion treatment. That suggests the practical relevance of this method for applying organic formulations to timber (Hewage et al., 2024). However, uptake behaviour alone does not fully establish field performance against visible blue stain discoloration, under varying environmental exposure conditions.

### 2.5 RESEARCH GAP

The reviewed literature shows that blue stain fungi reduce the visual quality and commercial value of pinewood. The environmental exposure influences visible staining, and preservative treatment is an important method of control. It shows growing interest in plant based wood preservatives, although their field performance depends on treatment method, retention, exposure, and environmental conditions. However, limited field based evidence is available on the comparative performance of plant extract based organic preservatives and commercially available inorganic preservatives for reducing visible blue stain affected surface area in pinewood under Sri Lankan exposure conditions. This gap is addressed in the present study through a field based comparative evaluation of organic and commercial preservatives under different environmental exposure and treatment timing conditions.

## 3. METHODOLOGY

### 3.1 SITE SELECTION

A field based experimental approach was used to evaluate the performance of organic and commercial preservatives in reducing visible blue stain development on pinewood. The study was conducted over a six-month exposure period using freshly cut pinewood specimens placed at three different geographical locations in Sri Lanka i.e. (i) Bandarawela, (ii) Ratnapura, and (iii) Colombo.

The three locations were selected to represent different field exposure conditions in terms of average temperature and relative humidity. Climate data obtained from Climate-Data.org (refer Table 1) were used to identify the general climatic characteristics of the selected locations.

*Table 1: Average temperature and relative humidity of selected locations*

| Selected Site | Annual Average Temperature (°C) | Average RH (%) |
|---|---|---|
| Bandarawela | 21.2 | 82.8 |
| Ratnapura | 24.3 | 87.0 |
| Colombo | 26.5 | 79.5 |

The selected sites were not intended to represent laboratory controlled conditions; rather, they were used to compare preservative performance under practical field exposure conditions where temperature, humidity, rainfall exposure, and drying behaviour vary.

### 3.2 SAMPLE PREPARATION

Freshly cut pinewood was obtained from selected pinewood plantation sites. The specimens were prepared from randomly selected freshly cut trees to reduce sampling bias. A total of 162 pinewood specimens were prepared for the study, with 54 specimens

allocated to each location. Each specimen had a cross section of 50 mm × 50 mm and a length of 450 mm.

The experimental arrangement included untreated control specimens and preservative treated specimens. For each test condition, three replicate specimens were used, and the reported values were calculated as the average of the three replicates.

## 3.3 PRESERVATIVE TREATMENTS

Four preservative treatments were evaluated. Two plant extract based organic preservatives were used i.e. (i) FSWM and (ii) FSWOM. These preservatives were developed at the ProGreen Laboratory, Department of Civil Engineering, University of Moratuwa, and are associated with local patent numbers 21896 and 21911 (Halwatura & Mendis, 2023). The formulations are based on leaf extracts of *Gliricidia sepium*, *Tithonia diversifolia*, and *Mikania micrantha*. FSWM includes a prepared paddy field mud component, whereas FSWOM is prepared without the mud component. Previous work has examined preservative uptake of similar plant extract based organic formulations using dipping diffusion treatment (Hewage et al., 2024). The other two treatments were commercially available inorganic boron-based preservatives, Anti-blue and Anti-boron. These preservatives are commonly used in the Sri Lankan pinewood industry and were included as reference commercial treatments for comparison with the organic formulations. The dipping method was used for preservative application. Each treated specimen was immersed in the relevant preservative solution for 48 hours. Untreated specimens were maintained as control samples.

## 3.4 EXPOSURE CONDITIONS AND TREATMENT TIMING

Two exposure conditions were considered: non-sheltered and sheltered. Non-sheltered specimens were placed at the site and exposed to direct field conditions, including rainfall and ambient environmental conditions. Sheltered specimens were placed in a protected area near the site, where direct rainfall was avoided while still allowing exposure to the surrounding ambient environment.Treatment timing was considered. Early treatment refers to preservative application started two days after cutting. Delayed treatment refers to preservative application started twelve days after cutting. These two treatment timings were used to evaluate whether a short delay after cutting influenced the blue stain development after treatment. Untreated specimens were used as control specimens. The experimental variables, therefore, included location, exposure condition, treatment type, and treatment timing. Each site included untreated specimens and treated specimens under sheltered and non-sheltered conditions, with three replicates for each test condition. Table 2 presents the variables and levels of those variables used in the experiment.

*Table 2: Experimental variables and levels*

| Variable | Levels |
|---|---|
| Location | Bandarawela, Ratnapura, Colombo |
| Exposure condition | Sheltered, Non-sheltered |
| Treatment type | Untreated, FSWM, FSWOM, Anti-blue, Anti-boron |
| Treatment timing | Early treatment: 2 days after cutting, Delayed treatment: 12 days after cutting |
| Replicates | Three specimens per test condition |

### 3.5 MEASUREMENT OF VISIBLE BLUE STAIN AFFECTED SURFACE AREA

The assessment focused on visible blue stain discoloration on the surface of the pinewood specimens. Inspections were carried out once per month for six months. During each inspection, photographs were taken from all four longitudinal faces of each specimen. The visible blue stain affected surface area was quantified using a Python based image processing procedure adapted from the affected pixel area estimation approach used by Islam and Rafiqul (2015). Each image was converted into grayscale and then processed as a binary image using a calibrated threshold value to separate visibly stained regions from unstained wood surface areas. The threshold was calibrated by comparing image processing outputs with manual visual classification of representative images. The image processing procedure is presented in Figure 1.

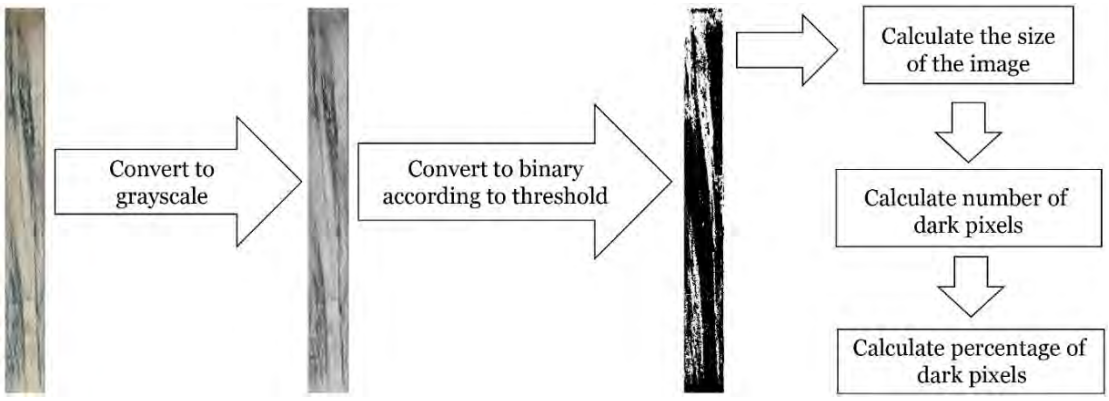



*Figure 1: Image processing procedure used to quantify visible blue stain affected surface area*

The blue stain affected surface area of each photographed face was calculated as the ratio between the number of stained pixels and the total number of visible wood surface pixels. The affected surface area percentage was calculated using Eq. (1):

$$A_b = \frac{A_S}{A_t} \times 100 \qquad (01)$$

where, $A_b$ = visible blue stain affected surface area (%), $A_s$ = stained pixel area and $A_t$ = total visible wood surface pixel area. The final value for each specimen was obtained by considering all four photographed faces. The values reported for each test condition were calculated as the mean of three replicate specimens. Therefore, the reported percentage represents visible blue stain surface coverage rather than fungal biomass or internal fungal colonisation.

## 4. RESULTS

### 4.1 VISIBLE BLUE STAIN DEVELOPMENT IN UNTREATED NON-SHELTERED SPECIMENS ACROSS LOCATIONS

Visible blue stain affected surface area increased with exposure time in untreated non-sheltered pinewood specimens at all three locations. Therefore, this section presents the untreated control condition only. However, the extent of discoloration differed among locations (refer Figure 2). After six months, Bandarawela recorded the highest visible blue stain affected surface area, with 19.60% of the photographed surface area affected. Ratnapura recorded 12.48%, while Colombo recorded the lowest value, at 10.58%.

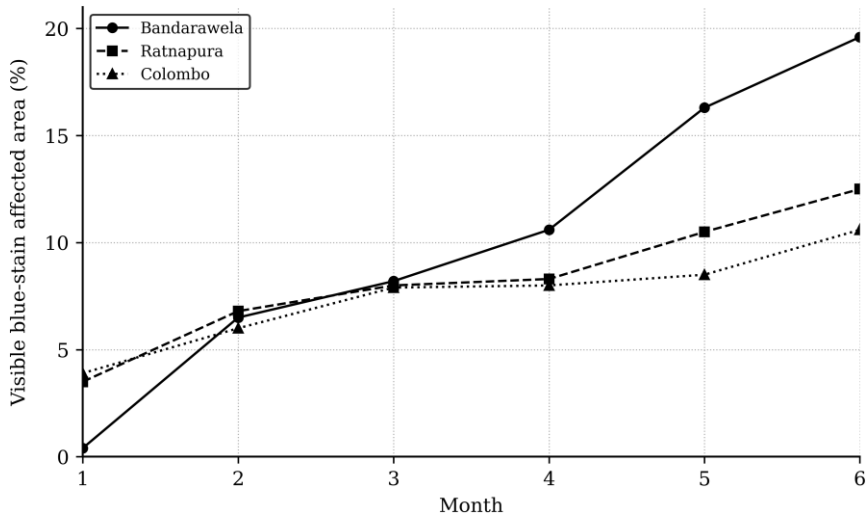



*Figure 2: Variation of visible blue stain affected surface area in untreated non-sheltered pinewood specimens across selected locations*

The results show that location influenced the progression of visible blue stain discoloration under non-sheltered field exposure. Therefore, Bandarawela was selected as the baseline condition for the detailed preservative effectiveness comparison because it represented the most severe visible blue stain development observed among the untreated non-sheltered specimens.

## 4.2 EFFECT OF SHELTERED AND NON-SHELTERED EXPOSURE CONDITIONS ON UNTREATED SPECIMENS

This comparison was also carried out using untreated control specimens only, in order to examine the influence of exposure condition before comparing preservative treatments. Sheltering reduced visible blue stain development in untreated pinewood specimens. In Bandarawela, untreated non-sheltered specimens showed a continuous increase in visible blue stain affected surface area over the six months of exposure period, reaching 19.60% at the end of the observation period. In comparison, untreated sheltered specimens recorded 9.27% affected surface area after six months (refer Figure 3).

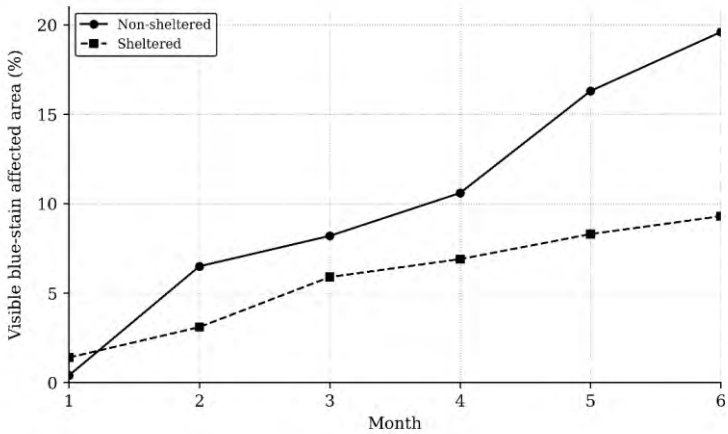



*Figure 3: Variation of visible blue stain affected surface area under sheltered and non-sheltered exposure in Bandarawela*

The blue stain affected area under sheltered exposure was less than half of that recorded under non-sheltered exposure. This indicates that avoiding direct rainfall reduced visible surface discoloration, even though the specimens remained exposed to the surrounding ambient environment.

## 4.3 EFFECT OF PRESERVATIVE TREATMENT UNDER DELAYED APPLICATION

The delayed treatment condition refers to preservative application started twelve days after cutting. Under the non-sheltered Bandarawela condition, all preservative treated specimens showed substantially lower visible blue stain affected surface area than untreated specimens throughout the observation period. The results are shown in Figure 4.

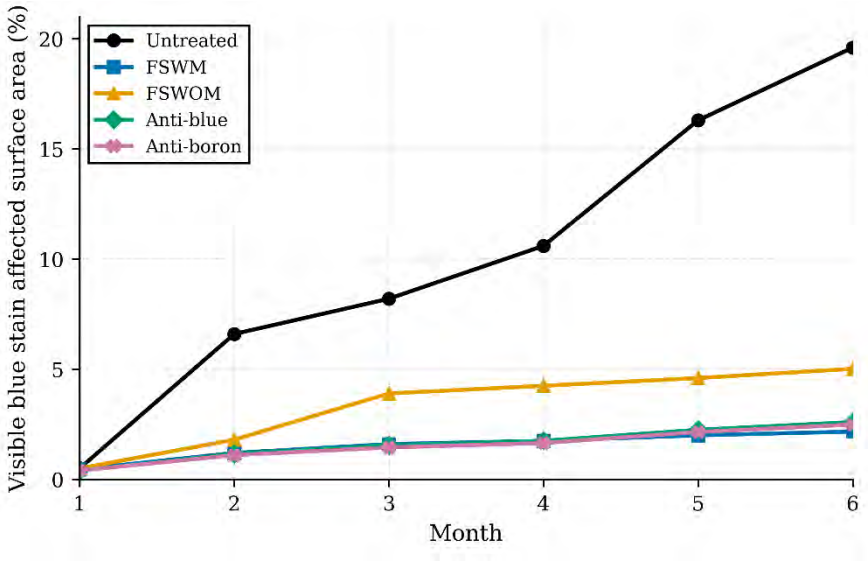



*Figure 4: Visible blue stain affected surface area of untreated and delayed treatment pinewood specimens in Bandarawela under non-sheltered exposure condition*

The values presented in Figure 4 are based only on non-sheltered specimens exposed in Bandarawela and are not averages across the three study locations.

After six months, untreated non-sheltered specimens recorded 19.60% visible blue stain affected surface area. In contrast, FSWM recorded 2.17%, FSWOM recorded 5.02%, Anti-blue recorded 2.60%, and Anti-boron recorded 2.49%. These results show that all preservative treatments reduced visible blue stain development compared with untreated specimens. Among the organic preservatives, FSWM showed the lower affected surface area and performed competitively with the commercial preservatives.

## 4.4 EFFECT OF PRESERVATIVE TREATMENT UNDER EARLY APPLICATION

The early treatment condition refers to preservative application started two days after cutting. Similar to the delayed treatment condition, early preservative application reduced visible blue stain affected surface area compared with untreated non-sheltered specimens in Bandarawela (refer Figure 5). The values presented in Figure 5 are based only on non-sheltered specimens exposed in Bandarawela.

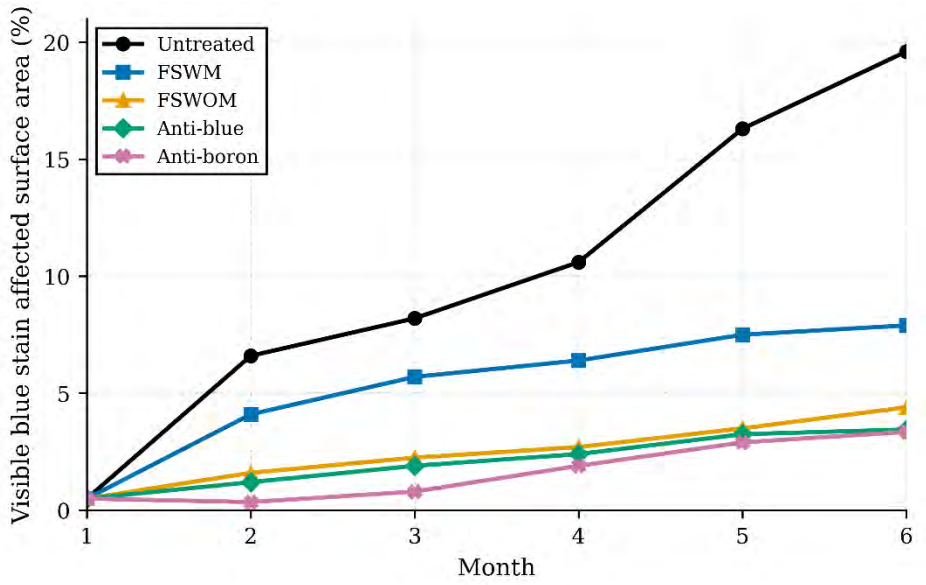



*Figure 5: Visible blue stain affected surface area of untreated and early treatment pinewood specimens in Bandarawela under non-sheltered exposure condition*

The comparison between early and delayed treatment showed that both treatment timings reduced visible blue stain affected surface area compared with untreated specimens. However, the differences between early and delayed treatment were not consistent across all preservatives. Therefore, the results cannot not be interpreted as proving that treatment timing has no effect under all conditions. They indicate that preservative application within the tested period remained effective in reducing visible discoloration.

## 4.5 COMPARATIVE PRESERVATIVE EFFECTIVENESS AFTER SIX MONTHS

The final six month values under the severe non-sheltered Bandarawela condition were used to compare preservative effectiveness. The reduction in visible blue stain affected surface area was calculated relative to untreated specimens. The results are shown in Table 3.

*Table 3. Final visible blue stain affected surface area and reduction compared with untreated non-sheltered specimens in Bandarawela*

| Treatment | Visible Blue Stain Affected Surface Area (%) | Reduction Compared with Untreated Specimens (%) |
|---|---|---|
| Untreated | 19.60 | — |
| FSWM | 2.17 | 88.93 |
| FSWOM | 5.02 | 74.39 |
| Anti-blue | 2.60 | 86.73 |
| Anti-boron | 2.49 | 87.30 |

The final comparison shows that FSWM produced the lowest visible blue stain affected surface area among all tested preservatives under this condition. Anti-boron and Anti-blue showed strong performance, with final affected areas close to FSWM. FSWOM reduced visible blue stain development compared with untreated specimens, yet its final affected surface area was higher than FSWM and the two commercial preservatives.

Therefore, the results indicate that FSWM showed competitive performance against the commercial preservatives, while FSWOM was effective yet less protective under the severe non-sheltered Bandarawela condition.

# 5. DISCUSSION

## 5.1 INFLUENCE OF LOCATION AND FIELD EXPOSURE ON VISIBLE BLUE STAIN DEVELOPMENT

The variation in visible blue stain affected surface area across locations confirms that field exposure conditions influenced discoloration development. Although Ratnapura recorded the highest average relative humidity among the selected locations, Bandarawela showed the highest visible blue stain coverage, indicating that relative humidity alone cannot explain the observed pattern. This interpretation is consistent with Hukka and Viitanen (1999), who showed that mould development on wooden materials depends on the combined influence of temperature, relative humidity, and exposure duration. Ringman et al. (2019) similarly emphasised that moisture availability should be understood together with wood condition, exposure, and treatment. Rice et al. (2008) showed that blue stain fungi may differ in their temperature adaptation, further supporting the view that environmental response is not controlled by a single climatic parameter. Therefore, the higher discoloration in Bandarawela may be related to the combined influence of surface wetting, drying behaviour, temperature, and exposure duration rather than a single climatic parameter.

The lower discoloration observed under sheltered exposure further confirms the practical value of reducing direct rainfall exposure during pinewood storage. Since sheltered specimens remained exposed to the surrounding ambient environment, the reduction in visible blue stain development suggests that direct surface wetting played an important role in the observed discoloration pattern.

## 5.2 PERFORMANCE OF ORGANIC AND COMMERCIAL PRESERVATIVES

All preservative treatments reduced visible blue stain affected surface area compared with untreated specimens under the severe non-sheltered Bandarawela condition, confirming the practical value of preservative treatment for freshly cut pinewood. However, the treatments did not perform equally. FSWM showed the strongest performance among the organic preservatives and achieved a similar level with Anti-blue and Anti-boron. FSWOM was effective compared with untreated specimens but less protective than FSWM and the commercial treatments.

The observed difference between FSWM and FSWOM is consistent with broader literature showing that plant based preservatives can have wood protective potential but require formulation specific evaluation. Natural compounds and plant extractives may show antifungal or protective effects, yet their effectiveness depends on chemical composition, target organism, wood species, exposure conditions, and formulation stability (Broda, 2020; Singh & Singh, 2012). Extractives may contribute to wood protection through both biocidal and non-biocidal mechanisms (Binbuga et al., 2008).

The stronger performance of FSWM may be related to formulation composition, particularly the presence of the paddy field mud component, which may have contributed to surface coverage, retention, or resistance to removal during wetting and drying cycles.

However, these mechanisms were not directly tested in this study. Since bio based preservative performance depends not only on biological activity but also on retention and leaching behaviour (López et al., 2021), the stronger performance of FSWM can be interpreted as an observed formulation level outcome.

The strong performance of Anti-blue and Anti-boron is consistent with the established role of commercial preservatives in controlling bio deterioration and staining. Boron-based treatments are widely discussed in wood protection because boron compounds can be effective against fungi and insects (Lloyd et al., 2020). However, their performance under wet exposure may be influenced by leaching.

## 5.3 EFFECT OF TREATMENT TIMING

The comparison between early and delayed treatment showed that both treatment timings reduced visible blue stain affected surface area compared with untreated specimens. This suggests that preservative application within the tested period remained effective in reducing visible discoloration. However, the differences between early and delayed treatment were not uniform across all preservatives. Therefore, the results should not be interpreted as proving that treatment timing has no effect under all circumstances.

From a practical perspective, early treatment remains preferable because freshly cut pinewood is vulnerable to blue stain development during storage and handling. Jankowiak et al. (2021) showed that blue stain fungi can be isolated from freshly felled pine logs, supporting the importance of post felling management. The present results suggest that preservative treatment can reduce visible discoloration even when application is delayed within the tested period, but rapid treatment and sheltered storage would still be safer recommendations for industry practice.

## 5.4 PRACTICAL IMPLICATIONS AND LIMITATIONS

The findings have practical implications for the pinewood industry in Sri Lanka. Freshly cut pinewood should be protected from direct field exposure where possible, because sheltered storage substantially reduced visible blue stain development. Preservative treatment is also important under severe exposure conditions. Among the tested organic preservatives, FSWM showed the greatest practical potential because it showed similar effectiveness to the commercial inorganic preservatives. Since the organic formulations are based on locally available plant materials, they may support more locally adaptable timber protection practices and reduce dependence on imported or commercially sourced inorganic preservatives. However, wider industrial promotion requires further studies on cost, production scalability, preservative retention, leaching, and long term durability.

Several limitations should be acknowledged. The comparative ranking of preservatives should be interpreted as context specific to the severe non-sheltered Bandarawela condition, and further analysis is required before generalising treatment performance across all Sri Lankan field exposure conditions. The image processing method quantified visible blue stain affected surface area, not fungal biomass or internal fungal colonisation. Grayscale thresholding may also classify some dark surface features as stained regions, although this was reduced by calibration against manual visual classification. Future work should include leaching tests, preservative retention measurements, fungal identification, evaluation of the mud component, and longer exposure periods.

## 6. CONCLUSIONS

This study evaluated the field performance of two plant extract based organic preservatives, FSWM and FSWOM, against two commercially available inorganic Boron-based preservatives, Anti-blue and Anti-boron. The study examined the reduction of visible blue stain affected surface area in pinewood under Sri Lankan field exposure conditions. Visible blue stain development varied across locations, with untreated non-sheltered specimens in Bandarawela recording the highest affected surface area after six months. Sheltered storage reduced visible discoloration by approximately 52.7% compared with non-sheltered exposure in Bandarawela, indicating that protecting freshly cut pinewood from direct rainfall can help limit blue stain development during storage and handling. All preservative treatments substantially reduced visible blue stain affected surface area compared with untreated specimens. Under the severe non-sheltered Bandarawela condition, FSWM produced the highest reduction, approximately 88.9%, followed by Anti-boron at 87.3%, Anti-blue at 86.7%, and FSWOM at 74.4%. These results show that FSWM performed comparably with the commercial preservatives, while FSWOM was effective compared with untreated specimens yet less protective than FSWM and the commercial treatments. Both early and delayed treatment applications reduced visible blue stain development, although the timing effect was not uniform across all preservatives. Therefore, early preservative treatment combined with sheltered storage is recommended as the safer practical approach for freshly cut pinewood. Future studies should examine preservative retention, leaching resistance, long term field durability, fungal species identification, and the specific contribution of the mud component to FSWM performance.

## 7. ACKNOWLEDGEMENTS

The authors acknowledge the Sri Lanka State Timber Corporation for supporting access to pinewood materials and field-related activities.

## 8. REFERENCES

Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. (2022). Durability and protection of mass timber structures: A review. *Journal of Building Engineering, 46*, 103731. https://doi.org/10.1016/j.jobe.2021.103731

Barbero-López, A., Akkanen, J., Lappalainen, R., Peräniemi, S., & Haapala, A. (2021). Bio-based wood preservatives: Their efficiency, leaching and ecotoxicity compared to a commercial wood preservative. *Science of the Total Environment, 753*, 142013. https://doi.org/10.1016/j.scitotenv.2020.142013

Binbuga, N., Ruhs, C., Hasty, J. K., Henry, W. P., & Schultz, T. P. (2008). Developing environmentally benign and effective organic wood preservatives by understanding the biocidal and non-biocidal properties of extractives in naturally durable heartwood. *Holzforschung, 62*(2), 264–269. https://doi.org/10.1515/HF.2008.038

Brischke, C., & Alfredsen, G. (2023). Biological durability of pine wood. *Wood Material Science & Engineering, 18*(3), 1050–1064. https://doi.org/10.1080/17480272.2022.2104134

Broda, M. (2020). Natural compounds for wood protection against fungi—A review. *Molecules, 25*(15), 3538. https://doi.org/10.3390/molecules25153538

Climate-Data.org. (n.d.). *Climate data for cities worldwide*. Retrieved March 1, 2024, from https://en.climate-data.org/

Halwatura, R. U., & Mendis, M. S. (2023). *Wood preservative formulation, and method of preparation thereof* (Sri Lanka Patent Nos. 21896 and 21911). National Intellectual Property Office of Sri Lanka.

Hewage, I. S., Mendis, M. S., Muthumala, C. K., & Halwatura, R. U. (2024). The effect of wood preservative uptake for organic wood preservatives by dipping diffusion method. In R. Dissanayake, G. Y. Jayasinghe, S. Setunge, K. Kanchanamala, & P. Mendis (Eds.), *Proceedings of the 1st International Conference on University-Industry Collaborations for Sustainable Development* (pp. 381–392). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-5944-6_31

Hukka, A., & Viitanen, H. A. (1999). A mathematical model of mould growth on wooden material. *Wood Science and Technology, 33*(6), 475–485. https://doi.org/10.1007/s002260050131

Humar, M., Vek, V., & Bučar, B. (2008). Properties of blue-stained wood. *Drvna Industrija, 59*(2), 75–79.

Islam, R., & Rafiqul, M. (2015). An image processing technique to calculate percentage of disease affected pixels of paddy leaf. *International Journal of Computer Applications, 123*(12), 28–34. https://doi.org/10.5120/ijca2015905495

Jankowiak, R., Szewczyk, G., Bilański, P., Linnakoski, R., & Solheim, H. (2021). Blue-stain fungi isolated from freshly felled Scots pine logs in Poland, including *Leptographium sosnaicola* sp. nov. *Forest Pathology, 51*(2), e12672. https://doi.org/10.1111/efp.12672

Lloyd, J. D., Taylor, A. M., Brischke, C., & Irby, N. (2020). Protecting the heartwood of wood infrastructure: Improving performance with borate dual treatments. *Wood Material Science & Engineering, 15*(6), 361–367. https://doi.org/10.1080/17480272.2020.1749881

Obanda, D. N., Shupe, T. F., & Barnes, H. M. (2008). Reducing leaching of boron-based wood preservatives—A review of research. *Bioresource Technology, 99(*15), 7312–7322. https://doi.org/10.1016/j.biortech.2007.12.077

Rice, A. V., Thormann, M. N., & Langor, D. W. (2008). Mountain pine beetle-associated blue-stain fungi are differentially adapted to boreal temperatures. *Forest Pathology, 38*(2), 113–123. https://doi.org/10.1111/j.1439-0329.2007.00525.x

Ringman, R., Beck, G., & Pilgård, A. (2019). The importance of moisture for brown rot degradation of modified wood: A critical discussion. *Forests, 10*(6), 522. https://doi.org/10.3390/f10060522

Singh, T., & Singh, A. P. (2012). A review on natural products as wood protectant. *Wood Science and Technology, 46*(5), 851–870. https://doi.org/10.1007/s00226-011-0448-5

Xing, D., Magdouli, S., Zhang, J., & Koubaa, A. (2020). Microbial remediation for the removal of inorganic contaminants from treated wood: Recent trends and challenges. *Chemosphere, 258*, 127429. https://doi.org/10.1016/j.chemosphere.2020.127429

Jeewananda, W.D.B.J., Kudasinghe, K.S.K.N.J. and Rupasinghe, A.R., 2026. Conceptual digital twin framework for conserving urban cultural heritage: A case of Slave island, Colombo. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 419-432. DOI: https://doi.org/10.31705/WCS.2026.31. Available from: https://ciobwcs.com/papers/

# CONCEPTUAL DIGITAL TWIN FRAMEWORK FOR CONSERVING URBAN CULTURAL HERITAGE: A CASE OF SLAVE ISLAND, COLOMBO

**W.D.B.J. Jeewananda[1], K.S.K.N.J. Kudasinghe[2] and A.R. Rupasinghe[3]**

## *ABSTRACT*

*Digital twins have emerged as significant tools within architecture and construction, enabling the creation of precise virtual representations of physical structures and environments. However, no universal digital twin system is applicable across all contexts, as development processes must be tailored according to specific site conditions, project objectives, and user requirements. Within heritage conservation, Building Information Modelling (BIM) and digital twin principles support documentation, performance assessment, behavioural analysis, and preventive maintenance of historic environments. Nevertheless, their implementation remains complex, particularly within developing-country contexts where technological limitations and data constraints exist. In Sri Lanka, research and application of digital twins for urban cultural heritage conservation remain limited. Simultaneously, rapid modernization increasingly threatens colonial-era streetscapes and historically significant urban structures within Colombo. In response, this conceptual study proposes a site-specific digital twin framework for conserving disappearing urban cultural heritage, focusing on the De Soysa building and the surrounding streetscape of Slave Island, Colombo. The study adopts a qualitative exploratory approach combining a literature review, case study analysis, and semi-structured professional interviews to identify suitable framework components, implementation challenges, and future application strategies. The proposed conceptual workflow integrates archival documentation, digital reconstruction approaches, and comparative visualization techniques to support heritage documentation and long-term digital preservation. Findings indicate that heritage-oriented digital twin development within Sri Lanka requires context-sensitive and adaptable implementation strategies due to challenges associated with data acquisition, software accessibility, interoperability, cost, and ethical considerations. The study contributes by establishing an initial conceptual foundation for future digital twin implementation in urban cultural heritage conservation within resource-constrained contexts.*

***Keywords:*** *Conservation; Digital Twins; Urban Cultural Heritage.*

[1] Lecturer (Probationary), Department of Quantity Surveying, Faculty of Built Environment & Spatial Sciences, General Sir John Kotelawala Defence University, Sri Lanka, bimsaraj@kdu.ac.lk
[2] Lecturer (Probationary), Department of Architecture, Faculty of Built Environment & Spatial Sciences, General Sir John Kotelawala Defence University, Sri Lanka, ksknjkudasinghe@kdu.ac.lk
[3] Senior Lecturer (Grade I), Department of Spatial Sciences, Faculty of Built Environment & Spatial Sciences, General Sir John Kotelawala Defence University, Sri Lanka, a.ranjith.r@kdu.ac.lk

# 1. INTRODUCTION

The "digital twin" phenomenon has seen widespread adoption across sectors such as aerospace, healthcare, and the Architecture, Engineering, and Construction (AEC) industry (Grieves, 2014). Formulated by Grieves in the early 2000s within industrial design, a digital twin serves as a standalone digital mirror of a physical system (Grieves, 2014, 2016). This model archives the physical system's data and maintains a continuous link throughout its lifecycle (Huzzat et al., 2025). Essentially, it acts as a virtual proxy for a tangible object or process.

Over the last ten years, cross-disciplinary efforts have positioned BIM as a primary tool for managing historic landscapes, proving effective for behavioural analysis and preventive upkeep of heritage sites (Jouan & Hallot, 2019). Digital twins enhance this by providing a dynamic method to manage accurate digital representations of structures (Fuller et al., 2020). This technology allows engineers to execute multiscale simulations to detect defects and suggest repairs. It merges diverse survey methods (Martínez et al., 2021) with BIM-centric semantics (Woodward & Heesom, 2019). However, because implementation is technically demanding and time-intensive, establishing a project-specific input framework is vital (Semeraro et al., 2021). No "one-size-fits-all" system exists for digital twins (Huzzat et al., 2025; Pasupuleti, 2025); therefore, the development workflow must be customized for every site.

Digital twin implementation within the built environment is highly context-specific and cannot be standardized through a single universal framework. The selection of suitable algorithms, modelling techniques, and data input flows must be tailored according to project requirements, user objectives, and site conditions (Dembski et al., 2020). Subsequently, development workflows differ significantly from one heritage context to another. Consequently, heritage-oriented digital twin research often adopts phased implementation approaches that integrate HBIM, photogrammetry, archival reconstruction, AR visualization, and structured digital repositories as foundational components for future digitally connected heritage management environments (Dore & Murphy, 2017; Jouan & Hallot, 2019; Massafra et al., 2022). Previous studies have demonstrated that heritage digitization frequently begins with the creation of accurate digital documentation and information models before progressing towards more advanced digital twin functionalities such as real-time monitoring, predictive analysis, and lifecycle management (Murphy et al., 2013; Boje et al., 2020). This staged development approach is particularly common within heritage contexts where data availability, technological infrastructure, and conservation requirements often limit immediate implementation of fully synchronized digital twin systems.

In Sri Lanka, the adoption of these technologies remains sparse compared to global leaders (Opoku et al., 2021), though interest in their transformative potential is rising (Bandara et al., 2023). Despite the volume of literature linking architecture to digital twins, professional consensus on who should operate them and their total utility remains elusive (Attaran & Celik, 2023; Lucchi, 2023; Semeraro et al., 2021). Research regarding their specific application in cultural heritage maintenance is particularly underdeveloped (Jouan & Hallot, 2019; Kudasinghe & Jeewananda, 2024). This is a critical gap, as Sri Lanka’s rapid modernization often leads to the neglect of historical significance (Pasupuleti, 2025; Munasinghe et al., 2023).

Within the Sri Lankan context, research on digital twins for heritage conservation remains at an early stage. Existing studies have primarily focused on individual religious or monument-based heritage structures rather than broader urban cultural landscapes. For example, Egodawela et al. (2023) explored the use of 3D photogrammetric modelling and digital twin principles in the restoration process of Rankoth Wehera/Stupa in Sri Lanka. However, applications addressing dynamic urban cultural heritage environments and disappearing historical streetscapes remain largely unexplored. Furthermore, digital twin implementation is inherently context-specific and user-specific, meaning that no universal digital twin system can be applied across all projects (Dembski et al., 2020). The selection of algorithms, modelling approaches, and data input workflows must therefore be tailored according to the specific heritage context and project objectives. Consequently, establishing a conceptual and site-specific framework is a necessary preliminary step toward implementing digital twins for historical urban environments such as Slave Island, Colombo.

The vanishing colonial streetscapes of Slave Island (Kompannaveediya) in Colombo highlight this preservation crisis. Precise restoration is necessary to protect architectural integrity, and digital twins support this by creating intricate virtual models that capture materials and historical contexts (Ćosović & Maksimović, 2022).

This research explores using digital twins to conserve Sri Lankan urban heritage, with a focused case study on the disappearing streetscape of Slave Island, Colombo. The objectives are:

- Objective 01: Identify facilitator areas where digital twins aid heritage preservation via literature synthesis.
- Objective 02: Formulate a site-specific framework for historical landscapes to allow for comparative visualization of urban shifts.
- Objective 03: Pinpoint and address the challenges of implementing these twins in the built environment.

## 2. LITERATURE REVIEW

A thorough literature review was conducted prior to the study as well as during the study, since the first objective for this study is to identify key facilitator areas where digital twins can enable the preservation of cultural heritage within the built environment through the findings of previously conducted studies. While industrial digital twins commonly rely on continuous real-time synchronization through IoT sensors and automated data exchange, heritage-focused digital twins often evolve through phased development due to limitations in historical data availability, monitoring infrastructure, and conservation constraints. Consequently, early-stage heritage digital twin studies frequently incorporate HBIM, photogrammetry, archival reconstruction, AR visualization, and structured digital repositories as foundational components toward future fully synchronized systems. Therefore, this study adopts a conceptual framework-oriented approach intended to establish the preliminary architecture for future real-time heritage digital twin implementation.

The literature review followed a structured exploratory review approach focused on digital twin applications within architecture, HBIM, urban heritage conservation, and cultural heritage management. Sources were selected based on relevance to digital twin implementation frameworks, heritage applications, and built environment studies.

## 2.1 DIGITAL TWINS IN ARCHITECTURE

Digital twins permit architects to test designs in virtual spaces, enhancing stakeholder communication and decision-making (Guo et al., 2025). By incorporating sensor data, they optimize building performance and energy use (Sharma et al., 2022). Their role in physical prototyping follows a three-stage logic (Grieves, 2014):

- See: Sensors and tools capture data for visualization.
- Think: Analytics detect issues and propose solutions.
- Do: Algorithms enact optimal remedies.

A digital twin acts as a synchronized, virtual counterpart to a physical asset or system, mirroring both the constituent elements and the operational dynamics of a complex system as it changes over time. Consequently, the architecture of a digital twin is comprised of three fundamental pillars (Hu et al., 2021; Grieves 2014, 2016): physical objects, virtual model, their connection.

The physical objects are indispensable to the twin because they act as the source for vast, heterogeneous datasets originating in the real world (Therias & Rafiee, 2023). These tangible components generate an immense volume of multi-source and diverse data. Currently, the most prevalent techniques for data acquisition include laser scanning and photogrammetry, both of which demonstrate high efficacy in the generation of digital replicas for existing structures (Dagnaw et al., 2026).

Virtual modelling technologies encompass the methodologies used to translate a physical asset into digital formats that are compatible with computer-based analysis, management, and processing (Alam & Saddik, 2017). Modelling is arguably the most critical phase of the digital twin lifecycle. A robust digital twin model incorporates its geometric data (including shape, dimensions, orientation, and assembly logic), physical properties (such as material characteristics, tolerances, and structural information), behavioural patterns (the model's reaction to external environmental stimuli), and governing rules (the constraints and associations utilized to judge, optimize, and forecast the performance of the object) (Alam & Saddik, 2017).

Regarding connection and data transmission, high-fidelity mechanisms are required for the digital twin to offer near-real-time synchronization and accurate state mapping (Grieves 2014, 2016). Various connection protocols facilitate the flow of data between the physical environment and the digital twin, as well as between different software applications within cyberspace (Sun et al., 2025). The execution of a digital twin is a sophisticated and time-intensive undertaking that necessitates the integration of numerous tools and technologies. Therefore, selecting a framework and a sequence of inputs tailored specifically to the project is vital (Dembski, 2020). Because no universal digital twin system exists that can be applied to every context, development processes must be site-specific and flexible.

## 2.2 DIGITAL TWINS IN THE CULTURAL HERITAGE OF THE BUILT ENVIRONMENT

The digital twin is a highly promising technology for the preservation of cultural heritage, enabling a sophisticated level of interaction between tangible physical objects (such as historical landmarks or archaeological sites) and their virtual counterparts (Pasupuleti, 2025). The framework introduced by Massafra et al. (2022) focuses on the integration of

historical building models into a digital twin environment specifically to support heritage conservation. This holistic methodology recognizes that model integration must extend beyond the initial project phase; it emphasizes the automation of simulation and data analytics within the twin, leading to a deeper comprehension of how preservation efforts affect both the heritage sites and the people who interact with them (Massafra et al., 2022).

## 3. METHODOLOGY

This study adopted a qualitative exploratory research approach to investigate the potential application of conceptual digital twin frameworks for conserving urban cultural heritage within the Sri Lankan context. A qualitative and exploratory methodology was considered appropriate because digital twin implementation for heritage conservation remains an emerging research area with limited established frameworks, particularly within developing-country urban environments (Creswell & Creswell, 2018).

The research methodology consisted of four primary stages;

- Step 01: Structured Literature Review- was conducted to identify key facilitator areas where digital twin technologies could support cultural heritage preservation.
- Step 02: Case Study Selection and Analysis- selecting the streetscape of Salve Island and the historical significant De Zoysa Building.
- Step 03: Development of the Conceptual Digital Twin Framework is created for a heritage-oriented digital twin framework were identified using archival and spatial data sources.
- Step 04: Semi-Structured Expert Interviews were conducted with industry experts to investigate implementation challenges, technological limitations, and future opportunities associated with digital twin applications for heritage conservation.

As illustrated in Figure 1, the methodology follows a logical progression from literature review and case study selection to conceptual framework development and implementation challenge analysis, thereby ensuring a systematic approach toward investigating urban cultural heritage conservation through digital twin principles.

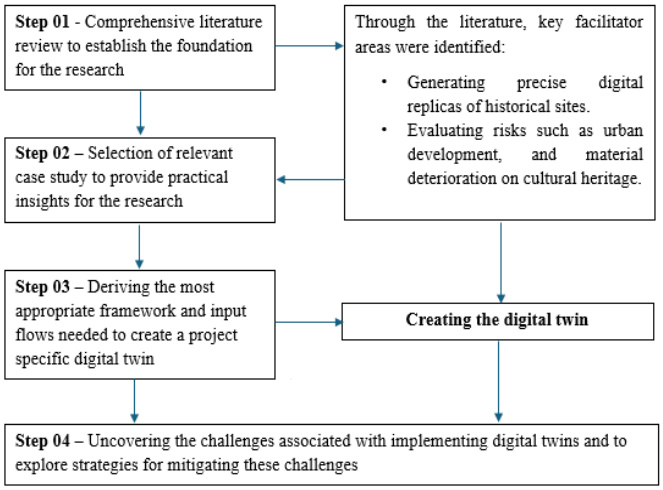



*Figure 1: Framework for developing the research.*

To begin, an extensive literature review was conducted to establish the theoretical foundation for the research. Literature reviews are widely utilized in exploratory built environment studies to identify existing knowledge gaps, conceptual relationships, and emerging implementation approaches (Snyder, 2019). To establish the theoretical foundation of the study, a structured exploratory literature review was undertaken. Exploratory reviews are particularly suitable for emerging research domains where concepts, applications, and implementation approaches are still evolving (Snyder, 2019). Academic journal articles, conference proceedings, and industry publications published between 2014 and 2025 were reviewed using databases including Scopus, Google Scholar, ScienceDirect, and IEEE Xplore. Search terms included "digital twin", "heritage conservation", "HBIM", "urban heritage", "cultural heritage preservation", and "digital reconstruction". Sources were selected based on their relevance to digital twin implementation frameworks, heritage applications, and built environment studies. The review facilitated the identification of key application areas, implementation challenges, and technological components relevant to the development of a conceptual digital twin framework for urban cultural heritage conservation.

Through the synthesis of existing academic work, the study identified key facilitator areas where digital twins can contribute to the maintenance and preservation of cultural heritage, including:

- the creation of highly precise digital replicas of historical landmarks to support documentation,
- and the assessment of risks such as material deterioration and urban redevelopment pressures affecting heritage assets.

These identified areas were considered particularly relevant to the colonial urban streetscapes of Sri Lanka, where rapid modernization and redevelopment increasingly threaten historically significant structures.

Secondly, a case study strategy was adopted to provide contextual depth and site-specific understanding. Case study approaches are particularly suitable for investigating complex contemporary phenomena within real-world settings where contextual conditions are highly significant (Yin, 2018). The selected case study focused on the disappearing urban landscape of Slave Island, Colombo, with particular emphasis on the De Soysa building.

The Slave Island streetscape and the De Soysa building were selected due to their historical significance and the immediate urban redevelopment pressures threatening their existence. Similar urban transformation has already resulted in the loss of nearby heritage structures such as the Castle Hotel, which was replaced by a modern structure lacking the architectural character of the original building. Therefore, the De Soysa building and the surrounding Slave Island streetscape represent a highly relevant case for investigating conceptual digital twin approaches for urban cultural heritage conservation, documentation, and comparative visualization.

To support the development of the proposed conceptual digital twin framework, semi-structured interviews were conducted with ten industry professionals selected through purposive sampling (Patton, 2015). Since digital twin implementation for cultural heritage remains a highly specialized and emerging field within Sri Lanka, participants were selected based on their professional knowledge and practical experience rather than through probabilistic sampling methods.

Semi-structured interviews were selected because they provide flexibility for participants to elaborate on emerging themes while ensuring consistency across core discussion areas (Kallio et al., 2016). The interviews explored themes relating to digital twin implementation challenges, heritage conservation concerns, and the future applicability of digital twin technologies within Sri Lanka's built environment sector.

The participants as indicated in Table 01 consisted of architects with experience in heritage conservation and urban design, archaeologists specializing in cultural heritage preservation, technical managers from engineering software organizations familiar with BIM and digital modelling technologies, and machine learning engineer with expertise in data integration and intelligent systems. This multidisciplinary composition was intended to capture both technological and conservation-oriented perspectives relevant to digital twin implementation within historical urban environments.

*Table 1: Interview participants.*

| Interviewee Code | Organizational Sector | Experience (Years) |
|---|---|---|
| I1 | Private architectural practices | 5 |
| I2 | Private architectural practices | 7 |
| I3 | Private architectural practices / conservation consultancy | 10 |
| I4 | Private architectural practices / conservation consultancy | 12 |
| I5 | Private architectural practices / conservation consultancy | 15 |
| I6 | Heritage and archaeological institutions | 6 |
| I7 | Heritage and archaeological institutions | 14 |
| I8 | Engineering software organizations | 5 |
| I9 | Engineering software organizations | 11 |
| I10 | Digital technology sector | 9 |

All participants possessed professional experience relevant to heritage conservation, digital modelling, BIM technologies, or data-driven built environment applications.

The conceptual framework was developed using multiple data sources, including: historical architectural drawings, archival photographs, contemporary site observations, publicly available urban imagery, and historical documentation relating to the De Soysa building and the surrounding Slave Island streetscape.

The study prioritized conceptual workflow development rather than geometric precision validation. Consequently, the generated models should be interpreted as representative heritage visualizations based on available archival data rather than exact metrically verified reconstructions. The accuracy of the model was therefore dependent on the quality and completeness of the historical records and visual references available.

The collected interview data were analysed using qualitative thematic analysis, where recurring implementation issues, technological constraints, and future opportunities were identified and grouped into thematic categories (Braun & Clarke, 2006). The findings from the interviews were subsequently synthesized with the literature review and case study observations to support the development of the proposed conceptual framework.

The proposed framework is intended to function as an evolving digital repository capable of accommodating future updates. Additional spatial, historical, environmental, or monitoring data can be integrated incrementally as new information becomes available, allowing the framework to support long-term urban heritage documentation and comparative analysis.

The study prioritised conceptual workflow development rather than geometric precision validation. The accuracy of the model was therefore dependent on the quality and completeness of the historical records and visual references available.

# 4. RESULTS AND DISCUSSION

The data collection was conducted through both primary and secondary data following a mixed method. Gathered data was then carefully analysed for the purpose of achieving the main aim of the study.

## 4.1 RESULTS FROM THE LITERATURE REVIEW

As noted in the previous chapter, the synthesis of literature pinpointed two essential facilitator zones where digital twins are vital for the protection of cultural identity within the built environment:

1) The generation of high-precision digital replicas for buildings and historical locations.
2) The evaluation of risks, specifically regarding the consequences of urban growth and the natural deterioration of materials on heritage sites.

Guided by these facilitator areas, the disappearing streetscape of Slave Island, Colombo (specifically the De Soysa building) was designated as the focus for applying the digital twin framework.

## 4.2 RESULTS AND DISCUSSION FROM THE CASE STUDY

### 4.2.1 The Selection of Case Study

In Sri Lanka, the UDA has determined that the 150-year-old De Soysa building in Slave Island will be demolished. To accommodate road widening, a new structure featuring a replicated facade will be built some distance away (Figures 02, 03). Architect Ismeth Raheem, in a statement published in the Sunday Times, characterized the building as a "century-old gem of colonial street architecture." The demolition is intended to clear land for the Indian-owned Tata Housing Development Company. A similar fate befell the Castle Hotel, which was replaced by a white structure that currently serves as the Tata project office and bears no resemblance to the original hotel.

The De Soysa building was historically significant as the headquarters for H.W. Cave & Co., which became the nation’s premier printing and publishing house starting in 1877. During the 1920s and 1930s, the H.W. Cave & Co. premises were regarded as one of Colombo's most elite addresses. Because the De Soysa building carries such cultural weight, a digital twin is a valuable tool for its promotion and preservation. It offers a way for future generations to engage with and understand the historical importance of the building within the context of Sri Lankan Street architecture. Digital twins enable the development of a highly precise, interactive 3D model that ensures architectural and historical nuances are archived and can be recreated with fidelity.

Even if a physical restoration is not possible, the digital twin serves as a virtual museum, providing a platform for people to explore the building in its original state.

*Figure 2 & 3: Demolished state of the De Soysa building.*

The findings from the De Soysa case study reinforce broader concerns identified within urban heritage conservation literature regarding the rapid disappearance of culturally significant historical streetscapes due to urban redevelopment pressures. Similar observations have been made in studies examining colonial urban environments in rapidly modernizing Asian cities, where economic development frequently outweighs heritage preservation priorities (Bruno et al., 2010; Jouan & Hallot, 2019). The present case further demonstrates the importance of digital documentation approaches for safeguarding architectural memory in situations where physical conservation may no longer be feasible.

### 4.2.2 Development of the Framework for its Digital Twin

This section outlines the specific framework and input sequences required to develop a digital twin for the De Soysa building in the Slave Island area. The first step involves gathering historical data on the building. While photogrammetry and laser scanning are excellent methods for digital recreation, such technologies are not widely available in Sri Lanka. As an alternative, this study utilized existing 2D documentation (such as scanned plans, sections, elevations, and old paper drawings) alongside historical site photographs to manually capture details and building updates.

Subsequently, a 3D-printed model would be created to represent the historical streetscape of Slave Island, the De Soysa Building included. This physical model offers a tangible representation of the urban environment of the past, capturing the fine details of the historical landscape. The use of 3D printing ensures that the physical attributes of the buildings and infrastructure are replicated accurately as they once existed.

To create a juxtaposition between the past and the present, a virtual 3D model (the digital twin) of the current streetscape is to be produced using data collected on recent urban developments. By utilizing the Outlier tool in SketchUp, it will facilitate a clear comparison between the original and modern states. Digitizing this information results in a detailed virtual representation of the current streetscape, acting as a dynamic digital twin that offers insights into urban and architectural evolution over time.

To allow for an immersive and interactive comparison, the 3D-printed historical model is to be integrated with a unique QR code which is linked to the digital twin; when scanned via a tablet or smartphone, it initiates an augmented reality (AR) experience.

This feature enables users to see the current digital twin superimposed onto the physical 3D-printed historical streetscape. By overlaying the digital model onto the physical one, users can observe and analyse the transformations that have occurred, creating a site-specific digital twin that can be continuously updated as new changes arise.

In summary, this process (Figure 4) involves the creation of a 3D-printed historical model, the development of a current virtual twin using SketchUp, and the use of QR codes to overlay the two versions via AR. This comparative visualization brings to light the urban planning choices, architectural changes, and cultural shifts that have defined Slave Island. The model functions as a living archive for preservation and monitoring, allowing researchers to track modifications to historical buildings through successive data versions. Thus, the digital twin becomes a robust tool for historians, architects, and the public to better understand the area's historical trajectory.

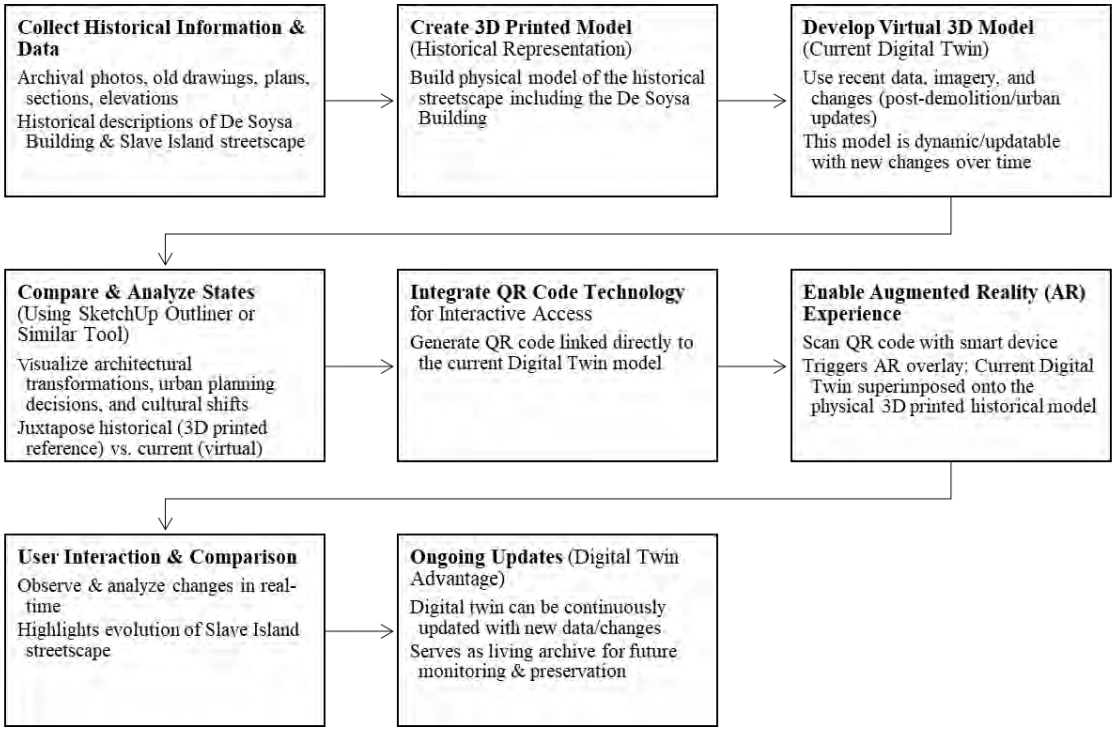



*Figure 4: Digital twin creation process*

Similar to prior research (Massafra et al., 2022; Dore & Murphy, 2017), the study demonstrates that digital heritage frameworks can function not only as documentation tools but also as interactive platforms for public engagement, comparative visualization, and long-term archival preservation.

Nevertheless, unlike industrial digital twin systems that rely heavily on real-time synchronization through IoT and sensor-based infrastructures, heritage-focused applications often require phased and adaptive implementation strategies due to limitations in historical datasets, technological accessibility, and conservation sensitivity (Dembski et al., 2020). The findings therefore support the argument that digital twin implementation within historical urban environments must remain context-specific and flexible rather than universally standardized.

In the Sri Lankan context, the study also highlights the necessity of adopting low-cost and adaptable workflows. The reliance on archival drawings, historical photographs,

SketchUp modelling, and AR-assisted visualization reflects practical constraints commonly faced in developing countries, where access to advanced scanning technologies such as LiDAR and continuous monitoring systems remains limited. Consequently, the proposed framework contributes toward establishing an accessible conceptual foundation for future heritage-oriented digital twin development within resource-constrained urban contexts.

#### 4.2.3 Challenges in Using Digital Twins for Cultural Heritage Preservation in the Built Environment

The concluding portion of the study identified various challenges and mitigation tactics for implementing digital twins in heritage conservation through semi-structured interviews with ten industry experts.

The challenges identified and the relevant mitigation tactics are as outlined below:

1. High-Resolution Data Collection: It can be difficult to capture precise data for heritage sites, particularly for hard-to-reach or complex areas. Furthermore, unavailable historical data can impede the creation of an accurate twin. To mitigate this, advanced tools like LiDAR and photogrammetry should be utilized for high-resolution 3D modelling. Additionally, artificial intelligence can be employed to reconstruct missing historical information by predicting gaps in the data.
2. Software Complexity and High Costs: The expertise and technology required for maintaining digital twins are often expensive, and the necessary software tools can be complex, requiring specialized training. Mitigation strategies include seeking grants and funding from governmental or non-governmental heritage organizations. It is also recommended to implement training programs for stakeholders and utilize open-source software to lower costs.
   The proposed workflow also aligns with previous heritage-oriented digital twin studies that integrate HBIM, photogrammetry, and visualization technologies to support cultural heritage documentation and interpretation (Jouan & Hallot, 2019; Massafra et al., 2022). However, unlike many existing studies conducted within technologically advanced contexts, the present framework adopts a comparatively low-cost and adaptable approach using archival records, SketchUp modelling, and AR-assisted comparative visualization suitable for developing-country contexts.
3. Data Management and Integration: It is challenging to integrate different data types, such as environmental data and 3D models, from multiple sources. Efficiently managing large data volumes while ensuring accessibility and integrity is also difficult. To address this, the industry should adopt standardized data protocols and formats to ensure compatibility, while leveraging cloud-based solutions for more effective data processing and storage.
   The findings support the observations of Dembski et al. (2020) and Semeraro et al. (2021), who emphasize that digital twin systems cannot be universally standardized across all built environment applications. Within the Sri Lankan context, these limitations become more significant due to restricted access to advanced scanning technologies and limited digital heritage infrastructure.
4. Legal and Ethical Concerns: Protecting the security and privacy of data is crucial, particularly regarding culturally sensitive information. Navigating legal regulations for data sharing and collection is also necessary. Mitigation involves creating

transparent data management policies that respect privacy and cultural sensitivities, ensuring all legal guidelines are followed and proper permissions are obtained.

The challenges identified through the professional interviews are consistent with findings reported in prior digital twin literature, particularly regarding data interoperability, software complexity, and high implementation costs (Fuller et al., 2020; Sharma et al., 2022). Ethical concerns relating to the digitization of culturally sensitive heritage assets have also been highlighted in previous cultural heritage studies (Pasupuleti, 2025). The findings therefore reinforce the need for phased and context-sensitive digital twin development strategies for heritage conservation projects.

## 5. CONCLUSIONS

In summary, the "digital twin" concept has become a significant force in the construction and architecture industries, serving as a vital tool for maintaining up-to-date and accurate digital mirrors of physical assets. Over the last decade, interdisciplinary research has highlighted the effectiveness of historic building information modelling for behaviour analysis, performance modelling, and the preventive maintenance of heritage sites. However, implementing a digital twin remains a complex task that requires a customized approach for every individual project. In the context of Sri Lanka, the adoption of digital twins lags behind more technologically advanced nations. This delay is worsened by a lack of professional consensus regarding their utility and operation, as well as sparse research on their specific role in maintaining cultural heritage. The conservation of historical structures is essential, as modernization threatens the cultural significance of urban areas like Slave Island in Colombo. Digital twins provide a viable solution by generating detailed virtual models that archive historical context and architectural features.

This research utilized a comprehensive literature review, a focused case study on the De Soysa building within the Slave Island streetscape, the development of a site-specific framework, and professional interviews. These steps successfully identified both the challenges and the strategies for successful digital twin implementation. For the De Soysa building, the digital twin offers a means to preserve its legacy amid rapid urban expansion through documentation, virtual reconstruction, and interactive AR tools. Ultimately, project-specific digital twins are vital for managing urban heritage and safeguarding cultural identity, ensuring these structures remain part of our collective history for future generations. The study concludes by emphasizing that while data capture, costs, and ethics present hurdles, the use of advanced technologies like laser scanning, standardized data formats, and strategic funding can significantly enhance how cultural heritage is preserved through digital twins. The development and testing of detailed prototype visualizations and user-interactive models are identified as important directions for future research.

## 6. REFERENCES

Alam, K. M., & Saddik, A. E. (2017). C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems.. *IEEE Access*, *5*, 2050-2062, https://doi.org/10.1109/ACCESS.2017.2657006

Attaran, M., & Celik, B. G. (2023). Digital twin: Benefits, use cases, challenges, and opportunities. *Decision Analytics Journal*, *6*, 100165. https://doi.org/10.1016/j.dajour.2023.100165

Bandara, D. W. J. W., Ranadewa, K. A. T. O., Parameswaran, A., Eranga, B. A. I., & Nawarathna, A. (2023). Lean iceberg model to minimise barriers for digital twin implementation: Sri Lankan construction industry perspective. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, & K. A. T. O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium* (pp. 671-685). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2023.55

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction, 114*, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bruno, F., Bruno, S., De Sensi, G., Luchi, M.-L., Mancuso, S., & Muzzupappa, M. (2010). From 3D reconstruction to virtual reality: A complete methodology for digital archaeological exhibition. *Journal of Cultural Heritage, 11*(1), 42-49. https://doi.org/10.1016/j.culher.2009.02.006.

Ćosović, M., & Maksimović, M. (2022). Application of the digital twin concept in cultural heritage. In A. Amelio, S. Montelpare, & D. Ursino (Eds.), *Proceedings of the 1st International Virtual Conference on Visual Pattern Extraction and Recognition for Cultural Heritage Understanding (VIPERC 2022)* (Vol. 3266, pp. 1-13). CEUR-WS.org. Retrieved from https://ceur-ws.org/Vol-3266/paper8.pdf

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Dagnaw, G., Capuano, R., & Muccini, H. (2026). Digital twins for cultural heritage: A systematic analysis of the state of the art. *ACM Computing Surveys*, 58(9), 237. https://doi.org/10.1145/3793541

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany. *Sustainability, 12*(6), 2307. https://doi.org/10.3390/su12062307

Dore, C., & Murphy, M. (2017). Current state of the art historic building information modelling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W5*, 185-192. https://doi.org/10.5194/isprs-archives-XLII-2-W5-185-2017

Egodawela, S., Buddika, H. A. D. S., Harischandra, W. A. N. I., Mahmoodian, M., & Mathota, M. R. S. N. M. (2023). Conservation and management of ancient stupa using digital twins: A case study of UAV-based 3D photogrammetric digitization of Rankoth Wehera Stupa. In R. Dissanayake, P. Mendis, K. Weerasekera, S. De Silva, S. Fernando, C. Konthesingha, & P. Gajanayake (Eds.), *ICSBE 2022: Proceedings of the 13th International Conference on Sustainable Built Environment* (pp. 493-508). Springer Singapore. https://doi.org/10.1007/978-981-99-3471-3_35

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access, 8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Grieves, M. (2014). *Digital twin: Manufacturing excellence through virtual factory replication* [White paper]. University of Michigan. https://theengineer.markallengroup.com/production/content/uploads/2014/12/Digital_Twin_White_Paper_Dr_Grieves.pdf

Grieves, M. (2016, August). *Origins of the digital twin concept*. Research Gate. Retrieved July 3, 2026, from https://doi.org/10.13140/RG.2.2.26367.61609

Guo, M., Shang, X., Zhao, J., Shi, Y., Sun, M., Huang, M., Wang, G., & Liao, L. (2025). Digital twin models for architectural heritage conservation. *Journal of Building Engineering, 112*, 113792. https://doi.org/10.1016/j.jobe.2025.113792

Hu, W., Zhang, T., Deng, X., Liu, Z., & Tan, J. (2021). Digital twin: A state-of-the-art review of its enabling technologies, applications and challenges. *Journal of Intelligent Manufacturing and Special Equipment, 2*(1), 1–34. https://doi.org/10.1108/JIMSE-12-2020-010

Huzzat, A., Anpalagan, A., Khwaja, A. S., Woungang, I., Alnoman, A. A., & Pillai, A. S. (2025). A comprehensive review of digital twin technologies in smart cities. *Digital Engineering, 4*, 100040. https://doi.org/10.1016/j.dte.2025.100040

Jouan, P., & Hallot, P. (2019). DIGITAL TWIN: A HBIM-based methodology to support preventive conservation of historic assets through heritage significance awareness. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W15*, 609-615. https://doi.org/10.5194/isprs-archives-XLII-2-W15-549-2019

Kallio, H., Pietilä, A. M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing, 72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kudasinghe, K. S. K. N. J., & Jeewananda, W. D. B. J. (2024, September 26-27). Utilizing digital twin technology in conserving cultural heritage within the built environment of Sri Lanka [Conference paper]. *17th International Research Conference*, General Sir John Kotelawala Defence University, Ratmalana, Sri Lanka. http://ir.kdu.ac.lk/handle/345/8744

Lucchi, E. (2023). Digital twins for the automation of the heritage construction sector. *Automation in Construction, 156*, 105073. https://doi.org/10.1016/j.autcon.2023.105073

Martínez-Carricondo, P., Carvajal-Ramírez, F., Yero-Paneque, L., & Navarro-Ortega, A. (2021). Combination of HBIM and UAV photogrammetry for modelling and documentation of forgotten heritage. Case study: Isabel II dam in Níjar (Almería, Spain). *Heritage Science, 9*, 95. https://doi.org/10.1186/s40494-021-00571-8

Massafra, A., Predari, G., & Gulli, R. (2022). Towards digital twin driven cultural heritage management: A HBIM-based workflow for energy improvement of modern buildings. *ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVI-5/W1-2022*, 149–157. https://doi.org/10.5194/isprs-archives-XLVI-5-W1-2022-149-2022

Munasinghe, J., Karunaratne, G., & Shafique, T. (2023). The invisible beyond the visible: The perils of urban regeneration in Colombo's Slave Island. In K. Dovey, T. Shafique, M. van Oostrum, & I. Chatterjee (Eds.), *Informal settlements of the Global South* (pp. 151–175). Routledge. https://doi.org/10.4324/9781003191407-13

Murphy, M., McGovern, E., & Pavia, S. (2013). Historic Building Information Modelling – Adding intelligence to laser and image-based surveys. *ISPRS Journal of Photogrammetry and Remote Sensing, 76*, 89–102. https://doi.org/10.1016/j.isprsjprs.2012.11.006

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering, 40*, 102726. https://doi.org/10.1016/j.jobe.2021.102726

Pasupuleti, M. K. (2025). Digital twin technology: Transforming cultural heritage preservation. *International Journal of Academic and Industrial Research Innovations, 5*(3), 121-130. https://doi.org/10.62311/nesx/97939

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE Publications.

Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry, 130*, 103469. https://doi.org/10.1016/j.compind.2021.103469

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration, 30*, 100383. https://doi.org/10.1016/j.jii.2022.100383

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Sun, Z., Jayasinghe, S., Sidiq, A., Shahrivar, F., Mahmoodian, M., & Setunge, S. (2025). Approach towards the development of digital twin for structural health monitoring of civil infrastructure: A comprehensive review. *Sensors, 25*(1), 59. https://doi.org/10.3390/s25010059

Therias, A., & Rafiee, A. (2023). City digital twins for urban resilience. *International Journal of Digital Earth, 16*(2), 4164–4190. https://doi.org/10.1080/17538947.2023.2264827

Woodward, A., & Heesom, D. (2019). Implementing HBIM on conservation heritage projects: Lessons from renovation case studies. *International Journal of Building Pathology and Adaptation, 39*(1), 96-114. https://doi.org/10.1108/IJBPA-06-2019-0054

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE Publications.

Gamagedara, H.M.D.C., Mallawaarachchi, H. and Jayakodi, J.A.D.K.S., 2026. Conceptualising a Value Stream Mapping (VSM) - based decision - making model for lean energy retrofitting of HVAC systems in high-rise buildings: Literature review approach. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 433-444. DOI: https://doi.org/10.31705/WCS.2026.32. Available from: https://ciobwcs.com/papers/

# CONCEPTUALISING A VALUE STREAM MAPPING (VSM) - BASED DECISION - MAKING MODEL FOR LEAN ENERGY RETROFITTING OF HVAC SYSTEMS IN HIGH-RISE BUILDINGS: LITERATURE REVIEW APPROACH

**H.M.D.C. Gamagedara[1], H. Mallawaarachchi[2] and J.A.D.K.S. Jayakodi[3]**

## *ABSTRACT*

*The built environment sector accounts for a considerable global energy consumption, making energy retrofitting a critical strategy for enhancing energy efficiency while reducing operational costs. However, conventional energy retrofitting exhibits several limitations often caused by fragmented interventions and limited long-term impacts. Previous studies across different industries demonstrated that the lean concept is capable of optimising processes while maximising the value. Hence, it is worth to explore on how to integrate lean concepts in energy retrofitting to optimise energy consumption and energy costs. As the initial step, this study aims to investigate the value stream mapping (VSM) as a decision-making approach for lean energy retrofitting through a non-systematic review approach. The collected data were analysed using thematic analysis technique. The findings reveal that the incorporation of the lean concept in energy retrofitting enables various advantages. Further, VSM, one of the key lean tools, can be identified as a promising solution for energy retrofitting that enables facilities managers to visualise energy flows and identify non-value adding items. Secondary data evidence indicates that VSM-guided interventions can yield significant reductions in both energy consumption and project lead times compared to conventional methods. Accordingly, this study proposed a conceptual VSM-based decision-making model for lean energy retrofitting in HVAC systems in high-rise buildings as the key outcome of this research. Overall, the study identified that lean-integrated energy retrofitting facilitates a more adaptive, resource-efficient, and sustainable approach for energy retrofitting than the conventional method.*

***Keywords:*** *Energy Retrofitting; High-rise Buildings; HVAC System; Lean Energy Retrofitting; Value Stream Mapping.*

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, dilushichamudika99@gamil.com
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, harshinim@uom.lk
[3] MSc scholar, Department of Facilities Management, University of Moratuwa, Sri Lanka, kavishkaj19@gmail.com

# 1. INTRODUCTION

Energy consumption in buildings has been a significant concern since the late 20th century, particularly due to its environmental and economic impacts (Omer, 2008; Shahid et al., 2025). According to Di Foggia (2018), the building sector stands out as one of the largest energy consumers globally, accounting for nearly 50% of total annual energy usage. The global energy demand in buildings has steadily increased due to urbanization and economic growth in many developed countries. The combined energy consumption of residential and commercial buildings now represents between 20% and 40% of total energy use, surpassing sectors like industry and transportation (Pérez-Lombard et al., 2008). Some building systems, such as HVAC systems and lighting systems are especially energy-intensive in buildings, and inefficiencies arising from design flaws, occupant behaviour, and maintenance practices result in significant energy wastage (Pompei et al., 2023). Also in Sri Lanka, as a developing country, the energy demand for buildings is rising rapidly due to strong economic growth and ongoing urban development (Siriwardhana & Namal, 2017). Olatunde et al. (2024) demonstrated that some buildings still use outdated HVAC systems and lack energy-efficient design features, resulting in high electricity consumption and operational costs.

To regulate this excessive energy consumption for HVAC systems in buildings, different approaches, including renewable integration, demand response, passive design, and energy retrofitting, have been adopted. Among these approaches, energy retrofitting is widely recognised as a cost-effective means of reducing consumption and operational costs without constructing new buildings (Ascione et al., 2021). Energy retrofitting means upgrading existing building systems to improve energy efficiency. However, conventional retrofit approaches often focus narrowly on technical upgrades and neglect process inefficiencies and operational waste (Dadzie et al., 2022). In 2003, Womack and Jones (2003) introduced lean principles to overcome these limitations in conventional retrofitting to eliminate waste and to optimize value, which were later applied to the energy management domain (Womack & Jones, 2003). When considering lean integration in energy retrofitting, it aims to systematically remove non-value-adding activities and streamline retrofit processes, thereby improving energy efficiency and reducing costs more effectively (Antony & Laureani, 2002; Ahamad et al., 2022). Among various lean tools, VSM can be identified as one of the most suitable approaches for energy retrofitting, as it facilitates resource optimisation and cost savings. VSM has been shown to effectively visualize energy usage, identify bottlenecks in building operations, and optimize energy consumption (Antony & Laureani, 2012). Several studies have demonstrated the utility of VSM in energy management, particularly in identifying inefficiencies in HVAC systems and implementing strategies to improve energy flow (Stanica et al., 2021). However, despite this significance, limited attention has been paid to the integration of VSM for energy retrofitting, particularly for HVAC systems in buildings.

Hence, this research aims to address this knowledge gap, focusing on developing a VSM-based decision-making model for lean energy retrofitting of HVAC, as it is the highest energy consumption system in high-rise buildings. This paper presents the conceptual model developed for integrating VSM and lean energy retrofitting of HVAC systems in high-rise buildings. To achieve this aim, two (02) research objectives are formulated: (i) To review the applications of VSM-based decision making for lean energy retrofitting of

HVAC systems, and (ii) To develop a conceptual decision-making model integrating VSM for lean energy retrofitting in HVAC systems in high-rise buildings.

# 2. LITERATURE REVIEW

## 2.1 ENERGY RETROFITTING OF HVAC IN BUILDINGS

According to Hossain et al. (2023) reveals that HVAC systems typically constitute over 40% of the total energy consumption in commercial office settings, followed by 20-25% of lighting, 15%-20% of plug loads, and 10%-15% of others from the total energy, which are critical areas for potential energy-saving strategies. The efficiency of HVAC equipment plays a crucial role in determining energy consumption (Alves et al., 2016; Olatunde et al., 2024). Recent research highlights that improving HVAC efficiency can reduce energy bills by 20-40%, depending on the building type and climate zone, representing one of the most cost-effective energy-saving strategies in commercial offices (Feng et al., 2024). Accordingly, the optimization of HVAC systems is a critical aspect of improving energy efficiency, reducing operational costs, and enhancing indoor environmental quality in buildings (Loonen, 2018). Various methods and strategies have been developed to address inefficiencies in HVAC operations, ranging from traditional control techniques to advanced intelligent systems (Buffa et al., 2021). Among these strategies, Duran (2018) identified HVAC energy retrofitting enable cost-efficiency approach while enhancing occupant comfort.

According to Ahmed and Asif (2021), energy retrofitting can be defined as “Upgrade a building's components which directly or indirectly impact the energy consumption of the building”. Previous studies demonstrated that energy retrofitting has become a pivotal approach for optimizing energy costs in office buildings, due to its economic and environmental benefits (Zuhaib, 2019; Martek et al., 2025). A study conducted by Bleyl et al. (2019) to explore the long-term cost benefits of retrofitting in office buildings found that energy retrofits in commercial office spaces can reduce energy consumption by up to 10%, with further savings achieved through optimized building management systems (BMS) (Data, 2021). By reducing energy costs, retrofitting also enhances building value, supporting both economic and environmental sustainability (Iwuanyanwu et al., 2024). A need to incorporate climate resilience in retrofit planning, as increased temperatures due to climate change exacerbate cooling demands, making energy-efficient retrofitting essential for future cost optimization (Robert & Ballarini, 2023). Furthermore, to improve the energy retrofitting can combine the principles of the lean concept to optimize the energy cost and enhance the building's energy performance.

## 2.2 TRADITIONAL VS VSM-BASED LEAN ENERGY RETROFITTING DECISIONS

Conventionally, the decision-making process for energy retrofitting follows a linear, phase-based model aimed at achieving energy efficiency improvements within existing buildings (Luther & Rajagopalan, 2014). According to Luther and Rajagopalan (2014), this process can be segmented into five (05) key phases, including (i) Project set up and pre retrofitting survey, (ii) Energy auditing and performance assessment, (iii) Identification of retrofit options, (iv) Site implementation and commissioning, and (v) Validation and verification and presented in Figure 1.

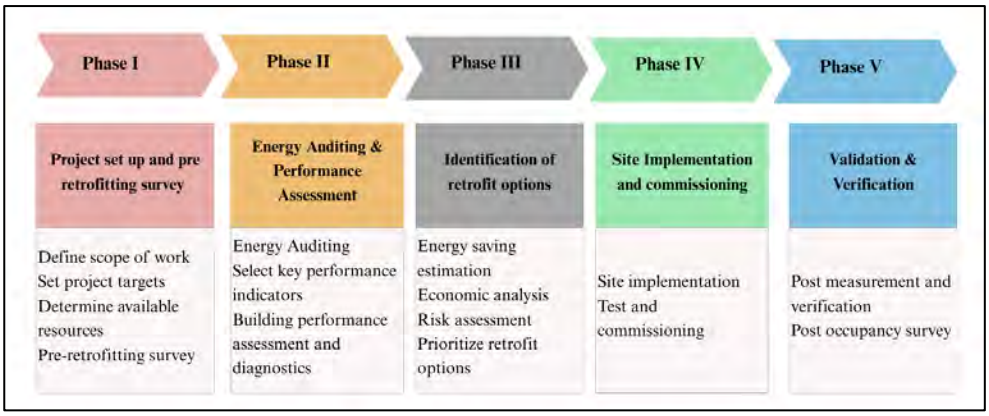



*Figure 1: Conventional energy retrofitting process*

While this conventional approach has provided structured guidelines for energy retrofitting, it has certain limitations. One of the main drawbacks is the rigidity of the phase-based model, which can lead to delays, increased costs and inefficiencies when unforeseen issues arise during the retrofitting process (Albatici et al., 2016). The linear progression of the model does not always accommodate the dynamic and complex nature of energy retrofitting, which often requires flexible adaptation to emerging challenges.

Hence, the integration of lean concept in energy retrofitting alleviates these limitations while maximizing energy efficiency while minimizing resource consumption, using low-impact, cost-effective measures that optimize existing building systems without the need for extensive modifications. By integrating lean principles, the energy retrofitting process becomes less reliant on heavy investments in new infrastructure, thus ensuring that the long-term benefits of sustainability and cost reduction can be realized in both the short and long term (Naylor et al., 2018; Panakaduwa et al., 2025). Thus, while traditional retrofitting offers substantial energy savings and performance improvements, the lean retrofitting approach presents a more efficient, cost-effective, and environmentally conscious alternative, aligning more closely with modern principles of sustainability and waste reduction (Ramos & Almeida, 2018). Table 1 presents comparison between conventional retrofitting and lean retrofitting.

*Table 1: Comparison between conventional retrofitting and lean retrofitting*

| Conventional Retrofitting | Lean Retrofitting |
|---|---|
| Achieves substantial energy savings by improving building systems | Focuses on a more efficient approach that optimizes overall processes |
| Improves building performance through system upgrades | Delivers improvements in a more cost-effective manner by reducing inefficiencies |
| Often involves high implementation costs due to major upgrades | Reduces costs by minimizing waste generation |
| Mainly focuses on technical upgrades of building systems | Emphasizes optimized utilization of existing resources |
| Limited emphasis on waste reduction | Environmentally conscious approach by actively minimizing waste |
| Primarily energy-performance oriented | Strongly aligns with sustainability principles through continuous improvement and resource efficiency |

Lean energy retrofitting for consumption optimisation involves applying lean principles to upgrade building systems, such as HVAC systems, to minimise energy consumption, reduce waste, and lower operational costs (Correia et al., 2022). In terms of the lean integration in energy retrofitting, VSM can be identified as a visual tool used in lean methodologies to analyse and optimise processes by identifying waste, inefficiencies, and areas for improvement (Rother, 1999; Martek et al., 2025). VSM plays a crucial role in streamlining retrofitting workflows, reducing energy losses, and enhancing overall efficiency.

# 3. RESEARCH METHODOLOGY

This study carried out a non-systematic narrative literature review to achieve the proposed aims and objectives. Ferrari (2015) also emphasised that narrative reviews can be used to synthesise general arguments, critically appraise previous studies, while also providing rationales for future research and speculating on potential new types of interventions. Accordingly, since this is the initial step in integrating the lean concept with energy retrofitting, a narrative review approach was more suitable for identifying the existing body of knowledge, evolving trends, current research frontiers, and gaps for this research domain.

Accordingly, the literature review was carried out in the Scopus database related to the lean concept, value stream mapping, energy retrofitting, HVAC systems, and high-rise buildings. The search was confined to articles based on the article title, abstract, and keywords using the search string: TITLE-ABS-KEY (“lean” OR “lean concept” OR “lean methodology” OR “lean method” OR “value stream mapping) AND TITLE-ABS-KEY (“energy retrofit” OR “energy renovation” OR “energy upgrade” OR “energy improvement” OR “energy efficiency” OR “energy performance” OR “energy optimisation” OR “HVAC retrofit” OR “HVAC upgrade” OR “HVAC renovation”) AND TITLE-ABS-KEY (“high-rise building” OR “tall building” OR “commercial building”). Initially, the database yielded 278 articles, and then several filtration criteria were applied, including Publication year: 2016 – 2026; Language: English; Document type: Article; Source type: Journal, and removing non-relevant subject areas to enhance the credibility of the retrieved literature. Finally, 52 articles were selected and analysed qualitatively using thematic analysis technique to identify applications of VSM for effective decision making in lean energy retrofitting of HVAC systems, providing a foundation for conceptual model development.

# 4. RESEARCH FINDINGS

## 4.1 APPLICATIONS OF VSM FOR LEAN ENERGY RETROFITTING DECISIONS OF HVAC

VSM provides a holistic view of the entire retrofitting process, ensuring that improvements are implemented strategically and sustainably (Hashempour et al., 2020). The significance of VSM in energy retrofitting lies in its ability to identify hidden inefficiencies and energy losses that may not be immediately apparent (Taher & Al Bashar, 2024). Many buildings experience unnecessary energy consumption due to poorly optimized HVAC systems, outdated lighting controls, insulation gaps, and inefficient equipment operation (Khafiso et al., 2025). VSM helps facility managers pinpoint these inefficiencies by creating a step-by-step visualization of energy use and

identifying non-value-added activities within the retrofitting process (Shou et al., 2017). For example, an energy audit might reveal that a building's air conditioning system operates continuously, even in unoccupied spaces, leading to excessive energy consumption (Dadzie et al., 2022). By using VSM, facility managers can analyse why this inefficiency exists, whether it is due to lack of automation, incorrect thermostat settings, or system malfunctions, and implement targeted solutions such as demand-controlled ventilation or occupancy-based HVAC controls (Pompei et al., 2023). One of the primary benefits of VSM is its ability to streamline retrofitting workflows by eliminating process bottlenecks (Stadtländer, 2009). In traditional retrofitting projects, delays often occur due to inefficient procurement, lengthy approval processes, and poor coordination among stakeholders (Raimi & Newell, 2024). VSM allows facility managers to map out the entire retrofitting process, from initial energy audits to project implementation and monitoring, identifying areas where time and resources are wasted (Seth et al., 2017). By analysing lead times, energy consumption patterns, and process inefficiencies, VSM enables the development of an optimized workflow that reduces downtime, accelerates implementation, and ensures that energy-saving measures are deployed effectively (Madushika et al., 2023).

A key aspect of VSM in energy retrofitting is its ability to provide quantifiable insights that guide decision-making (Fontoura et al., 2023). By measuring energy consumption at different stages of the retrofitting process, VSM helps facility managers identify which interventions will yield the highest Return on Investment (ROI) (Womack & Jone, 2003). For instance, if lighting upgrades provide quick energy savings but HVAC improvements require a longer payback period, VSM helps prioritize the most impactful energy-saving measures first (Rother, 1999). This strategic approach ensures that resources are allocated efficiently, leading to cost-effective retrofitting projects that maximize energy efficiency (Antony & Laureani, 2012). Several case studies demonstrate the effectiveness of VSM in improving energy retrofitting outcomes. For example, a large commercial office building in the United States implemented VSM to analyse HVAC inefficiencies and excessive energy use. The VSM process revealed that air handling units (AHUs) were running at full capacity during off-peak hours, leading to unnecessary energy consumption (Albatici et al., 2016).

By redesigning the HVAC schedule using demand-based controls and occupancy sensors, the facility reduced its energy costs by 20% within one year. Similarly, a manufacturing facility in Germany applied VSM to its lighting retrofit project, identifying delays in material procurement and installation scheduling. By optimizing the procurement process and implementing Just-in-Time (JIT) delivery for LED lighting components, the company reduced project lead time by 30% and achieved a 15% reduction in total energy costs. VSM is a powerful Lean tool that enhances energy retrofitting by identifying inefficiencies, reducing waste, and optimizing workflows (Stanica et al., 2021). By providing a clear visualization of energy consumption patterns and process flows, VSM enables facility managers to implement targeted and strategic interventions that maximize energy savings (Kumanayake et al., 2018). The successful application of VSM in office buildings, manufacturing plants, and university campuses highlights its potential to transform traditional retrofitting approaches into more efficient, cost-effective, and sustainable processes (Stadtlander, 2009). As buildings continue to seek energy efficiency and carbon footprint reduction, the use of VSM in Lean energy retrofitting will play a critical role in achieving long-term sustainability goals.

## 4.2 THE PROPOSED VSM-BASED DECISION-MAKING MODEL FOR LEAN ENERGY RETROFITTING OF HVAC SYSTEMS IN HIGH-RISE BUILDINGS

The application of Value Stream Mapping (VSM) in the HVAC operation and maintenance phase offers critical insights into system performance, inefficiencies and opportunities for process optimization. In this context, the VSM serves not only as a Lean management tool but also as a performance diagnostic framework that aligns with sustainable building operation goals. Accordingly, a VSM-based decision-making model for lean energy retrofitting of HVAC system in high-rise buildings was conceptualised as shown in Figure 1, which illustrates the Value Stream Mapping (VSM) framework applied to the HVAC operation and maintenance (O&M) process within a Lean Energy Retrofitting context. The diagram is grounded in Lean production theory, where VSM is used as a diagnostic and analytical tool to distinguish between value-adding and non-value-adding activities across a process flow.

In this model, the HVAC system is represented as an integrated energy system, where environmental conditions (hot and cool air) are continuously monitored through a feedback control loop. The system is governed by the Building Management System (BMS), which acts as the central decision-making interface connecting field devices such as thermostats, air handling units (AHUs), chillers, and control room operations.

The developed model focuses on the operational phase of the HVAC lifecycle, where repetitive tasks begins with, temperature sensing, followed by signal processing, chiller activation, water circulation, air distribution, and finally room cooling. Each stage is mapped with associated operational performance indicators including process time, cycle time, waiting time, downtime, and energy consumption. This enables the identification of inefficiencies such as delays in signal transmission, system idling, and energy losses during equipment transitions.

The lower section of the figure distinguishes between non-value-adding time and value-adding process time, reinforcing Lean principles by highlighting where inefficiencies accumulate in the HVAC operational cycle. This supports decision-making for energy retrofitting interventions such as automation upgrades, predictive control systems, and optimization of high-energy components.

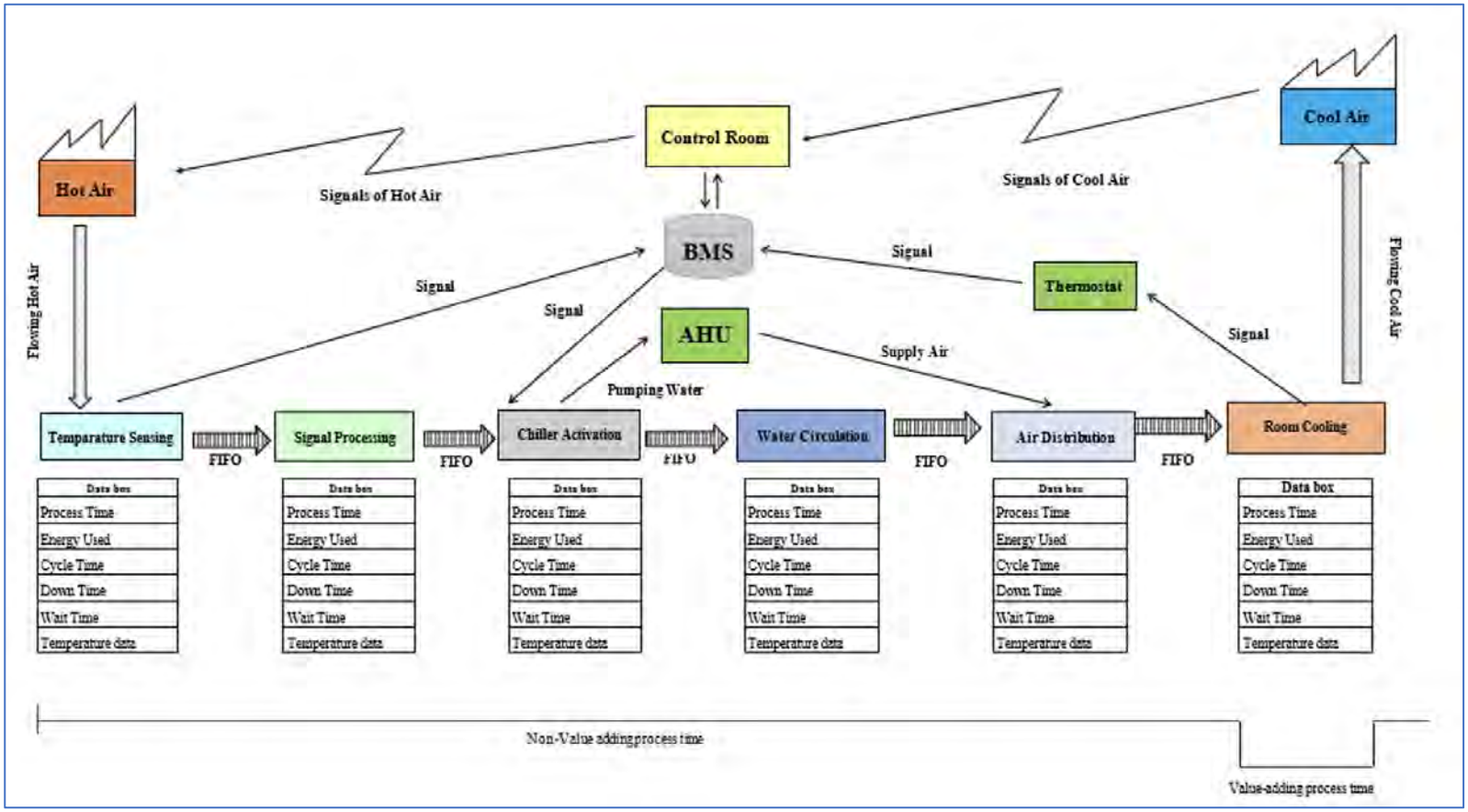



*Figure 1: Proposed VSM-based decision-making model for energy retrofitting in HVAC systems in high-rise buildings*

# 5. CONCLUSIONS AND THE WAY FORWARD

Increasing energy demand is one of the critical concerns in the current built environment sector. In this background, energy retrofitting gained considerable attention due to its various advantages in terms of economic and sustainability aspects. However, conventional energy retrofitting practices exhibit several limitations, such as fragmented, technology-focused, lack of process efficiency, and poor integration. Hence, this study aims to integrate VSM with energy retrofitting in HVAC systems for optimizing energy consumption and energy costs in high-rise buildings. As the initial step of this collaboration, this study conducted a non-systematic literature review in this research domain to identify the current research frontiers. Accordingly, several key research findings have been derived, integrating VSM for lean energy retrofitting decisions in buildings.

This study contributes to the body of knowledge by introducing a novel approach to energy retrofitting, emphasizing the importance of considering energy efficiency as a process flow issue rather than a technical challenge. The research demonstrates that lean principles, when integrated with traditional retrofitting practices, can provide a more sustainable and effective solution for optimising energy consumption in office buildings. By using VSM to map energy flows, identify inefficiencies, and prioritize improvements, building managers can achieve significant long-term energy savings while improving operational efficiency. For industry practitioners, the research highlights the importance of adopting a systemic approach to energy retrofitting. It recommends integrating lean principles into energy management strategies, encouraging the use of VSM in decision-making, and fostering professional development to ensure the effective implementation of lean practices. Further, the findings revealed from the study, particularly the conceptual model, support industry practitioners in decision-making in reducing unnecessary operational costs while maintaining proper indoor environmental quality conditions.

Despite the academic and industry contributions, this study also reveals some significant research gaps. Since the model was conceptually designed, further studies can be recommended to focus on the empirical evaluation of this model using a real-world case study. These studies can provide solid evidence regarding the effectiveness of incorporating lean principles in HVAC energy retrofitting. Further, a comparative analysis between conventional and lean-integrated energy retrofitting can be conducted to validate the operational and financial benefits of lean energy retrofitting.

Beyond this, it is recommended to focus on integrating novel technologies with lean energy retrofitting. Here, the incorporation of the Internet of Things (IoT), Building Information Modelling (BIM), Artificial Intelligence (AI), and Building Management Systems (BMS) can be considered. These collaborations can strengthen the informed decision-making on energy retrofitting based on real-time data.

# 6. REFERENCES

Ahamad, A. H., Zakaria, R., Aminudin, E., Abidin, N. I. A., Redzuan, A. A., Lau, S. E. N., Ahamad, N., & Khan, J. S. (2022). The influence of lean energy retrofitting initiatives on Malaysian school building. *AIP Conference Proceedings, 2644*, 050001. https://doi.org/10.1063/5.0107005

Ahmed, W., & Asif, M. (2021). A critical review of energy retrofitting trends in residential buildings with particular focus on the GCC countries. *Renewable and Sustainable Energy Reviews, 144*, 111000. https://doi.org/10.1016/j.rser.2021.111000

Albatici, R., Gadotti, A., Baldessari, C., & Chiogna, M. (2016). A decision making tool for a comprehensive evaluation of building retrofitting actions at the regional scale. *Sustainability, 8*(10), 990. https://doi.org/10.3390/su8100990

Alves, O., Monteiro, E., Brito, P., & Romano, P. (2016). Measurement and classification of energy efficiency in HVAC systems. *Energy and Buildings, 130*, 408–419. https://doi.org/10.1016/j.enbuild.2016.08.070

Antony, J., & Laureani, A. (2002). Critical Success Factors for the effective implementation of lean sigma: Results from an empirical study and agenda for future research. *International Journal of Lean Six Sigma, 3*(4), 274–283. http://dx.doi.org/10.1108/20401461211284743

Ascione, F., Bianco, N., Iovane, T., Mastellone, M., & Mauro, G. M. (2021). The evolution of building energy retrofit via double-skin and responsive façades: A review. *Solar Energy, 224*, 703–717. https://doi.org/10.1016/j.solener.2021.06.035

Bleyl, J. W., Bareit, M., Casas, M. A., Chatterjee, S., Coolen, J., Hulshoff, A., Lohse, R., Mitchell, S., Robertson, M., & Ürge-vorsatz, D. (2019). Office building deep energy retrofit: life cycle cost benefit analyses using cash flow analysis and multiple benefits on project level. *Energy Efficiency, 12*(51), 261–279. https://doi.org/10.1007/s12053-018-9707-8

Buffa, S., Fouladfar, M. H., Franchini, G., Gabarre, I. L., & Chicote, M. A. (2021). Advanced control and fault detection strategies for district heating and cooling systems—A review. *Applied Sciences (Switzerland), 11*(1), 1–32. https://doi.org/10.3390/app11010455

Correia, A., Coimbra, P., Moura, P., & Almeida, T. De. (2022). Smart thermostats for a campus microgrid: Demand control and improving air quality. *Energies, 15*(4), 1359. https://doi.org/10.3390/en15041359

Dadzie, J., Pratt, I., & Frimpong-Asante, J. (2022). A review of sustainable technologies for energy efficient upgrade of existing buildings and systems. *IOP Conference Series: Earth and Environmental Science, 1101*(2), 022028. https://doi.org/10.1088/1755-1315/1101/2/022028

Data, M. (2021). Development and analysis of a dynamic energy model of an office using a building management system (BMS) and actual measurement data. *Enerigies, 14*(19), 6419. https://doi.org/10.3390/en14196419

Di Foggia, G. (2018). A review on buildings energy consumption information. *Heliyon, 4*(11), e00953. https://doi.org/10.1016/j.heliyon.2018.e00953

Duran, Ö. (2018). *Evaluation of retrofitting strategies for post-war office buildings* [Doctoral Thesis, Loughborough University]. Loughborough University. https://hdl.handle.net/2134/32268

Feng, K., Chokwitthaya, C., & Lu, W. (2024). Exploring occupant behaviors and interactions in buildings with energy-efficient renovations: A hybrid virtual-physical experimental approach. *Building and Environment, 265*, 111991. https://doi.org/10.1016/j.buildenv.2024.111991

Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing, 24*(4), 230–235. https://doi.org/10.1179/2047480615Z.000000000329

Fontoura, L., De Mattos Nascimento, D. L., Neto, J. V., Garcia-Buendia, N., Garza-Reyes, J. A., Lima, G. B. A., Tortorella, G. L., Caiado, R. G. G., & Meiriño, M. J. (2023). Real-time energy flow mapping: A VSM-based proposal for energy efficiency. *Journal of Cleaner Production, 419*, 137871. https://doi.org/10.1016/j.jclepro.2023.137871

Hashempour, N., Taherkhani, R., & Mahdikhani, M. (2020). Energy performance optimization of existing buildings: A literature review. *Sustainable Cities and Society,* 54. 101967. doi:10.1016/j.scs.2019.101967

Hossain, J., Kadir, A. F. A., Hanafi, A. N., Shareef, H., Khatib, T., Baharin, K. A., & Sulaima, M. F. (2023). A review on optimal energy management in commercial buildings. *Energies, 16*(4), 1609. https://doi.org/10.3390/en16041609

Khafiso, T., Adekunle, S. A., & Aigbavboa, C. (2025). Assessment of energy-saving strategies mitigating high energy usage in residential buildings. *Property Management, 43*(4), 540-561. https://doi.org/10.1108/PM-12-2024-0126

Kumanayake, R., Luo, H., & Paulusz, N. (2018). Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy and Buildings, 166*, 250–257. https://doi.org/10.1016/j.enbuild.2018.01.065

Loonen, R. (2018). Approaches for computational performance optimization of innovative adaptive façade concepts (978-90-386-4554-4). Eindhoven University of Technology. https://pure.tue.nl/ws/files/102239772/20180906_Loonen.pdf

Luther, M. B., & Rajagopalan, P. (2014). Defining and developing an energy retrofitting approach. *Journal of Green Building, 9*(3), 151–162. https://doi.org/10.3992/1943-4618-9.3.151

Madushika, U. G. D., Ramachandra, T., Karunasena, G., & Udakara, P. A. D. S. (2023). Energy retrofitting technologies of buildings: A review-based assessment. *Energies, 16*(13), 1–16. https://doi.org/10.3390/en16134924

Martek, I., Amirkhani, M., & Khan, A. A. (2025). Retrofitting for sustainable building performance: A scientometric–pestel analysis and critical content review. *Buildings, 15*(22), 4106. https://doi.org/10.3390/buildings15224106

Naylor, S., Gillott, M., & Lau, T. (2018). A review of occupant-centric building control strategies to reduce building energy use. *Renewable and Sustainable Energy Reviews, 96*, 1–10. https://doi.org/10.1016/j.rser.2018.07.019

Iwuanyanwu, O., Gil-Ozoudeh, I., Okwandu, A. C., & Ike, C. S. (2024). Retrofitting existing buildings for sustainability: Challenges and innovations. *Engineering Science & Technology Journal, 5*(8), 2616–2631. https://doi.org/10.51594/estj.v5i8.1515

Omer, A. M. (2008). Energy, environment and sustainable development. *Renewable and Sustainable Energy Reviews, 12*(9), 2265–2300. https://doi.org/10.1016/j.rser.2007.05.001

Panakaduwa, C., Coates, P., & Munir, M. (2025). Lean retrofit: Methods and application for best practice. In *International Retrofit Conference 2025*. University of Salford Energy House Labs. https://salford-repository.worktribe.com/output/4736764/lean-retrofit-methods-and-application-for-best-practice

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394–398. https://doi.org/10.1016/j.enbuild.2007.03.007

Pompei, L., Nardecchia, F., Viglianese, G., Rosa, F., & Piras, G. (2023). Towards the renovation of energy-intensive building: The impact of lighting and free-cooling retrofitting strategies in a shopping mall. *Buildings, 13*(6), 1409. https://doi.org/10.3390/buildings13061409

Raimi, D., & Newell, R. G. (2024). Global energy outlook comparison methods: 2024 update (Report 24-06). Resources for the Future. https://media.rff.org/documents/Report_24-06_Methodology_v3.pdf

Ramos, N. M. M., & Almeida, R. M. S. F. (2018). Building information modelling for energy retrofitting – A review. *Renewable and Sustainable Energy Reviews 89*, 249-260. https://doi.org/10.1016/j.rser.2018.03.064

Robert, A., & Ballarini, I. (2023). Supporting climate-neutral cities with urban energy modeling: A review of building retrofit scenarios, focused on decision-making , energy and environmental performance , and cost. *Sustainable Cities and Society, 98*, 104832. https://doi.org/10.1016/j.scs.2023.104832

Rother, M. (1999). Value stream mapping to create value and eliminate Muda. In J. Womack (Ed) *Learning to see*. Lean Enterprise Institute Brookline. https://www.researchgate.net/publication/244433983_Learning_to_See_Value_Stream_Mapping_to_Create_Value_and_Eliminate_Muda

Salwin, M., Pszczółkowska, K., Pałęga, M., & Kraslawski, A. (2023). Value-Stream Mapping as a Tool to Improve Production and Energy Consumption: A Case Study of a Manufacturer of Industrial Hand Tools. *Energies, 16*(21), 7292. https://doi.org/10.3390/en16217292

Seth, D., Seth, N., & Dhariwal, P. (2017). Application of value stream mapping (VSM) for lean and cycle time reduction in complex production environments: A case study. *Production Planning & Control, 28*(5), 398–419. https://doi.org/10.1080/09537287.2017.1300352

Shahid, M. N., Shahid, M. U., & Irfan, M. (2025). Advances in building energy management: A comprehensive review. *Buildings, 15*(23), 4237. https://doi.org/10.3390/buildings15234237

Shou, W., Wang, J., Wu, P., Wang, X., & Chong, H. Y. (2017). A cross-sector review on the use of value stream mapping. *International Journal of Production Research, 55*(13), 3906–3928. https://doi.org/10.1080/00207543.2017.1311031

Siriwardhana, M., & Namal, D. D. A. (2017). Comparison of energy consumption between a standard air conditioner and an inverter-type air conditioner operating in an office building. *SLEMA Journal, 20*(1–2), 1-6. https://doi.org/10.4038/slemaj.v20i1-2.5

Stadtländer, C. T. K.-H. (2009). Qualitative, quantitative, and mixed-methods research. *Microbe Magazine, 4*(11), 485–485. https://doi.org/10.1128/microbe.4.485.1

Stanica, D. I., Karasu, A., Brandt, D., Kriegel, M., Brandt, S., & Steffan, C. (2021). A methodology to support the decision-making process for energy retrofitting at district scale. *Energy and Buildings, 238*, 110842. https://doi.org/10.1016/j.enbuild.2021.110842

Taher, A., & Al Bashar, M. (2024). The impact of lean manufacturing concepts on industrial processes' efficiency and waste reduction. *International Journal of Progressive Research in Engineering Management and Science, 4*(6), 338-349. https://www.researchgate.net/publication/381250819

Olatunde, T.M., Okwandu, A.C., Akande, D. O. & Sikhakhane, Z.Q. (2024). Review of energy-efficient HVAC technologies for sustainable buildings. *International Journal of Science and Technology Research Archive, 6*(2), 012–020. https://doi.org/10.53771/ijstra.2024.6.2.0039

Womack, J. P. and D. T. Jones. (2003). *Lean thinking: Banish waste and create wealth in your corporation* (2nd ed.). Free Press. https://books.google.lk/books?id=2eWHaAyiNrgC&printsec=frontcover#v=onepage&q&f=false

Zuhaib, S. (2019). *Deep-retrofit decision-making support for achieving nearly zero-energy buildings with enhanced comfort* [Doctoral Dissertation, National University of Ireland]. Research Repository – University of Galway. http://hdl.handle.net/10379/15117

Hulathdoowage, N. D., Karunasena, G., Udawatta, N., Harrington, P. and Liu, C., 2026. Conceptualising an inclusive compliance approach to sustain the energy efficiency of new residential buildings. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 445-458. DOI: https://doi.org/10.31705/WCS.2026.33. Available from: https://ciobwcs.com/papers/

# CONCEPTUALISING AN INCLUSIVE COMPLIANCE APPROACH TO SUSTAIN ENERGY EFFICIENCY OF NEW SINGLE-FAMILY HOMES

**Nimasha Dilukshi Hulathdoowage[1], Gayani Karunasena[2], Nilupa Udawatta[3], Philip Harrington[4] and Chunlu Liu[5]**

## *ABSTRACT*

*Just as a roadworthy certificate for a motor vehicle relies on periodic inspections to verify continued safety, residential buildings should also be subject to scheduled compliance checks to ensure they continue to perform safely, efficiently, and sustainably over time. Moving from foresight to action, this study conceptualises an inclusive compliance approach to sustain the energy efficiency of new single-family homes through regular inspection cycles. Developed through a scoping review and desk study, the concept proposes: (i) a practical workflow and supporting equations to determine when new residential buildings should enter their first compliance cycle, and (ii) a method for defining a minimum penalty-free retrofit window to support timely, proactive upgrades, within the initial cycle. The study lays the groundwork for a forward-looking policy framework that strengthens inclusive compliance pathways, promotes early intervention, and advances the transition toward a resilient, energy-efficient, and regenerative housing sector.*

***Keywords:*** *Compliance Cycles; Energy Efficiency; Staged Retrofitting; Staged Renovation; Stepwise Retrofitting.*

## 1. INTRODUCTION

Many dwellings were built before the introduction of minimum energy performance standards, resulting in low baseline efficiency (Birchall et al., 2016). At the same time, millions of new homes are expected to be constructed in the coming decades (Grandolini et al., 2016). Although new homes may comply with energy standards at the point of construction, initial compliance does not ensure sustained performance over the building life cycle. Residential energy performance can drift over time due to climate change, changing occupancy patterns, degradation of building envelope thermal properties,

[1] Postgraduate Researcher, School of Architecture and Built Environment, Deakin University, Australia, n.hulathdoowage@research.deakin.edu.au
[2] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, gayani.karunasena@deakin.edu.au
[3] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, nilupa.udawatta@deakin.edu.au
[4] Technical Advisor, Strategy. Policy. Research., Australia, philip@strategypolicyresearch.com.au
[5] Professor, School of Architecture and Built Environment, Deakin University, Australia, chunlu.liu@deakin.edu.au

Heating, ventilation, and air conditioning (HVAC) system wear, and reduced airtightness (Anh & Pásztory, 2021; Lee et al., 2022; Metehan et al., 2025). Therefore, sustaining the energy efficiency of new homes requires a shift from one-time construction-stage compliance towards periodic reassessment and timely intervention.

Existing policy instruments provide useful foundations but remain limited for this purpose. A notable example is the District of Columbia's Building Energy Performance Standards, which introduced 5–6-year compliance cycles for existing commercial and multifamily buildings (The District of Columbia Department of Energy & Environment, 2023). However, these cycle lengths reflect the governance, finance, and capital-improvement cycles of larger buildings and are not designed to account for the affordability constraints, retrofit scope, access to finance, or local delivery capacity of single-family households (Maia et al., 2021; Calama-González et al., 2025). As a result, such approaches offer limited guidance for designing inclusive compliance mechanisms for new single-family homes.

In Europe, renovation passports have advanced the concept of staged retrofitting by organising building upgrades across multiple steps over an agreed timeline (European Union, 2018). However, the European renovation passport is not currently mandatory and lacks guidance on sustaining the performance of newly built homes (European Commission, 2025). Current instruments, therefore, provide limited support for designing an inclusive compliance approach to sustain the energy efficiency of new single-family homes.

Nevertheless, staged retrofitting provides a useful basis for rethinking residential compliance because it recognises that energy upgrades are not only technical interventions but also time- and budget-dependent household decisions (Maia et al., 2021). This is particularly important for single-family homes, where immediate corrective action after non-compliance may be financially unrealistic. However, existing staged retrofit approaches are primarily designed to improve the performance of existing buildings, rather than to support ongoing compliance in newly built homes (Maia et al., 2021; Calama-González et al., 2025). This creates a gap in the linkage between staged retrofit logic and periodic energy performance reassessment.

Accordingly, this study aims to conceptualise an inclusive compliance approach based on staged retrofitting, thereby contributing to the development of innovative and inclusive residential energy policy.

## 2. SINGLE-STEP VS STAGED RETROFITTING

Energy retrofitting can be implemented either as a single-step intervention, in which all selected measures are completed at once, or as a staged process, in which measures are sequentially implemented over time. While single-step retrofitting may deliver faster performance improvements, it often requires substantial upfront investment and may be difficult for households with limited financial capacity (Maia et al., 2024). Staged retrofitting, by contrast, allows retrofit measures to be implemented progressively as budgets accumulate, making it particularly relevant for policy approaches that seek to balance energy performance requirements with household affordability. Staged retrofitting, therefore, involves four elements: (i) retrofit start year, (ii) timing between steps, (iii) measures included in each step, and (iv) sequence of steps (Hulathdoowage et al., 2026; Maia et al., 2021). Common energy retrofit measures include insulating the

building envelope, replacing windows, installing efficient HVAC, lighting and hot-water systems, and integrating green roofs and walls and domestic PV (Madushika et al., 2023). These measures enhance energy efficiency and climate resilience, reduce emissions, and promote regenerative outcomes in the built environment.

## 3. RESEARCH METHODOLOGY

The research methodology comprises two phases. First, a scoping review was conducted to identify dynamic parameters that may contribute to post-construction drift in residential energy performance and to inform the timing of the first compliance cycle. The scoping review linked existing evidence on residential performance drift to the simulation-based compliance structure, ensuring transparent, literature-informed parameter selection and decision-stage formulation (Munn et al., 2022). Parameters were selected based on their documented influence on residential energy performance over time, relevance to conditioned single-family homes, suitability as time-varying inputs in building performance simulation, and support from recent peer-reviewed literature. The retained parameters were then coded through content analysis according to the compliance decision stage they informed: benchmark definition, performance simulation, deviation measurement, smoothing of abnormal years, and breach identification. These categories informed the structure of Model 1.

Second, a desk study examined existing staged-retrofitting optimisation models to identify common variables, constraints, and modelling approaches relevant to defining a penalty-free retrofit window. Models were selected based on their focus on staged retrofit optimisation, their application to residential buildings, the transparency of their development, publication quality, and recency. The selected studies were coded according to retrofit costs, household affordability, energy savings, maintenance, residual-value treatment, and optimisation technique. These coded elements informed Model 2. A hierarchical multi-objective optimisation structure was adopted for two reasons: (1) the policy and household objectives are related yet distinct, and (2) Model 2 involves discrete decisions regarding the selection and timing of retrofit measures within a linear optimisation framework (Halffmann et al., 2022). This hierarchy prioritises the minimum penalty-free retrofit window before optimising household cash flow.

As this study proposes a conceptual decision-support framework, the models are not empirically calibrated at this stage. Rather, the study establishes a transparent, literature-informed set of equations and model structure as a necessary foundation for subsequent expert refinement and case-study testing within the broader research programme.

## 4. THE PROPOSED COMPLIANCE APPROACH FOR NEW SINGLE-FAMILY HOMES

This section conceptualises a method for developing an inclusive compliance approach. This includes designing two linked models: (i) model 1: determining the timing of the first compliance cycle for new single-family homes to provide advance notice of the first checkpoint, and (ii) model 2: defining a penalty-free retrofit window to allow retrofitting for houses whose performance deviates from the initial benchmarks before imposing any penalty. The workflows of these two models are presented in Figure 1.

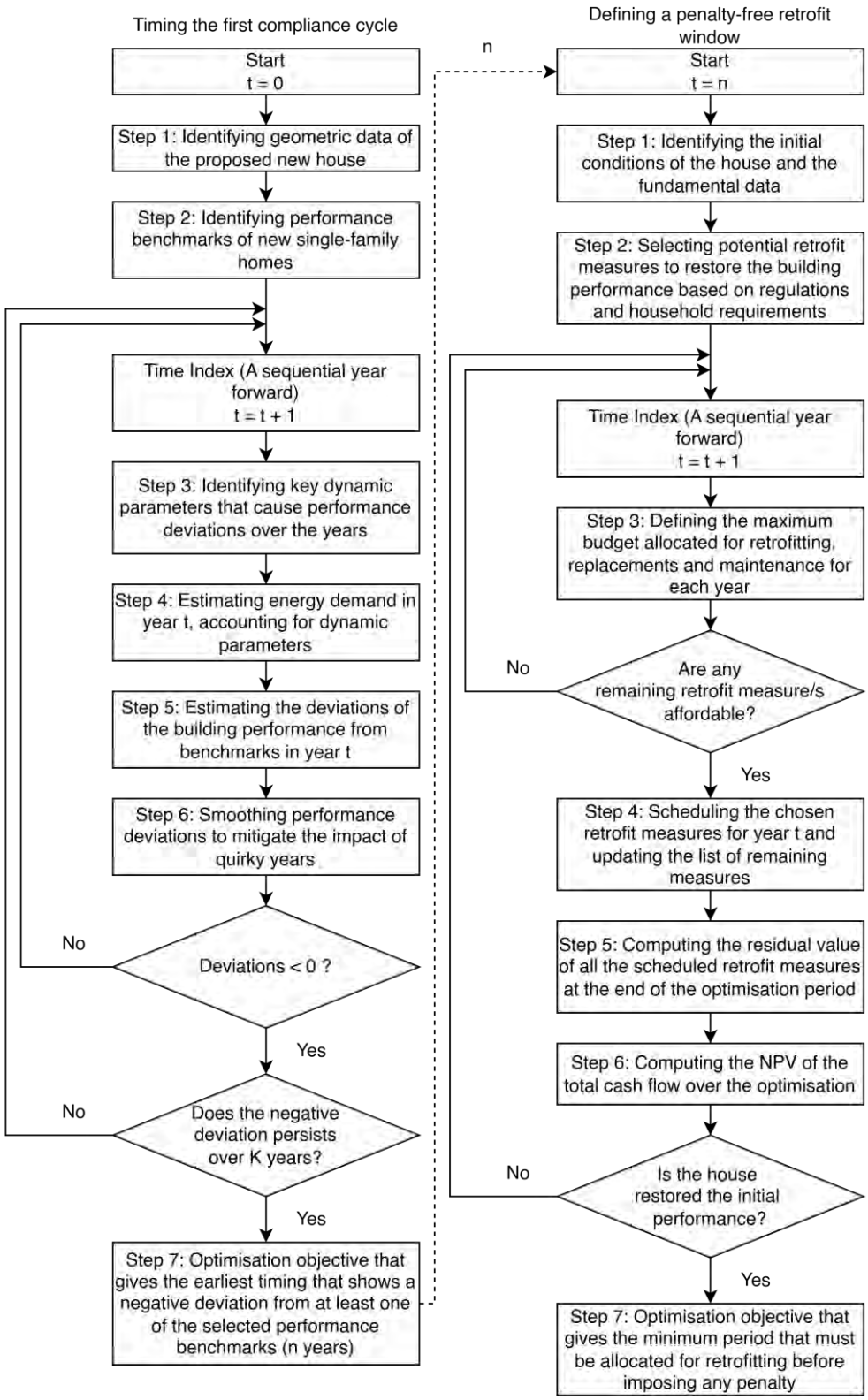



*Figure 1: The workflows of the two proposed models*

*Notes: t - any year within the optimisation period, K - the number of years used to check the persistence of the breach, n - the earliest year when the building's performance deviates from a benchmark, NPV – Net Present Value; The output of model 1 is an input to model 2.*

### 4.1 MODEL 1: TIMING THE FIRST COMPLIANCE CYCLE

Multiple dynamic factors can drive performance drift in residential buildings, including climate change and evolving occupancy patterns, material degradation that alters envelope thermal properties and HVAC efficiency, and broader system shifts such as changes in the electricity mix that modify emissions outcomes for the same energy use (Eleftheriadis & Hamdy, 2018; Anh & Pásztory, 2021; Metehan et al., 2025; Taki & Zakharanka, 2023). For example, Taki and Zakharanka (2023) found that ageing can substantially increase cooling demand, with projected rises of 9.53%–38.40% over 25 years in UAE housing. Pajek et al. (2023) proposed a multi-objective retrofit framework, showing that optimal retrofit packages could reduce energy demand by 75%, 66%, and 59% under current and future climates (RCP4.5 and RCP8.5). Together, these studies underscore that performance drift is multi-causal. Yet, much of the literature still evaluates the performance deterioration in new homes through a single dynamic factor, most often climate change, rather than accounting for multiple interacting drivers. This leaves no defensible basis for determining when the first compliance cycle should begin to evaluate the performance of new single-family homes. Hence, Figure 1 presents a novel model workflow for timing the first compliance cycle of new homes, and the subsequent section describes its key components. This workflow accommodates jurisdiction-specific benchmarks and varying sets of dynamic parameters, depending on the regulatory context, climate conditions, and the scope of the energy performance assessment.

- Step 1: Identifying the geometric data of the proposed new house

A building simulation, a computer model that predicts how a house will perform (Beausoleil-Morrison, 2020), requires geometric data that defines the structure's 3D form and the boundaries of its spaces, including the volumes of rooms or thermal zones, boundary surfaces such as walls, roofs, and floors, along with their areas, orientations, and vertices, and the placement and dimensions of openings like windows and doors. It also needs adjacency and boundary classifications, basic orientation, site context, and any shading geometry that influences sun and wind exposure.

- Step 2: Identifying performance benchmarks of new single-family homes

Any voluntary/ mandatory benchmarks applicable to new house construction in the selected country/ region should be identified. These benchmarks can also be expressed as functions of time. For example, the equations introduced by the Australian government for 7-star benchmarks for new residential buildings include parameters associated with outdoor temperature and humidity. While these parameters are currently derived from historical climate data, the equations could also accommodate climate change as occupants adjust their comfort settings over time. Still, the static benchmarks can also be integrated into the model. The number and type of benchmarks depend on the selected country or region. For example, Australia uses three thermal energy benchmarks: heating, cooling, and total thermal energy demand.

- Step 3: Identifying key dynamic parameters that cause deviations in energy efficiency over time

According to the scoping review, four key dynamic parameters that cause deviations in thermal energy efficiency over time were identified, including (i) climate variations (Chen et al., 2021), (ii) thermal conductivity of insulation (Anh & Pásztory, 2021), (iii) Coefficient of Performance (COP) of heat pumps (Eleftheriadis & Hamdy, 2018), and

(iv) airtightness (Moujalled et al., 2021). These parameters are applicable to conditioned single-family homes globally. However, when evaluating the whole-building energy efficiency, the efficiency of other appliances, such as stoves and solar hot water systems, should also be considered. Thus, the number of dynamic parameters depends on the scope of the energy performance assessment.

- Step 4: Estimating energy demand each year, accounting for dynamic parameters

Annual energy demand is estimated using building simulation, updating the model inputs based on relevant dynamic parameters while holding time-invariant attributes (e.g., geometry, zoning, and fixed construction properties) constant. Accordingly, the annual simulations use a climate representation for each year (e.g., an actual or scenario-based weather file) and incorporate the evolution of relevant dynamic parameters, extracted from contemporary experimental studies. Simulation outputs are reported as annual metrics, including cooling demand, heating demand, total thermal demand, whole-house energy demand, and renewable energy generation, with the selected output categories depending on the performance benchmarks. Where dynamic parameters are uncertain, simulations are repeated across defined ranges or distributions to quantify sensitivity and avoid over-interpreting minor differences.

- Step 5: Estimating performance deviations from benchmarks in each year

The performance deviation from each benchmark is calculated annually as the difference between the buffered benchmark and the measured energy performance (see Equation 01) to understand whether the building still complies with the benchmark. A buffer (i.e., a tolerance margin) is intentionally applied to the benchmark to account for normal, non-actionable variation, so that minor exceedances are not automatically interpreted as genuine underperformance. For example, a 5% buffer is appropriate in the Australian residential context because Nationwide House Energy Rating Scheme (NatHERS) itself treats ±5% as an "acceptable difference" when accrediting software for energy rating: at least 95% of simulations must align with the benchmark within ±5% (or ±5 MJ/m²·annum) for both heating and cooling loads (Nationwide House Energy Rating Scheme, 2024).

$$PD_i(t) = (1 + \delta) \times PB_i(t) - BP(t) \quad \forall i \in [1, 2, 3, \dots, x] \qquad (01)$$

where, $PD_i(t)$ = performance deviation from a selected performance benchmark in year t, $PB_i(t)$ = the selected performance benchmark in year t, δ = buffer margin for the deviation, BP(t) = the building performance in year t, and x = the number of prevailing performance benchmarks for new home construction

- Step 6: Smoothing performance deviations to mitigate the impact of anomalous years

Annual performance deviations, calculated using Equation 01, are smoothed to prevent false alarms of building performance deviations caused by anomalous years. Annual deviations can vary non-monotonically due to climate variability and nonlinear material degradation, so raw values may show a breach in 2031, a return to compliance in 2032, and a breach again in 2033, making the "earliest breach year" unstable and misleading. Thus, Equation 02 smooths performance deviations over ω years, while Equation 03 smooths over three years, offering a simplified version of Equation 02. The selected smoothing period (ω) should be an odd number to provide a symmetric, centred window

around the current year, ensuring an equal number of years on either side and avoiding bias towards earlier or later years when estimating the smoothed deviation.

$$\overline{PD}_i(t) = \frac{1}{\omega} \sum_{j \epsilon J} PD_i(t+j) \quad \forall J \epsilon [-h, (-h+1), \dots, (h-1), h] \qquad (02)$$

where, $\overline{PD}_i(t)$ = smoothed performance deviation from a selected performance benchmark in year t, $\omega$ = smoothing period, $PD_i(t + j)$ = performance deviation from a selected performance benchmark in any year within the smoothing period, h = $\frac{(\omega-1)}{2}$, where $\omega \equiv 1$, j = any year within the smoothing period, and J = all the years within the smoothing period

$$\overline{PD}_i(t) = [PD_i(t-1) + PD_i(t) + PD_i(t+1)]/3 \qquad (03)$$

where, $\overline{PD}_i(t)$ = smoothed performance deviation from a selected performance benchmark in year t, and $PD_i(t - 1)$, $PD_i(t)$, and $PD_i(t + 1)$ = performance deviation from a selected performance benchmark in year (t - 1), t, and (t + 1)

- Step 7: Optimisation objective

Model 1 aims to identify the earliest year of a breach by simulating how key dynamic factors influence building performance over time. Equation 04 sets out the compliance rule for the selected performance benchmarks within a given country or region. The breach year is defined as the first year in which building energy performance exceeds at least one benchmark and then remains above that benchmark for K consecutive years. This breach year marks the start of the first compliance cycle.

$$\tau = min\{t: [(\overline{PD}_1 \leq 0) \vee (\overline{PD}_2 \leq 0) \vee (\overline{PD}_3 \leq 0) \dots \vee (\overline{PD}_x \leq 0)] \; for\ K\ consecutive\ years\} \qquad (04)$$

where, $\overline{PD}[1](t)$ = smoothed deviation from the first benchmark, and x = the number of benchmarks, and K = the number of years used to check the persistence of the breach

## 4.2 MODEL 2: DEFINING A PENALTY-FREE RETROFIT WINDOW FOR THE FIRST COMPLIANCE CYCLE

Five optimisation models were selected for the desk-study case comparison. These models focused on minimising energy-related expenses in social housing and maximising cash flows for owner-occupied single-family homes across various European settings (De Moortel et al., 2018; Maia et al., 2021, 2023, 2024; Nicoletti et al., 2025). Collectively, these studies focus on existing dwellings. They suggest that staged retrofitting can outperform single-step upgrades because household budgets accumulate over time, enabling deeper measures (Maia et al., 2021; Maia et al., 2024). Reported retrofit cycles range from 1–14 years, depending on replacement effects (Maia et al., 2021), and around 12 years when constrained by household income (Maia et al., 2024). However, these studies do not optimise the total retrofit duration to achieve a targeted performance level; instead, they optimise the spacing between retrofit steps to implement a pre-selected list of retrofit measures. In contrast, this study optimises the full duration required to restore the house to its original performance. This optimal duration defines a minimum retrofit window that must be allocated before any penalty is imposed. Unlike prior models, which are largely household-centred, this study incorporates both household and policymaker perspectives when modelling staged retrofitting to inform an inclusive policy framework.

The desk study identified common parameters used in staged retrofitting models (see Table 1). These parameters indicate that economic factors and budget constraints underpin staged retrofitting (De Moortel et al., 2018; Maia et al., 2021, 2023, 2024; Nicoletti et al., 2025). Using those parameters, the model workflow was developed for defining an optimal penalty-free retrofit window for the first compliance cycle of a new single-family home (see Figure 1). The following sections outline its main components.

*Table 1: Characteristics of existing staged retrofitting models*

| **Studies/ Models** | **[1]** | **[2]** | **[3]** | **[4]** | **[5]** |
|---|---|---|---|---|---|
| ***Parameters/ Variables/ Constraints*** | | | | | |
| Initial investment cost of retrofit measures | ✓ | ✓ | ✓ | ✓ | ✓ |
| Energy savings of retrofit measures | | ✓ | ✓ | ✓ | ✓ |
| Combinations of retrofit measures | | ✓ | ✓ | ✓ | |
| Maintenance cost | | ✓ | ✓ | ✓ | ✓ |
| Insurance cost | | | | | ✓ |
| Bank loan availability | | | | | ✓ |
| Bank loan repayment duration | | | | | ✓ |
| Bank loan interest rate | | | | | ✓ |
| Annual electricity and gas costs | ✓ | ✓ | ✓ | ✓ | ✓ |
| Inflation in general | | | | | ✓ |
| Inflation of electricity and gas prices | ✓ | ✓ | ✓ | ✓ | ✓ |
| Discount rate | ✓ | ✓ | ✓ | ✓ | ✓ |
| Material ageing | | ✓ | ✓ | ✓ | |
| Building life span | ✓ | | | | ✓ |
| Thermal resistance | ✓ | | | | |
| Lower calorific value | ✓ | | | | |
| Equivalent degree days | ✓ | | | | |
| Efficiency of the heating system | ✓ | | | | |
| The maximum budget allocated for retrofitting | | ✓ | ✓ | ✓ | ✓ |
| The maximum debt pressure | | | | | ✓ |
| Energy bill savings must cover the outstanding loan before the next retrofit step | | | | | ✓ |
| Dependency of replacements | | ✓ | ✓ | ✓ | |
| ***Optimisation Techniques*** | | | | | |
| MILP to formulate the optimisation problem | | ✓ | ✓ | ✓ | ✓ |
| Brute-force algorithm to evaluate possible combinations | | | | | ✓ |
| Gurobi solver to evaluate possible combinations | | ✓ | ✓ | ✓ | |
| Excel-based analysis of the Pareto front for LCC | ✓ | | | | |

[1] - De Moortel et al. (2018), [2] - Maia et al. (2021), [3] - Maia et al. (2023), [4] - Maia et al. (2024), [5] Nicoletti et al. (2025)

- Step 1: Identifying the initial conditions of the house and the fundamental data

Step 1 establishes the baseline for Model 2 by anchoring it to the breach year identified in Model 1. The associated benchmark and building energy performance define the initial performance gap and the onset of the first compliance cycle. The required economic data are then used to represent budget accumulation and to value retrofit costs and energy savings over time. These data include household income, income growth, energy prices, energy price inflation, general inflation, and the chosen discount rate for Net Present Value (NPV) calculations.

- Step 2: Selecting potential retrofit measures to restore the building performance based on regulations and household requirements

Step 2 compiles a feasible set of retrofit measures that could close the identified performance gap and return the dwelling to the required benchmark. Measures are first screened against applicable regulations and compliance requirements. These measures are then filtered for household suitability, considering practical constraints such as affordability, disruption, technical compatibility with the dwelling, and occupant needs. Clearly defining this measure set is critical because it bounds the optimisation to realistic, compliant options and ensures the resulting staged pathway reflects what can actually be delivered in practice, rather than an idealised solution. Accordingly, the resulting shortlist forms the candidate measure set for the staged retrofit optimisation.

- Step 3: Defining the maximum budget allocated for retrofitting in each year

A defined proportion of annual household income is allocated to the retrofit budget, which is used for retrofit measures and the maintenance of installed measures. A rationalised income allocation can be defined at the country or regional level as twice the median proportion of the household energy expenditure (Boardman, 1991; Nicoletti et al., 2025). The same approach can also be applied at the individual household level by using the household's own energy expenditure proportion rather than the regional median. Because the retrofit budget is cumulative, any unspent funds from the previous year are carried forward and added to the budget in year t. Accordingly, Equation 05 defines the maximum retrofit budget available in year t for investment in retrofit measures.

$$RB(t) = RB(t-1) + [IS(t) - EB(t) - MC(t)] \times DF(t) \qquad (05)$$

where, RB(t) = the maximum budget available for retrofitting in year t [$/yr], RB(t – 1) = the remaining funds carried over from the previous year [$/yr], IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], EB(t) = total cost of energy bill in year t [MJ/yr], MC(t) = total maintenance cost in year t, and DF(t) = discounting factor for year t

The real discounting factor for each year is defined in Equation 06, accounting for the evolution of the interest rate. This factor is important because it converts future costs and savings into present-value terms, reflecting the time value of money and enabling consistent comparison of retrofit investments and benefits that occur in different years.

$$DF(t) = 1/[\prod_{i=1}^{n+t} (1 + r_i)] \qquad (06)$$

where, DF(t) = discounting factor for year t, $r_i$ = interest rate in discounting year i, and n = breach year

Equation 07 derives household income in the current year from the previous year's income using the annual income growth rate. Then, the amount allocated to energy retrofitting is calculated by applying the retrofit-income proportion.

$$IS(t) = INC(t-1)[1+g(t)] \times f \qquad (07)$$

where, IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], INC(t – 1) = annual household income in the previous year [$/yr], g = annual household income growth in year t, f = the retrofit-income proportion [%]

Equation 08 estimates the household's total energy bill for the current year by summing the costs of each energy source, where each cost is calculated as the product of the energy quantity and its unit price. Forecasted annual unit prices are used when available; otherwise, initial prices can be used and updated using the energy inflation rate.

$$EB(t) = \sum_{es}[\, ED_{es}(t) \times pr_{es}(t)\,] \qquad (08)$$

where, EB(t) = total cost of energy bills in year t [$/yr], es = energy sources, $ED_{es}(t)$ = total energy demand of the energy source 'es' in year t [kWh/yr], and $pr_{es}(t)$ = energy unit price of the energy source 'es' in year t [$/kWh]

Equation 09 calculates the annual energy demand for each energy source in the current year. This demand is estimated by deducting the anticipated energy savings from retrofit measures installed in the previous year from the previous year's demand. The energy savings from each measure are assumed to be realised from the year after implementation and to continue in subsequent years.

$$ED(t) = ED(t-1) + \sum_{m=0}^{M} ES_m \qquad (09)$$

where, ED(t) = total energy demand in year t [kWh/yr], ED(t – 1) = total energy demand in the previous year [kWh/yr], $ES_m$ = energy savings of each retrofit measure [kWh/yr], and M = all the retrofit measures scheduled for the previous year

Equation 10 computes the annual maintenance costs associated with scheduled retrofit measures. The maintenance cost of each measure is assumed to be realised from the year after implementation and to continue in subsequent years. Maintenance is included because proper upkeep helps moderate the effects of natural ageing and mechanical wear of HVAC systems. In contrast, poor maintenance can lead to a near doubling of energy consumption over the long term (Eleftheriadis & Hamdy, 2018).

$$MC(t) = \sum_{m=0}^{MM} MC_m \qquad (10)$$

where, MC(t) = total maintenance cost in year t [$/yr], $MC_m$ = annual maintenance cost of each retrofit measure [$/yr], MM = all the retrofit measures scheduled before year t

Step 4: Scheduling the chosen retrofit measures for year t and updating the list of remaining measures

If the initial investment cost of an available retrofit measure falls within the budget defined in Equation 05, the measure is eligible for scheduling in the current year. Equation 11 computes the total initial investment cost of the measures scheduled for the current year. Next, the list of remaining retrofit measures is updated.

$$RC(t) = \sum_{m=0}^{y}[MaterialC_m(t) + LabourC_m(t)] \qquad (11)$$

where, RC(t) = total initial investment cost of retrofit measures scheduled for year t [$], [$MaterialC_m(t), LabourC_m(t)$ = material and labour costs of each retrofit measure [$], y = all the retrofit measures scheduled for year t, n = the breach year

Wright's law can be used to estimate price fluctuations in materials for retrofit measures because their cost reductions are associated with broader adoption and cumulative production (Moghaddam et al., 2023). Wright's law states that the cost of a technology tends to decrease by a roughly constant percentage each time its cumulative production doubles, driven by learning-by-doing and technological advancements (Wright, 1936).

- Step 5: Computing the residual value of all the scheduled retrofit measures at the end of the optimisation period

Equation 12 computes the residual value of all retrofit measures scheduled up to the current year by the end of the optimisation period. The residual value is included because many retrofit measures retain useful life and economic value beyond the optimisation period. This is particularly important in staged retrofitting pathways, where retrofit measures are implemented at different time intervals. Crediting this remaining value prevents the undervaluation of late investments, enhances fairness when comparing measures with varying lifetimes, and minimises bias at the end of the optimisation period.

$$L(T) = DF(T) \times \sum_{m=0}^{N} C_m \times \frac{max\,(0,\ TL_m - (T - i_m))}{TL_m} \qquad (12)$$

where, L(T) = discounted residual value of all the retrofit measures scheduled up to the current year by the end of the optimisation period [$/yr], N = the total number of measures scheduled up to the current year, $C_m$ = initial investment cost of each measure [$], $i_m$ = the year each measure is scheduled, $TL_m$ = technical life time of each measure, T = end of the optimisation period, and DF(T) = discounting factor in year T

- Step 6: Computing the NPV of the total cash flow over the optimisation period

Equation 13 computes the NPV by summing the discounted annual cash flows over the optimisation period, including allocated household income, retrofit costs, energy costs and savings, maintenance costs, and residual values of retrofit measures. By converting costs and savings from different years into a consistent present-value basis, the NPV formulation provides the economic basis for evaluating alternative staged-retrofit pathways and their timing across the optimisation period. Thus, this formula underpins the optimisation objective.

$$NPV = \sum_{t=n}^{T} \{[IS(t) - RC(t) - EB(t) - MC(t)] \times DF(t)\} + L(T) \qquad (13)$$

where, NPV = net present value of the total cash flow over the optimisation period, n = the breach year, T = end of the optimisation period, IS(t) = the amount of household income allocated for energy retrofitting in year t [$/yr], RC(t) = total initial investment cost of retrofit measures scheduled for year t [$], EB(t) = total cost of energy bills in year t [MJ/yr], MC(t) = total maintenance cost in year t, DF(t) = discounting factor in year t, L(T) = discounted residual value of all the scheduled retrofit measures up to year t by the end of the optimisation period, r = interest rate, and tp = depreciation time

- Step 7: Optimisation objective that gives the minimum period that must be allocated for retrofitting before imposing any penalty

Model 2 aims to determine the minimum retrofit period to allocate during the initial compliance cycle, prior to the enforcement of penalties, also known as the penalty-free

retrofit window. As presented in Equation 14, the model first minimises the retrofitting period as the primary objective. The model then maximises the household's cash flow as the secondary objective, allowing retrofit measures to be scheduled without compromising the minimum retrofitting window. This hierarchical multi-objective approach ensures that the minimum retrofit window is not compromised when maximising the household's cash flow. Retrofit measures will be implemented as the budget is accumulated and until the house regains its initial energy performance. The model adjusts the timing and sequence of scheduled retrofit measures during the optimisation process to achieve the best outcomes for the optimisation objective, given in equation 14.

$$Min\ (T_{\omega}\ at\ priority\ 1), Max\ (NPV\ at\ priority\ 2) \qquad (14)$$

where, $T_{\omega}$ = timing to restore the energy performance and NPV = net present value of the total cash flow over the optimisation period

## 5. CONCLUSIONS AND FUTURE OUTLOOKS

This study conceptualises an inclusive compliance approach to sustaining the energy efficiency of new single-family homes through periodic reassessment, timely intervention, and adaptive and inclusive policy design. It introduces two linked models for: (i) determining the timing of the first compliance cycle by estimating when building performance first exceeds the required benchmark under key dynamic parameters, and (ii) defining a minimum penalty-free retrofit window within that first cycle using staged retrofitting.

The proposed models shift compliance from a one-off approval requirement toward a more adaptive process for sustaining building energy performance over time. In doing so, the study contributes to policy discussions on long-term building performance and practical compliance mechanisms for sustainable housing. The models can be recalibrated across different climatic, regulatory, and socio-economic contexts, allowing policy settings to remain responsive to changing conditions.

Unlike existing staged retrofitting models, which primarily reflect the homeowner perspective, the proposed approach incorporates the roles of both households and policymakers, revealing an underexplored opportunity in staged retrofitting. Given that macroeconomic conditions may shift over time, the retrofit window should be recalibrated before implementation to keep policy settings aligned with prevailing conditions. The models are therefore intended as adaptive decision-support tools that can guide early intervention, support staged upgrades, and help sustain energy efficiency beyond initial compliance.

Further potential lies in automating compliance through utility bills to enable continuous monitoring, early warnings of likely non-compliance, and more proactive retrofit planning. While this study focuses specifically on energy efficiency, future research could examine whether a similar modelling logic may be adapted to other resource-efficiency domains, such as water efficiency, subject to the development of appropriate performance indicators, cost variables, monitoring mechanisms, and regulatory benchmarks.

Overall, the proposed models lay the foundation for an innovative and inclusive policy framework for sustaining energy-efficiency compliance in new single-family homes. By promoting continuous monitoring, timely upgrades, and adaptive performance

improvements beyond initial compliance, this framework can support the sustained resilience, energy efficiency, and progressive regeneration of the housing sector. The next step is to refine and validate the proposed workflows and equations with input from an expert focus group. The broader scope involves testing the models through real-world case studies across diverse climatic, regulatory, and socio-economic contexts.

## 6. ACKNOWLEDGEMENT

The authors used Grammarly for proofreading, then reviewed and edited the content, taking full responsibility for the final article.

## 7. REFERENCES

Anh, L. D. H., & P´asztory, Z. (2021). An overview of factors influencing thermal conductivity of building insulation materials. *Journal of Building Engineering, 44*, 102604. https://doi.org/10.1016/j.jobe.2021.102604

Beausoleil-Morrison, I. (2020). *Fundamentals of building performance simulation*. Routledge. https://doi.org/10.1201/9781003055273

Birchall, S., Gustafsson, M., Wallis, I., Dipasquale, C., Bellini, A., & Fedrizzi, R. (2016). Survey and simulation of energy use in the European building stock. In P.K. Heiselberg (Ed), *CLIMA 2016 - Proceedings of the 12th REHVA World Congress* (Vol. 1). Aalborg University. https://vbn.aau.dk/ws/portalfiles/portal/233774195/paper_273.pdf

Boardman, B. (1991). *Fuel poverty: From cold homes to affordable warmth*. Belhaven Press.

Calama-González, C. M., Escandón, R., Suárez, R. & Ascione, F., (2025). Decision-making for renovating the Mediterranean social housing: A practical approach through an interactive open access tool. *Energy and Buildings, 336*, 115629. https://doi.org/10.1016/j.enbuild.2025.115629

Chen, S., Ren, Z., Tang, Z., & Zhuo, X. (2021). Long-term prediction of weather for analysis of residential building energy consumption in Australia. *Energies, 14*(16), 4805. https://doi.org/10.3390/en14164805

De Moortel, E. V., De Troyer, F., Allacker, K., Stijnen, L., & Schoofs, E. (2018). Avoiding financial lock-in effects in case of a stepwise energy renovation of social housing in Flanders. *WEENTECH Proceedings in Energy, 4*(2), 160-176. https://www.researchgate.net/publication/330099120_Avoiding_financial_lock-in_effects_in_case_of_a_stepwise_energy_renovation_of_social_housing_in_Flanders

Eleftheriadis, G., & Hamdy, M. (2018). The impact of insulation and HVAC degradation on overall building energy performance: A case study. *Buildings, 8*(2), 23. https://doi.org/10.3390/buildings8020023

European Commission (2025). *Renovation Passports* (Article 12, Annex VIII, EU/2024/1275). https://energy.ec.europa.eu/document/download/0a4a6d59-58c0-4e80-a58a-a6ee944573ab_en?filename=Renovation%20passport%20%28Article%2012%2C%20Annex%20VIII%29%20-%20annex%204.pdf

European Union (2018, May 30). *Directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency*. Retrieved January 15, 2026, from https://eur-lex.europa.eu/eli/dir/2018/844/oj/eng

Grandolini, G. M., & Ijjasz-Vasquez, E. (2016, May 25). *3 reasons why 'Housing for All' can happen by 2030*. World Bank Blogs. https://blogs.worldbank.org/en/voices/3-reasons-why-housing-all-can-happen-2030

Halffmann, P., Schäfer, L. E., Dächert, K., Klamroth, K., & Ruzika, S. (2022). Exact algorithms for multi objective linear optimization problems with integer variables: A state of the art survey. *Journal of Multi-Criteria Decision Analysis, 29*(5–6), 341–363. https://doi.org/10.1002/mcda.1780

Hulathdoowage, N. D., Karunasena, G., Udawatta, N., & Liu, C. (2026). The applicability of stepwise retrofitting in the Australian residential sector: An exploratory qualitative study. *Smart and Sustainable Built Environment*. Emerald Insight. https://doi.org/10.1108/SASBE-04-2025-0180

Lee, J. H., Kim, D. G., Jeong, S. K., & Song, Y. H. (2022). Analysis of heat source system degradation due to aging and evaluation of its effect on energy consumption. *Energies, 15*(23), 9217. https://doi.org/10.3390/en15239217

Madushika, U. G. D., Ramachandra, T., Karunasena, G., & Udakara, P. A. D. S. (2023). Energy Retrofitting Technologies of Buildings: A Review-Based Assessment. *Energies, 16*(13), 4924. https://doi.org/10.3390/en16134924

Maia, I., Kranzl, L., & Müller, A. (2021). New step-by-step retrofitting model for delivering optimum timing. *Applied Energy, 290*, 116714. https://doi.org/10.1016/j.apenergy.2021.116714

Maia, I.E.N., Harringer, D., & Kranzl, L. (2023). Staged renovation and the time perspective: Which other metric should be used to assess climate-optimality of renovation activities?, *Smart Energy, 11*, 100110. https://doi.org/10.1016/j.segy.2023.100110

Maia, I.E.N., Harringer, D., & Kranzl, L. (2024). Household budget restrictions as reason for staged retrofits: A case study in Spain. *Energy Policy, 188, 114047*. https://doi.org/10.1016/j.enpol.2024.114047

Metehan, A. A., Solmaz, A. S., Gök, O., & Tokuç, A. (2025). Adapting to climate change: Assessing future residential energy demands for different climate and occupancy scenarios in Turkey. *Buildings, 15*(8), 1255. https://doi.org/10.3390/buildings15081255

Moghaddam, S.A., Serra, C., da Silva, M.G., & Simões, N. (2023). Comprehensive review and analysis of glazing systems towards nearly zero-energy buildings: Energy performance, thermal comfort, cost-effectiveness, and environmental impact perspectives. *Energies, 16*(17), 6283. https://doi.org/10.3390/en16176283

Moujalled, B., Leprince, V., Berthault, S., Litvak, A., & Hurel, N. (2021). Mid-term and long-term changes in building airtightness: A field study on low-energy houses. *Energy and Buildings, 250*, 111257. https://doi.org/10.1016/j.enbuild.2021.111257

Munn, Z., Pollock, D., Khalil, H., Alexander, L., McInerney, P., Godfrey, C. M., Peters, M., & Tricco, A. C. (2022). What are scoping reviews? Providing a formal definition of scoping reviews as a type of evidence synthesis. *JBI Evidence Synthesis, 20*(4), 950–952. https://doi.org/10.11124/JBIES-21-00483

Nationwide House Energy Rating Scheme. (2024). *Software accreditation protocol – New homes 2025* (Version 20241122). https://www.nathers.gov.au/sites/default/files/2025-11/SAP%20New%20Homes%202025%2020241122.pdf

Nicoletti, F., Carpino, C., Barbosa, G., Domenico, A., Arcuri, N., & Almeida, M. (2025). Building renovation passport: A new methodology for scheduling and addressing financial challenges for low-income households. *Energy and Buildings, 331*, 115353. https://doi.org/10.1016/j.enbuild.2025.115353

Pajek, L., Jevrić, M., Ćipranić, I., & Košir, M. (2023). A multi-aspect approach to energy retrofitting under global warming: A case of a multi-apartment building in Montenegro. *Journal of Building Engineering, 63*, 105462. https://doi.org/10.1016/j.jobe.2022.105462

Taki, A., & Zakharova, A. (2023). The impact of degradation on a building's energy performance in hot-humid climates. *Buildings, 15*(2), 1145. https://doi.org/10.3390/su15021145

The District of Columbia Department of Energy & Environment. (2023). *Building energy performance standards compliance and enforcement guidebook for compliance cycle 1* (Version 1.1). https://dc.beam-portal.org/helpdesk/kb/BEPS_Guidebook/78/

Wright, T.P. (1936). Factors affecting the cost of airplanes. *Journal of the Aeronautical Sciences*, 3(4), 122–128. https://doi.org/10.2514/8.155

Fernando, R.D.L., Bandara, R.M.H.R. and Menaha, M., 2026. Contractual provisions inducing construction waste generation: An analysis of Sri Lankan standard forms of contract. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 459-470. DOI: https://doi.org/10.31705/WCS.2026.34. Available from: https://ciobwcs.com/papers/

# CONTRACTUAL PROVISIONS INDUCING CONSTRUCTION WASTE GENERATION: AN ANALYSIS OF SRI LANKAN STANDARD FORMS OF CONTRACT

**R.D.L. Fernando[1], R.M.H.R. Bandara[2], and M. Thayaparan[3]**

## *ABSTRACT*

*Construction waste remains a major challenge in the construction industry due to its environmental, economic, and resource implications. While previous studies have mainly focused on operational and site management practices as causes of construction waste, limited attention has been given to the role of contractual provisions in influencing waste generation. This study investigates how contractual clauses may contribute to construction waste during project execution. A qualitative document analysis was conducted on CIDA/SBD/02 (Section 3) to examine the potential mechanisms through which contractual clauses may lead to waste generation. The analysis identified several contractual provisions related to the priority of documents, Engineer's instructions, inspection requirements, rejection of materials or workmanship, and variations. The findings reveal that these provisions may create circumstances that lead to demolition, rework, replacement of materials, and material obsolesce during construction. Discrepancies among contract documents, late instructions, rejection of non-compliant materials, and design changes introduced through variations were identified as key contractual processes that may contribute to waste generation. The study demonstrates that contractual governance mechanisms embedded within standard forms of contract can unintentionally create conditions that lead to material waste. By revealing the relationship between contract administration processes and waste generation, the research contributes to expanding construction waste management beyond managerial and operational site practices towards governance dimensions.*

***Keywords:*** *Clauses; Construction Industry; Construction Waste; Contracts; Sri Lanka.*

## 1. INTRODUCTION

The construction industry forms a part of a country's economy, providing services for planning, designing, building, altering, refurbishing, maintaining, repairing, and demolishing structures (Towey, 2012). Since the countries are moving towards sustainable development, sustainable construction has become a necessity in the

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, fernandordl.21@uom.lk
[2] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, bandararmhr20@uom.lk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk

construction industry to ensure that all construction activities, from planning to completion, are carried out sustainably, considering economic, social, and environmental impacts (Ismail et al., 2012). When experts in the construction industry are working to move forward with sustainable development objectives, the management of construction waste is highly considered (Saad et al., 2022). According to Wimalarathna et al., (2023) construction waste management is the most discussed major sustainable construction practice within the construction industry. Construction waste contributes to increased construction costs, pollution, climate change, and resource depletion (Purchase et al., 2021). Therefore, both public and commercial organisations are being forced to reduce construction waste generation (Kartam et al., 2004).

It can be noticed that 'construction waste' is an integral term used in most literature without indicating its specific origins. However, Elgizawy et al., (2016) define construction as waste generated from the construction, remodelling, repairing, and demolition of buildings and other structures. This study focuses on construction waste generated from the construction of buildings or other structures, including remodelling and repairing (rework) and associated demolitions, processing and installation losses, handling and storage losses, and material obsolescence during the construction phase.

Even though construction waste materials might be considered harmless, other than the increased construction cost, they cause a lot of trouble because they are often dumped as huge masses of materials, facilitating illegal dumping of other types of waste and garbage as well (Kartam et al., 2004). Especially, developing countries poorly handle such waste through uncontrolled landfills, leading to scarce landfill space and environmental issues (Kartam et al., 2004). Construction waste management aims to minimise waste as much as possible before it is sent for final disposal, such as landfilling. The solid waste hierarchy is a widely used conceptual framework for achieving this goal, prioritising waste management in the following order: reduction, reuse, recycling, recovery, and, as a last option, disposal. Reduction is the most preferred, while disposal remains the least attractive option on the hierarchy (Gillespie, 2015). Accordingly, this study focuses on reducing construction waste.

Construction waste originates directly or indirectly from activities of different stages of the construction project life cycle, such as design, construction, maintenance, and demolition (Lu & Yuan, 2011). The most prevalent waste management strategies in the construction sector primarily address problems with construction waste, where waste is already generated (Jahan et al., 2022). However, according to Saad et al., (2022) 33% of construction waste is attributable to deficiencies in the design process. The same author identified that one of the major causes of waste generated by deficiencies in the design process is communication, clarity, and understanding-related issues. Ambiguous communication, e.g. failing to specify exactly what, when, and how a task is to be completed, can lead to rework later, which generates waste (Love et al., 2009). According to Muneer et al., (2022) communication problems arise when project drawings, documentation, contract paperwork, and instructions contain ambiguous information. Contract clauses stated in the bid or contract agreements serve as a means of communicating the owner's ideas to contractors, specifying their responsibilities (Jergeas, Hartman, 1996 as cited in Mendis et al., 2015). The parties that draft the contract documents transfer greater risk to the other parties through contract clauses concerning construction waste management (Sawant et al., 2021). Thus, Mendis et al., (2015) had

identified several instances of waste generation influenced by certain contractual clauses in standard construction contracts.

In Sri Lanka, the Construction Industry Development Authority (CIDA) was established to implement standards for construction work, practices, procedures, processes, and documentation relating to the construction industry (Construction Industry Development Act, No. 33 of 2014). Sri Lanka has its own standard forms of contract published by CIDA. Although these have been prepared primarily using international standard contract formats, such as the World Bank Conditions of Contract and FIDIC, there are some deviations from these standards (Dilshani & Disaratna, 2014). Among the standard forms of contract published by CIDA, the standard bidding document procurement of works of major contracts (CIDA/SBD/02) is recommended for use on works contracts over Rs. 100 million, and for contracts of lesser value, which are of a complex nature.

Even though this study is based on the Sri Lankan CIDA/SBD/02, the contractual mechanisms identified are not unique to the specific standard form of contract or Sri Lanka. Priority of documents, Engineer's instructions, inspection, rejection, and variation procedures are governance functions that also appear in other standard forms of contract, including FIDIC-based forms. Therefore, the findings are context-specific for the selected form of contract, yet the underlying mechanism by which contract administration can generate waste has broader international relevance.

Although extensive research has examined operational and managerial causes of construction waste, there has been no published research on contractual clauses and their impact on waste generation in Sri Lanka. Therefore, this study aims to fill the existing research gap by identifying contractual clauses in CIDA/SBD/02 (Section 3–Conditions of Contract) that have the potential to contribute to construction waste generation through their implementation and contractual administration during project execution.

# 2. CONSTRUCTION WASTE AND CONTRACTUAL GOVERNANCE

## 2.1 CONSTRUCTION WASTE IN THE CONSTRUCTION INDUSTRY

Construction waste is among the fastest-growing waste streams in Sri Lanka. As a developing country, construction waste generation is higher than in developed countries (Medawala & Dassanayake, 2024).

Construction activities in Sri Lanka generate various types of waste, including concrete, brick, ceramic tile, and wood waste (Chathury et al., 2025). According to Medawala and Dassanayake, (2024), the industry generates a higher proportion of concrete as construction waste but generated concrete waste is not much reused or recycled in the construction industry. They are transported and illegally dumped or end up in landfills.

According to Victar and Waidyasekara, (2023), in Sri Lanka, secondary material markets for construction waste are hindered by a lack of government support. This includes insufficient funding, regulations, and infrastructure, leading to challenges in managing and disposing of construction waste. Many areas in Sri Lanka lack designated waste disposal sites, and there is a shortage of vehicles and equipment for waste collection and transportation. As an insufficient regulatory measure, it is identified that the lack of financial penalties or disincentives for individuals or organisations that fail to manage their waste properly. This means there is no cost for improper disposal of waste, and as a

result, waste management practices may be neglectful or inadequate (Victar & Waidyasekara, 2023). Therefore, understanding the underlying causes of construction waste generation is essential for developing effective strategies aimed at reducing waste at its source.

## 2.2 CAUSES OF CONSTRUCTION WASTE

Various researchers identified different causes of construction material waste. According to Fadiya et al., (2014) construction material waste can be generated in any stage of the construction life cycle and arises from design, logistics, and physical construction processes. However, this study is limited to the physical construction process. Therefore, the causes of material waste were categorised as rework (associated with demolition), processing and installation losses, handling and storage losses, and material obsolescence for ease of study.

*Rework (Associated with Demolition)*

Rework is defined as the unnecessary effort of redoing a process or activity that was incorrectly implemented the first time (Mahamid, 2022). It frequently requires the demolition of already completed work (Karunasena et al., 2025).

Frequent design changes and modifications during construction often necessitate rework, which consumes additional materials and generates considerable waste, and if the design change is made during construction, it can lead to the demolition of already completed work, resulting in waste of both labour and material (Alotaibi et al., 2025; Karunasena et al., 2025). Lack of labour skills and untrained laborers leads to workers' mistakes, which necessitate remedial works, and then rework is required (Mahamid, 2022). According to Alotaibi et al., (2025) design and planning errors and omissions could adversely affect project progress and lead to rework on construction sites. Moreover, the same author has identified that the lack of site supervision allows errors to go unnoticed until they are finished, which leads to remedial work involving demolition and rework of the faulty elements.

*Processing and Installation Losses*

Operational errors, including faults in construction execution, and potential inefficiencies in material installation practices, emerge as a notable cause of waste across all components, with an exceptionally high impact observed in finishes, as decorative features are easily damaged during placement (Rathnayake et al., 2024). According to the authors, the high percentages reported were mainly due to cutting waste resulting in different sizes and uneconomical shapes, due to incorrect decision-making, and the lack of supervision (Karunasena et al., 2023).

*Handling and Storage Losses*

Bad material storage, lack of material management on site, with careless handling and use of some goods, is another cause of material waste generation (Mahamid, 2022).

For example, cement have to be stored in a closed or shaded area to maintain its quality but construction sites store cement in open spaces under direct weather. Poor handling and storage expose materials to various environmental factors, such as moisture and high temperatures, which lead to defects and loss of initial properties (Alotaibi et al., 2025).

All materials should be unpacked and arranged properly to avoid any damage (Kaliannan et al., 2018).

*Material Obsolescence*

Material obsolescence refers to materials that are discarded without adding value to the project, often because they are no longer needed or do not meet requirements (Mahamid, 2022). The procurement of low-quality materials or products that do not comply with the contract specifications can render them obsolete for the intended task (Karunasena et al., 2025). Poor order of material without referring to details can result in overordering of materials, which will also end up as construction waste (Kaliannan et al., 2018). Changes in design during the project can make previously ordered or even installed materials redundant and unusable, leading to their total loss (Karunasena et al., 2025). Small quantities of leftover supplies (e.g., mortar or opened paint containers) are frequently discarded after a task is completed because they cannot be easily reused elsewhere (Alotaibi et al., 2025).

While these causes are commonly associated with management and operational inefficiencies, several of them are closely connected with contractual arrangements governing project communication, variation management, and decision-making authority.

### 2.3 ROLE OF CONTRACTS IN CONSTRUCTION PROJECTS

Effective governance mechanisms are necessary to ensure the timely, cost-effective, and high-quality delivery of construction projects (Yi & Nie, 2024). According to Chen et al., (2018) contracts have three main functions: control, coordination, and adaptation. The control function ensures compliance and limits the parties' opportunistic behaviour. The coordination function provides clear procedures for communication, task allocation, and information sharing. The adaptation function enables parties to respond to unforeseen changes and evolving project conditions (Yang et al., 2025).

To limit opportunistic behaviour by the parties, contracts separately stipulate their rights and obligations, thereby aligning with their interests (Chen et al., 2018). To enhance effectiveness and efficiency, the contract implements mechanisms to improve communication and clarify the objectives and the division of labour for the project's tasks. This helps to reduce task ambiguity and facilitate better understanding (Mellewigt, 2007). Contracts provide procedures to deal with adjustments to the initial agreements that are made by the parties such as variations and value engineering ideas (Wambeke et al., 2011).

Accordingly, these governance functions influence how construction activities are executed and how project decisions are implemented during the construction phase (Karunasena et al., 2025). Hence, contractual processes may unintentionally create circumstances where construction materials become redundant or unusable, leading to the generation of construction waste.

## 3. METHODOLOGY

A qualitative research approach was adopted for this study. Qualitative approach is a scientific method that emphasises contextual depth and individual voices in understanding social phenomena, often taking a constructive or interpretive perspective

(Lim, 2023). This approach explores the everyday routines and challenges people encounter and focuses on understanding the deeper meaning and motivations behind these experiences, which cannot be captured through numerical data (Taherdoost, 2022). It aims to unveil the “what”, “why”, “when”, “where”, “who”, and “how” (or the “5W1H”) behind social behaviors and interactions (Lim, 2024). This approach utilises various empirical sources, such as case studies, document analysis, life experiences, and narratives (Taherdoost, 2022). This study requires critically evaluating contractual clauses within the CIDA/SBD/02 document, identifying clauses that have the potential to generate construction waste. It is required to investigate the 'what' and 'how' questions that a qualitative approach values; 'What' are the clauses, and 'How' do they contribute to waste generation? Therefore, the qualitative approach was selected for the study.

The primary data source for this study was the Sri Lankan standard form of contract CIDA/SBD/02 (Section 3–Conditions of Contract). This document is widely used in major construction projects in Sri Lanka and governs the contractual relationships between project stakeholders, including the Employer, Engineer, and Contractor.

A qualitative document analysis technique was employed as the analysis technique. Document analysis is a structured procedure for reviewing or assessing documents, both electronic and printed, to extract meaning, gain understanding, and develop empirical knowledge (Bowen, 2009). In this study, document analysis is employed to systematically examine the CIDA/SBD/02 document to identify contractual clauses that have the potential to generate construction waste. Document analysis enabled the integration of literature findings, such as recognised causes of construction waste, with the content of the contract, allowing for a comprehensive interpretation of how contractual governance can contribute to or mitigate waste.

To enhance analytical reliability, clauses were identified by interpreting the established causes of construction waste in the literature. Clause-by-clause triangulation between the contract text, the literature on construction waste causes, and the theoretical functions of contract governance strengthened the validity of the clauses. Each identified clause was re-read to ensure that the waste pathway was supported by the clause wording and was consistent with established causes of demolition, rework, processing, and installation losses, handling and storage losses, or material obsolescence. This review process helped improve the consistency of the analysis.

# 4. FINDINGS AND DATA ANALYSIS

## 4.1 CONTRACTUAL PROVISIONS INFLUENCING CONSTRUCTION WASTE GENERATION

A clause that may directly or indirectly trigger or lead to any of the following causes of construction waste generation identified from the literature review was considered as a contractual clause that has the potential to contribute to construction waste generation through its implementation and contractual administration during project execution.

- Demolition (during construction)
- Rework (can be associated with demolition)
- Processing and Installation losses
- Handling and storage losses
- Material obsolescence

Table 1 presents the results of the document analysis conducted on CIDA/SBD/02 (Section – 3) to identify how contractual provisions may influence construction waste generation.

*Table 1: Document analysis CIDA/SBD/02*

| Clause No. | Clause Title | Clause Extract | How waste can be generated |
|---|---|---|---|
| 1.5 | Priority of Documents | For the purposes of interpretation, priority of the documents shall be in accordance with the following sequence:<br>(a)<br>(b)<br>….<br>(g) the Specifications;<br>(h) the Drawings; and<br>(i) the Bills of Quantities, and any other… | When there is an ambiguity or discrepancy between documents, this clause gives the right to the Contractor or obligate him to execute the work according to the highest priority document in the sequence. If the considered document's information is incorrect, it sometimes leads to demolition and/or rework, generating construction waste. |
| 3.3 | Instructions of the Engineer | The Engineer may issue to the Contractor (at any time) instructions, which may be necessary for the execution of the Works and the remedying of any defects, all in accordance with the Contract. | Engineer's instructions can be issued 'at any time'. Late or uncoordinated instructions can lead to changes after procurement of materials and work execution, leading to waste of materials. |
| 7.2 | Inspection | If the Contractor fails to give the notice, he shall, if and when required by the Engineer, uncover the work and thereafter reinstate and make good, all at the Contractor's cost. | If the Contractor has to uncover the work, there will be demolition and rework, which leads to construction waste |
| 7.4 | Rejection | the Engineer may reject the Plant, Materials, or workmanship by giving notice to the Contractor, with reasons. The Contractor shall then promptly make good the defect and ensure that the rejected item complies with the Contract. | Rejection typically results in removal, rework, and disposal, leading to construction waste |
| 13.1 | Right to Vary | Variations may be initiated by the Engineer at any time prior to issuing the Taking-Over Certificate for the Works, either by an instruction or by a request for the Contractor to submit a proposal | Changes after procurement of material and work execution create surplus materials, and demolition waste. |

| Clause No. | Clause Title | Clause Extract | How waste can be generated |
|---|---|---|---|
| 13.3 | Variation Procedure | The Engineer shall, as soon as practicable after receiving such proposal, respond with approval, disapproval, or comments. The Contractor shall not delay any work whilst awaiting a response. | This clause forces the Contractor to proceed under uncertainty, leading to rework if the final proposal is approved. |

Table 1 is structured into four main columns, which mention the particular clause extract relevant to the case and the corresponding explanation of how the clause may lead to waste generation with respect to their clause number and title.

#### 4.1.1 Priority of Contract Documents

Clause 1.5 establishes the order of precedence among contract documents when discrepancies arise between them. The clause specifies that documents such as the specifications, drawings, and Bills of Quantities are to be interpreted according to a defined hierarchy. While this provision provides a mechanism to resolve ambiguities, discrepancies between these documents can still lead to incorrect interpretation during the execution of works. When construction activities are carried out based on conflicting or inaccurate information contained in higher-priority documents, rectification of completed work may become necessary. Such rectification often involves demolition or rework of already completed elements, which contributes to the generation of construction waste.

#### 4.1.2 Engineer's Instructions

Clause 3.3 grants the Engineer the authority to issue instructions to the Contractor at any time during the execution of the works. Although this clause facilitates effective project management and allows the Engineer to address issues that arise during construction, instructions issued after materials have been procured or after work has commenced can lead to modifications in the executed work. Late or uncoordinated instructions may require the removal of completed work or the replacement of installed materials. Consequently, this can result in wastage of materials and additional demolition waste generated from the altered construction elements.

#### 4.1.3 Inspection of Work

Clause 7.2 requires the Contractor to provide notice before covering up any part of the work. If the Contractor fails to provide such notice, the Engineer may require the Contractor to uncover the work for inspection and subsequently reinstate it. This process involves the removal and reconstruction of construction elements. The uncovering and reinstatement of work can lead to demolition of previously completed portions and the generation of waste materials such as concrete fragments, finishes, or other building components that cannot be reused.

#### 4.1.4 Rejection of Materials or Workmanship

Clause 7.4 empowers the Engineer to reject materials, plant, or workmanship that do not comply with contractual requirements. Upon rejection, the Contractor is required to remove the defective materials or work and replace them with compliant alternatives. This process often results in the disposal of rejected materials and demolition of non-

compliant work. As a result, defective materials and demolished construction elements become part of construction waste generated on site.

#### 4.1.5 Variation and changes in Design

Clause 13.1 provides the Engineer with the right to initiate variations to the works at any time before the issuance of the Taking-Over Certificate. Variations may involve changes to the design, quantities, or specifications of the work. When such variations are introduced after materials have already been procured or construction activities have been executed, previously completed work may need to be modified or demolished. Additionally, materials that were procured based on the original design may become surplus or obsolete. These circumstances contribute significantly to construction waste generation.

#### 4.1.6 Variation Procedure and Continuation of Work

Clause 13.3 outlines the procedure for variations and requires the Contractor to proceed with the execution of work without delaying ongoing activities while awaiting responses to variation proposals. This requirement may result in situations where construction activities continue despite uncertainty regarding approval of the variation. If the variation proposal is approved, completed portions may need to be altered or reconstructed. Consequently, rework and demolition may occur, leading to additional construction waste.

## 5. DISCUSSION

The findings of the document analysis do not deny that the management and operational problems lead to waste generation. Rather, they show contractual governance and other causes are complementary. Contractual clauses shape project information flows, decision authority, and timing, influencing on-site behaviours that produce operational waste. For example, late design changes may occur due to poor management, yet contractual governance supports issuing late variation instructions. Moreover, ambiguous document precedence (priority of documents) as contractual governance raises the likelihood of executing work from high-priority documents with errors, which then results in an operational problem that triggers rework.

This integrative perspective advances the literature by moving beyond the causal perspective of waste generation, which highlights contractual design, administrative practice, construction sequencing, and the material outcome. The chain highlights intervention points at different stages, such as contract drafting, contract administration, and on-site supervision thus broadening the focus of waste mitigation.

Theoretically, this study contributes to contract governance literature by showing that contract functions (control, coordination, adaptation) have consequences beyond traditional economic performance metrics. Whereas most contract theory evaluates contracts in terms of cost, time, and dispute management, the present analysis focuses on environmental and resource outcomes, specifically material waste as legitimate contract performance indicators. This positions waste reduction as a governance objective, and it invites future work to treat sustainability as an explicit contractual function alongside traditional goals.

Moreover, the findings of the study create opportunities for the development of testable hypotheses. For instance, whether contractual provisions requiring obtaining

clarifications for ambiguities in documents can reduce resulting rework and demolition works. In doing so, the study facilitates the empirical measurement of governance-related waste drivers and contributes to advancing the field from primarily descriptive case-based observations toward a more systematic and testable theoretical understanding.

Even though the present document analysis demonstrates probable contract provisions that have the potential to waste generation, it does not provide implications to mitigate them. Future studies should assess the viability of amending the identified contract provisions to address the potential waste generation risk. Comparative research across different standard forms of contracts would also provide different mechanisms they have incorporated to address the identified issues. Finally, further studies should be conducted to suggest amendments to the identified contractual clauses to reduce the generation of construction waste. These studies will provide a solid foundation when the CIDA/SBD/02 is going to be revised with more consideration towards sustainable considerations.

## 6. CONCLUSIONS

This study examined how contractual provisions within the CIDA/SBD/02 may influence the generation of construction waste during project execution. Through document analysis, the study identified several contractual clauses that can create conditions leading to demolition, rework, processing, and installation losses, handling and storage losses and material obsolescence. The analysis revealed that clauses related to the priority of contract documents, the Engineer's instructions, inspection requirements, rejection of materials or workmanship, and variations can influence construction activities in ways that may result in material wastage.

The findings indicate that discrepancies between contract documents may lead to incorrect execution of work, which subsequently requires rectification and generates demolition waste. Similarly, the authority granted to the Engineer to issue instructions and initiate variations during the construction phase can result in modifications to completed works or previously procured materials. Inspection requirements and the rejection of non-compliant materials or workmanship may also necessitate removal and replacement of construction elements, further contributing to waste generation.

These findings demonstrate that construction waste generation is not solely a consequence of site-level inefficiencies or poor material management yet can originate from contractual processes that govern the execution of construction projects. The contractual framework establishes procedures and decision-making authority that may unintentionally create situations where waste can be generated. Overall, the study highlights the importance of considering contractual governance when addressing construction waste management. By recognising the potential influence of contractual provisions on construction practices, project stakeholders can better understand the broader institutional factors that contribute to waste generation. Such understanding is essential for developing more comprehensive strategies aimed at minimising construction waste and improving resource efficiency within the construction industry.

## 7. REFERENCES

Alotaibi, S., Martinez-Vazquez, P., & Baniotopoulos, C. (2025). Factors causing waste in construction of mega-projects: Case studies from Saudi Arabia. *Sustainability*, *17*(9), 4011. https://doi.org/10.3390/su17094011

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, *9*(2), 27–40. https://doi.org/10.3316/QRJ0902027

Chathury, N. V. J., Gunarathna, K. A. N., & Guruge, K. (2025). Private sector role as a key stakeholder towards the circular economy in the construction industry in Sri Lanka. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *13th world construction symposium—2025* (pp. 1137–1149). Ceylon Institute of Builders - Sri Lanka. https://doi.org/10.31705/WCS.2025.85

Chen, Y., Wang, W., Zhang, S., & You, J. (2018). Understanding the multiple functions of construction contracts: The anatomy of FIDIC model contracts. *Construction Management and Economics*, *36*(8), 472–485. https://doi.org/10.1080/01446193.2018.1449955

Dilshani, L. D. T., & Disaratna, P. A. P. V. D. S. (2014). A review of ICTAD standard bidding document 02 (2007) for major contracts. *The 3rd world construction symposium 2014: Sustainability and development in built environment* (pp. 36-46). Department of Building Economics. https://ciobwcs.com/downloads/WCS2014-Proceedings.pdf

Elgizawy, S. M., El-Haggar, S. M., & Nassar, K. (2016). Approaching sustainability of construction and demolition waste using zero waste concept. *Low Carbon Economy*, *07*(01), 1–11. https://doi.org/10.4236/lce.2016.71001

Fadiya, O. O., Georgakis, P., & Chinyio, E. (2014). Quantitative analysis of the sources of construction waste. *Journal of Construction Engineering*,1-9. https://doi.org/10.1155/2014/651060

Gillespie, A. (2015). *Waste policy: International regulation, comparative and contextual perspectives*. Edward Elgar Publishing. https://doi.org/10.4337/9781784715885

Ismail, Z., Idris, N. H., & Nasir, N. M. (2012). Comparative analysis on the policies in promoting sustainable construction in developed Asian countries. *2012 IEEE symposium on business, engineering and industrial applications, Bandung, Indonesia. (2012*, pp. 647-652) https://doi.org/10.1109/ISBEIA.2012.6422969

Jahan, I., Zhang, G., Bhuiyan, M., Navaratnam, S., & Shi, L. (2022). Experts' perceptions of the management and minimisation of waste in the Australian construction industry. *Sustainability*, *14*(18), 11319. https://doi.org/10.3390/su141811319

Kaliannan, S., Nagapan, S., Abdullah, A. H., Sohu, S., & Jhatial, A. A. (2018). Determining root cause of construction waste generation: A global context. *Civil Engineering Journal*, *4*(11), 2539–2547. https://doi.org/10.28991/cej-03091179

Kartam, N., Al-Mutairi, N., Al-Ghusain, I., & Al-Humoud, J. (2004). Environmental management of construction and demolition waste in Kuwait. *Waste Management*, *24*(10), 1049–1059. https://doi.org/10.1016/j.wasman.2004.06.003

Karunasena, G., Fernando, G., Ashokkumar, D., & Liu, C. (2023). Influence of labour experience in the generation of construction material waste in the Sri Lankan construction industry. *Sustainability*, *15*(6), 5406. https://doi.org/10.3390/su15065406

Karunasena, G., Gurmu, A., Shooshtarian, S., Udawatta, N., Perera, C. S. R., & Maqsood, T. (2025). Effect of construction defects on construction and demolition waste management in building construction: A systematic literature review. *Integrated Environmental Assessment and Management*, *21*(2), 233–244. https://doi.org/10.1093/inteam/vjae026

Lim, W. M. (2023). Philosophy of science and research paradigm for business research in the transformative age of automation, digitalization, hyperconnectivity, obligations, globalization and sustainability. *Journal of Trade Science*, *11*(2/3), 3–30. https://doi.org/10.1108/JTS-07-2023-0015

Lim, W. M. (2024). What is qualitative research? An overview and guidelines. *Australasian Marketing Journal*, 33(2), 199-229. https://doi.org/10.1177/14413582241264619

Love, P. E. D., Edwards, D. J., Irani, Z., & Walker, D. H. T. (2009). Project pathogens: The anatomy of omission errors in construction and resource engineering project. *IEEE Transactions on Engineering Management*, *56*(3), 425–435. https://doi.org/10.1109/tem.2008.927774

Lu, W., & Yuan, H. (2011). A framework for understanding waste management studies in construction. *Waste Management*, *31*(6), 1252–1260. https://doi.org/10.1016/j.wasman.2011.01.018

Mahamid, I. (2022). Impact of rework on material waste in building construction projects. *International Journal of Construction Management*, *22*(8), 1500–1507. https://doi.org/10.1080/15623599.2020.1728607

Medawala, U. G. H. T., & Dassanayake, D. R. (2024). Environmentally friendly construction waste management method to Sri Lanka. *Journal of Research Technology and Engineering*, *5*(2), 38–44.

Mellewigt, T. (2007). Trust and formal contracts in interorganizational relationships: Substitutes and complements. *Managerial and Decision Economics., 28,* 833-847. https://doi.org/10.1002/mde.1321

Mendis, D., Hewage, K. N., & Wrzesniewski, J. (2015). Contractual obligations analysis for construction waste management in Canada. *Journal of Civil Engineering and Management*, *21*(7), 866–880. https://doi.org/10.3846/13923730.2014.893907

Muneer, M., Khan, N., Hussain, M. A., Shuai, Z., Khan, A. A., Farooq, R., Moawwez, M. A., & Tariq, M. A. U. R. (2022). A quantitative study of the impact of organizational culture, communication management, and clarity in project scope on constructions' project success with moderating role of project manager's competencies to enhance constructions management practices. *Buildings*, *12*(11), 1856. https://doi.org/10.3390/buildings12111856

Purchase, C. K., Al Zulayq, D. M., O'Brien, B. T., Kowalewski, M. J., Berenjian, A., Tarighaleslami, A. H., & Seifan, M. (2021). Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials*, *15*(1), 76. https://doi.org/10.3390/ma15010076

Rathnayake, R. M. L. D., Madushantha, R. M. L., Gunawardhana, W. A. P. C. P., & Dissanayaka, P. B. R. (2024). Unveiling construction and demolition waste dynamics: A case study of the building construction sector in Sri Lanka. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *57*(4), 47–54. https://doi.org/10.4038/engineer.v57i4.7665

Saad, A. S., Othman, A. A. E., & Alamoudy, F. O. (2022). Causes influencing construction waste generation during the design process: An analytical study. *IOP Conference Series: Earth and Environmental Science*, *1056*(1), 012012. https://doi.org/10.1088/1755-1315/1056/1/012012

Sawant, R., Chandgude, S., Shewale, M., Logesh, M., Thakkar, K., & Ram, G. C. (2021). Improvement in construction contract management to reduce the construction waste. *Design Engineering*, (8), 16497-16519.https://www.researchgate.net/publication/356555821_Improvement_in_Construction_Contract_Management_to_Reduce_the_Construction_Waste

Taherdoost, H. (2022). What are different research approaches? Comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Towey, D. (2012). *Construction quantity surveying: A practical guide for the contractor's QS.* A John Wiley & Sons, Ltd. https://books.google.lk/books?hl=en&lr=&id=5EkzDwAAQBAJ&oi=fnd&pg=PR7&dq#v=onepage&q&f=false

Victar, H. C., & Waidyasekara, K. G. A. S. (2023). Construction and demolition waste management issues in building project life cycle stages: A case of Sri Lanka. *11th world construction symposium - 2023*, 392–406. Ceylon Institute of Builders - Sri Lanka. https://doi.org/10.31705/WCS.2023.33

Wambeke, B. W., Hsiang, S. M., & Liu, M. (2011). Causes of variation in construction project task starting times and duration. *Journal of Construction Engineering and Management*, *137*(9), 663–677. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000342

Wimalarathna, K. B. K. R. G. G., Fernando, M. L. S. S., & Kulatunga, U. (2023). Investigation of the challenges of executing sustainable construction practices in the Sri Lankan construction industry. *11th world construction symposium - 2023*, Ceylon Institute of Builders - Sri Lanka. 620–633. https://doi.org/10.31705/wcs.2023.51

Yang, M., Chen, H., Xu, Y., & Wu, J. (2025). The impact of contract functions on contractors' performance behaviors: A mixed-methods approach. *Buildings*, *15*(19), 3438. https://doi.org/10.3390/buildings15193438

Yi, B., & Nie, N. L. S. (2024). Effects of contractual and relational governance on project performance: he role of BIM application level. *Buildings*, *14*(10), 3185. https://doi.org/10.3390/buildings14103185

Wijesinghe, T., Sandanayake, Y.G., Jayanetti, J.K.D.D.T. and Perera, B.A.K.S., 2026. Convergence of circular economy strategies for sustainable timber usage in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 471-484. DOI: https://doi.org/10.31705/WCS.2026.35. Available from: https://ciobwcs.com/papers/

# CONVERGENCE OF CIRCULAR ECONOMY STRATEGIES FOR SUSTAINABLE TIMBER USAGE IN SRI LANKA

**Tilanka Wijesinghe[1], Y. G. Sandanayake[2], J.K.D.D.T. Jayanetti[3] and B.A.K.S. Perera[4]**

## *ABSTRACT*

*The construction industry is a major consumer of natural resources, creating increasing pressure for sustainable material utilisation. Timber, as a renewable construction material with favourable environmental characteristics, offers significant potential to support circular economy practices within the built environment. However, the effective application of circular economy strategies for timber utilisation remains limited in many developing construction contexts, specifically in Sri Lanka. This study investigates how circular economy strategies can be converged to enhance sustainable timber usage in the Sri Lankan construction industry. A qualitative research approach was adopted, using semi-structured expert interviews with 12 professionals with expertise in the research area. The collected data were analysed using qualitative content analysis to identify circular economy strategies relevant to sustainable timber utilisation. The analysis identified thirteen circular economy strategies that can support sustainable timber usage across the timber lifecycle. These include reclaimed timber utilisation, design for disassembly, prefabricated construction, lifecycle assessment-based design, materials passports and digital traceability, industrial symbiosis, modular thinking, circular public procurement, stakeholder education, commercial plantation regeneration, preservation and treatment for prolonged use, and engineered timber promotion. The findings indicate that the convergence of these strategies can improve timber lifecycle performance, enhance resource efficiency, and strengthen sustainable timber supply systems. Effective implementation requires alignment between design practices, supply chain transparency, industry awareness, and supportive policy mechanisms. The study contributes to circular construction research and provides practical insights to advance sustainable timber utilisation in the Sri Lankan construction industry.*

***Keywords:*** *Circular Construction; Circular Economy; Sustainable Timber Utilisation; Timber Construction.*

[1] Head, Department of Quantity Surveying, Faculty of Engineering, Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka, tilanka.w@sliit.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ysandanayake@uom.lk
[3]Assistant Professor, Department of Quantity Surveying, Faculty of Engineering, Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka, thamasha.j@sliit.lk
[4] Senior Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk

# 1. INTRODUCTION

The construction industry plays a critical role in economic development (Ravinder, 2025). However, it is also recognised as one of the most resource-intensive sectors, contributing significantly to environmental degradation and resource depletion. The sector consumes large quantities of raw materials and energy while generating considerable waste and greenhouse gas emissions, placing increasing pressure on natural ecosystems (Kulah et al., 2022). Globally, the built environment accounts for a substantial share of energy demand and carbon emissions, underscoring the urgent need to adopt more sustainable construction practices and material utilisation. In response to these sustainability challenges, attention has increasingly shifted toward the use of environmentally responsible construction materials. Timber has emerged as a promising alternative due to its renewable nature, relatively low embodied energy, and capacity to sequester carbon during its growth cycle (Mosly, 2025). Compared with conventional materials such as steel and concrete, timber demonstrates significantly lower embodied carbon and energy values, making it a favourable option for sustainable construction (Ravinder, 2025; Koca, 2018). Furthermore, timber offers high strength to weight ratio and structural versatility, enabling its application in a wide range of construction systems including both traditional timber structures and modern engineered wood products (Ghobadi & Sepasgozar, 2026). Despite these advantages, the utilisation of timber within the Sri Lankan construction industry remains constrained by several logistic, practice and governance related challenges. Although timber continues to be widely used for various construction applications, the sustainable management and utilisation of timber resources face limitations associated with supply chain restrictions and inefficiencies (Praboda et al., 2017). In addition, limited investment in modern timber-processing technologies and have further constrained the development of a sustainable timber supply system in the country.

In parallel with these challenges, global sustainability discourse has increasingly emphasised the transition from traditional linear economic models toward circular economy approaches. The conventional “take make dispose” production model has been widely criticised for its dependence on continuous resource extraction and waste generation (Benachio et al., 2020). In contrast, the circular economy promotes regenerative systems in which the value of resources once extracted is retained for as long as possible through strategies such as reuse, refurbishment, remanufacturing, and recycling (Geissdoerfer et al., 2017). Within the built environment, circular economy principles encourage lifecycle thinking, efficient material utilisation, and design approaches that facilitate the prolongation of the use of building components (Zhang et al., 2026). Timber possesses several characteristics that make it particularly compatible with circular economy principles. Its renewable nature, ease of processing, and potential for reuse enable timber components to circulate within multiple life cycles when appropriate design and management strategies are adopted (Islam et al., 2026). Circular economy strategies such as design for disassembly, modular construction, lifecycle assessment, and material traceability have the potential to significantly enhance the sustainability of timber utilisation in construction (Timm et al., 2023). Through the implementation of such strategies, timber resources can be utilised more efficiently while reducing pressure on forest ecosystems. However, despite the increasing recognition of circular economy concept within the construction sector, limited research has examined how circular strategies can be systematically integrated to enhance the sustainable

utilisation of timber in the Sri Lankan construction industry (Rahla et al., 2021). Existing studies largely focus on forest conservation, and timber supply dynamics, while the convergence of circular economy strategies for sustainable timber usage in construction remains insufficiently explored (Schukoske, 2009). Moreover, existing studies are focused on the applicability of CE strategies in general in the construction while applicability with timber remains insufficiently explored (Zhang et al., 2026). Therefore, the aim of this study is to investigate how circular economy strategies can be converged for sustainable timber usage in the Sri Lankan construction industry. In order to achieve this aim, the research objectives were defined as (1) to identify the key circular economy strategies that support sustainable timber utilisation in the construction sector, and (2) to examine the applicability of these strategies within the Sri Lankan construction context to enhance sustainable timber governance and resource efficiency.

# 2. LITERATURE REVIEW

## 2.1 CIRCULAR ECONOMY AND ITS APPLICATION IN CONSTRUCTION

Circular economy (CE) has emerged as a response to the limitations of traditional linear economic systems characterised by the take make dispose model (Cancela et al., 2026), aiming to minimise resource input and waste output while extending the lifecycle of materials through strategies such as reduction, reuse, and recycling (Kirchherr et al., 2017). It is increasingly conceptualised as a regenerative and systemic approach that integrates environmental sustainability with economic development, supported by practices that slow, close, and narrow material loops (Kirchherr et al., 2023). Achieving circular economy objectives requires coordinated industry efforts and supportive policy frameworks (Merli et al., 2018). Within the construction sector, which is highly resource intensive and generates significant construction and demolition waste, circular economy principles are particularly relevant (Benachio et al., 2020), promoting lifecycle thinking, efficient material utilisation, and design for reuse and recovery (World Green Building Council, 2023). However, despite its potential, the adoption of circular construction remains limited due to barriers such as weak regulatory frameworks, low awareness, and insufficient infrastructure (Bilal et al., 2020), highlighting the need for stronger policy support, stakeholder collaboration, and institutional incentives to enable the transition towards circular construction systems (Ghufran et al., 2022)

## 2.2 CIRCULAR ECONOMY STRATEGIES

Circular economy strategies provide practical mechanisms for implementing CE principles across industrial systems (Das et al., 2026). These strategies focus on extending the lifecycle of materials, improving resource efficiency, and minimising waste generation within production and consumption processes (Cancela et al., 2026). One important strategy is design for disassembly, which allows building components to be dismantled and reused without significant damage, thereby facilitating material recovery at the end of a building's lifecycle (Rahla et al., 2021). Similarly, modular and prefabricated construction techniques support circular construction by improving material efficiency and enabling easier reuse of building components (Munaro et al., 2020). Another key strategy involves the reuse and recycling of construction materials, which reduces the demand for virgin resources while minimising waste generation (Amudjie et al., 2023; Ibáñez-Forés et al., 2023). Digital technologies also play a significant role in enabling circular construction practices. For example, Building

Information Modelling (BIM) can support lifecycle management of building materials and facilitate informed decision-making regarding material reuse and recycling (Chen et al., 2022). In addition, materials passports and digital traceability systems provide important information regarding the properties and reuse potential of construction materials, thereby improving transparency and supporting circular material flows (Rahla et al., 2021; Schroeder et al., 2018). Public sector policies, such as circular public procurement, can further promote circular construction by encouraging the use of sustainable materials and circular design approaches in public infrastructure projects (Ogunmakinde et al., 2022; Schroeder et al., 2018).

## 2.3 SUSTAINABLE TIMBER USAGE IN CONSTRUCTION

Timber has long been recognised as one of the most sustainable construction materials due to its renewable nature and environmental performance. Responsibly sourced timber provides several environmental benefits including carbon sequestration, low embodied energy, and lower greenhouse gas emissions compared to conventional construction materials such as steel and concrete (Koca, 2018; Ramage et al., 2017). Timber also offers several functional advantages including high strength to weight ratio, thermal insulation properties, and suitability for prefabricated construction systems (Ramage et al., 2017). These characteristics make timber an attractive material for sustainable construction practices. In the Sri Lankan context, timber has historically been used extensively in residential construction, particularly for roofing structures, joinery, and interior finishes (Sudeshika et al., 2019). However, the availability and utilisation of timber resources have been influenced by regulatory restrictions and supply chain limitations. Government policies aimed at protecting natural forests have imposed restrictions on timber harvesting, which has reduced domestic timber supply (Ruwanpathirana, 2012). In addition, challenges such as inconsistent timber quality, fragmented supply chains, and lack of standardised grading systems have limited the efficient use of timber in construction projects. These challenges highlight the need for improved resource management approaches that can enhance sustainable timber utilisation.

## 2.4 USE OF CIRCULAR ECONOMY IN SUSTAINABLE TIMBER USAGE IN CONSTRUCTION

Circular economy strategies provide significant opportunities to enhance sustainable timber utilisation in the construction sector. Due to its renewable and biodegradable nature, timber is particularly well suited for circular resource cycles when appropriate management strategies are implemented (Benachio et al., 2020). Several circular economy strategies can be applied to optimise timber utilisation. For example, design for disassembly allows timber components to be dismantled and reused in new construction projects, thereby extending the lifecycle of timber resources (Thormark, 2007; Rahla et al., 2021). Lifecycle assessment (LCA) is another important approach for evaluating the environmental performance of construction materials. LCA enables designers to compare the environmental impacts of different materials and select options that minimise environmental burdens throughout the building lifecycle (Chen et al., 2022). Furthermore, , such as material passports, can record information related to timber origin, species, and treatment processes. These systems improve transparency and facilitate the reuse of timber components by providing reliable information regarding material properties (Rahla et al., 2021; Timm et al., 2023).

### 2.5 NEED TO CONVERGE CIRCULAR ECONOMY STRATEGIES FOR SUSTAINABLE TIMBER USAGE IN SRI LANKA

Despite the potential benefits of circular economy strategies, their implementation within the Sri Lankan construction industry remains limited. The presumption that the use of timber as a construction material exerts pressure on forest cover leads to stringent legislation that focuses solely on forest conservation but does not consider timber as a sustainable construction material (Wikramanayake et al., 2021; Buliga & Nichiforel, 2019). As a result, opportunities to enhance timber sustainability through circular strategies remain underexplored. Several barriers hinder the adoption of circular timber practices in Sri Lanka. These include fragmented legislation, limited technical infrastructure for material recovery, lack of awareness among industry stakeholders, and negative perceptions regarding the use of reclaimed timber (Munaro et al., 2020; Rahla et al., 2021). In addition, the absence of integrated policy frameworks that promote circular construction practices further restricts the adoption of circular economy strategies. Therefore, there is a need to systematically examine how circular economy strategies can be converged to support sustainable timber utilisation within the Sri Lankan construction industry. Understanding these strategies and their practical applications can contribute to improved resource efficiency, reduced environmental impacts, and more sustainable timber governance in the construction sector.

## 3. METHODOLOGY

This study adopted a qualitative research approach to investigate circular economy strategies that can support sustainable timber utilisation in the Sri Lankan construction industry. Qualitative research methods are particularly suitable for exploratory investigations that seek to understand complex industry practices, stakeholder perspectives, and emerging strategies within a specific context (Creswell & Creswell, 2018; Leavy, 2022). Since the objective of the research was to explore how circular economy strategies can be applied to timber usage within the construction sector, a qualitative approach enabled the collection of in-depth insights from industry experts with relevant knowledge and experience. Data were collected through semi structured interviews conducted with twelve experts representing sectors related to timber utilisation, construction practices, and timber supply chain,. Expert interviews are widely used in qualitative research to obtain detailed insights from individuals with specialised professional knowledge (Eppich et al., 2019; Gill et al., 2008). Engaging experts from multiple sectors enabled the study to capture diverse perspectives on circular economy strategies relevant to sustainable timber usage in the construction industry. A purposive sampling strategy was used to select the interview participants. Purposive sampling enables researchers to deliberately select participants who possess relevant expertise and knowledge related to the research topic (Etikan et al., 2016; Campbell et al., 2020). Data saturation was achieved at the 10th Expert, thus two more interviews were conducted. The selected experts had substantial professional experience in construction, timber utilisation, environmental management, or policy related to forest resources and the built environment as depicted in Table1.

*Table 1. Expert profile*

| Expert Code | Designation / Role | Sector | Experience | Area of Expertise |
|---|---|---|---|---|
| E1 | Director / Consultant | Construction sector | 33 | Contract Administration, Timber in Construction & CE |
| E2 | Director | Regulatory body for timber | 25 | Timber in Construction, Regulation and supply chain |
| E3 | Managing Director / Consultant | Construction sector | 33 | Contract Administration, Timber in Construction & CE |
| E4 | Conservator of forest | Regulatory body for forest resources | 19 | Timber Legislation, CE & Sustainable Forest Management, Supply chain |
| E5 | Engineer | Construction supplier | 17 | Timber in Construction, Timber Trade & Certification |
| E6 | Charted Civil Engineer / Professor | Non-state university/ Construction sector | 28 | Circular Economy / Life cycle Assessment & CE |
| E7 | Chartered QS / Professor | State university/ Construction sector | 29 | CE |
| E8 | Professor | Non-state university/Construction sector | 27 | Timber in Construction & CE |
| E9 | Researcher | State university/Construction sector | 5 | CE |
| E10 | Academic / Lawyer | State university/Construction sector | 25 | Policy Implementation Supply chain and CE |
| E11 | Chartered QS / Lawyer | Construction sector | 25 | CE/ Regulation and Trade |
| E12 | Director | Construction sector/timber treatment | 25 | Timber Trade & Certification & CE |

Participants were purposively selected based on professional experience, involvement in decision-making related to timber use or construction practices, and familiarity with sustainability or circular economy initiatives, ensuring the inclusion of individuals with adequate technical and contextual expertise to provide informed insights relevant to the Sri Lankan construction industry. The interview data were analysed using manual qualitative content analysis, which enables the systematic identification of patterns, themes, and relationships within qualitative data (Amudjie et al., 2023). Responses were coded and categorised to derive key circular economy strategies for sustainable timber utilisation, with the resulting themes forming the basis for identifying relevant strategies and examining their applicability within the Sri Lankan construction context.

# 4. FINDINGS AND ANALYSIS

## 4.1 CIRCULAR STRATEGIES THAT CAN BE USED FOR SUSTAINABLE TIMBER USAGE IN THE SRI LANKAN CONSTRUCTION INDUSTRY

The expert interviews were analysed using qualitative content analysis to identify circular economy strategies that can support sustainable timber utilisation in the Sri Lankan

construction industry. Through the analysis of the interview responses, a total of thirteen circular economy strategies were initially identified as shown in below Table 2.

*Table 2- Circular economy strategies for sustainable timber usage in Sri Lankan construction industry*

| Code | CE Strategy | Usage | Experts Support |
|---|---|---|---|
| S1 | Use of Reclaimed Timber | • Reuse and Recycle<br>• Extend the life in use as timber is a durable material<br>• Minimise the resource extraction | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S2 | Design for Disassembly | • Joints are one of the most important aspects in timber<br>• Allowed the convenience of disassembly<br>• Improve the recovery efficiency | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S3 | Prefabricated Construction | • Modified from Modular and Prefabricated Construction<br>• Improve the material efficiency | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S4 | Lifecycle Assessment (LCA) Based Design | • Encourage the use of timber due to its sustainability properties<br>• Encourage the use of it in CE modes. | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S5 | Materials Passports and Digital Traceability | • Important to identify the place of growth, species, maturity<br>• Can create a lasting record for second hand use. | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S6 | Industrial Symbiosis | • Important for forward and backward linkage between industries | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S7 | Modular Thinking | | |
| | S7.1- Dimension modules | • Improve the material efficiency<br>• Increase the opportunities of reuse | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| | S7.2 - Time modules | • Encourage the use of fast growing medium dense timber in the element require regular modifications. | E3, E5, E6, E7, E9, E11, E12 |
| S8 | Circular Public Procurement | • Integration of CE provision to public procurement guidelines | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S9 | Stakeholder Education and Awareness | • Deal with lack of knowledge in timber species and its suitability for different uses<br>• Improve the knowledge in joinery<br>• Avoid social myths resisting the use of reclaimed material. | E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12 |
| S10 | Commercial plantation for regeneration | • Regeneration is an important aspect of circular use | E1, E2, E4, E5, E6, E7, E9, E10, E11, E12 |
| S11 | Preservation and Treatment for Prolonged Use | • Help to prolong in use as timber is susceptible to insect attacks. | E1, E2, E3, E5, E7, E8, E10, E12 |
| S12 | Encourage Engineered Timber | • Help to negate defects and challenges inherent with timber. | E1, E3, E5, E8, E12 |

The findings indicate that the majority of the strategies received strong support from the interviewed experts, particularly those related to reuse, design approaches, and supply

chain transparency. Strategies such as reclaimed timber use, design for disassembly, prefabricated construction, lifecycle assessment-based design, and circular public procurement received support from all interviewed experts, highlighting their perceived importance for improving sustainable timber utilisation within the Sri Lankan construction sector. In contrast, certain strategies such as modular time-based design, preservation and treatment practices, and engineered timber promotion received moderate levels of expert support, indicating emerging but still developing practices within the industry. Overall, the identified strategies demonstrate that circular economy principles can be applied across multiple stages of the timber lifecycle, from resource regeneration and material production to building design and construction practices.

## 4.2 APPLICATION OF EACH CIRCULAR STRATEGY FOR SUSTAINABLE TIMBER USAGE IN THE SRI LANKAN CONSTRUCTION INDUSTRY

The expert interviews provided valuable insights into how the identified circular economy strategies can be practically applied to enhance sustainable timber utilisation within the Sri Lankan construction industry. The experts highlighted that the implementation of these strategies requires improvements in design practices, supply chain management, resource regeneration, and industry awareness. The application of each strategy within the Sri Lankan context is discussed below.

The use of reclaimed timber was also strongly emphasised as a practical strategy for extending the service life of timber materials as indicated in Table 2. Initially described as the use of recycled and reused materials, the strategy was refined as use of reclaimed timber following the suggestion of E3. Experts highlighted that reclaiming timber from existing structures can significantly reduce resource extraction while allowing sufficient time for forest regeneration. As explained by E6, *"Timber comes from nature and goes back to nature therefore not a significant cause in terms of waste and its sequestration carbon performance can be further enhanced when prolonged in use through reclaiming that will also allow adequate time for regeneration while minimising the resource extraction."* Similarly, E9 highlighted the importance of reducing dependence on imported materials, stating *"Sri Lankan construction industry depends heavily on the imported material; it is important to seek more of local substitutes where timber is a definite option and use of reclaimed timber will further enhance the ability of using locally sourced material."* All experts agreed that reclaiming timber can significantly improve resource efficiency while reducing environmental impacts.

Design for Disassembly (DfD) emerged as a key design-oriented strategy for enabling circular timber utilisation, with experts emphasising the importance of joinery systems in facilitating material recovery and reuse. Traditional joinery was particularly valued, as highlighted by E8, "Joints have to be designed for disassembly," and E1, who noted that modern methods such as "nailing and gluing hinder the ability of disassembly," unlike traditional interlocking systems. Overall, experts agreed that incorporating disassembly considerations at the design stage enhances reuse, recycling, and recovery of timber. In addition, prefabricated construction was strongly supported as a strategy to improve efficiency and reduce material waste, with E6 stating that "production and material efficiency can immensely improve through offsite factory production," while E1 pointed to successful implementation in contexts such as Maldives. Based on expert feedback, the strategy was refined to focus specifically on prefabrication, highlighting its potential to enhance construction efficiency while minimising material losses. The interviews also

highlighted the importance of modular thinking in enabling circular timber utilisation. While eco-design was initially identified as a potential strategy, many experts indicated that eco-design considerations are already embedded within several circular construction practices. Therefore, the concept was refined as modular thinking, which focuses on designing building components using standardised dimensions that facilitate reuse and adaptability. As explained by E3, *"Timber is considered one of the most environmentally friendly materials, and its increased use in construction contributes significantly to ecological sustainability."* Similarly, E9 emphasised the reuse potential associated with modular design, stating *"Modular construction will give a better opportunity of reusing especially when it comes to timber."* Several experts also emphasised the importance of considering time-based modularity when selecting timber species. In particular, E11 highlighted that *"Medium dense timber like rubberwood shall contribute with less embodied carbon compared to hardwoods because it grows faster and is easier to process. Using low and medium-density timber is therefore recommended, especially for elements like interior works that often require modifications."* This perspective suggests that matching timber characteristics with the anticipated lifespan of building components can further enhance circular material utilisation.

Lifecycle assessment (LCA) was widely recognised as a strategy to promote timber use, with experts highlighting its favourable environmental performance due to low embodied carbon and high sequestration capacity. As noted by E2, "*Timber is highly sustainable material with lower embodied carbon, higher strength to weight ratio and higher sequestration carbon, therefore LCA will encourage the use of timber*." Experts also emphasised that LCA can encourage the use of reclaimed timber (E6), and could be further strengthened through policy integration, with E1 stating, "if LCA combined with carbon taxation or concessions, it will definitely boost the use of timber and its circular use." Material passports were also strongly supported due to variability in timber properties, with E3 explaining, "*There is a significant variance in properties among the different species while there are also difference in properties of the same species based on the place of origin*," and further noting that "*A material passport can certainly assist in identifying the suitability of the log or sawn timber member for specific applications, which contributes to a longer lifespan in use.*" Similarly, E2 highlighted their importance by stating, "*Laypeople in general and experts when it comes to certain species often struggle to identify sawn timber species by sight alone. The material passport in this regard can provide immense benefits*." Industrial symbiosis was identified as a key strategy to utilise timber residues across industries, with E5 noting, "*In our factory, around 80% of sawdust is wasted despite its potential for use in other sectors like particle board production and agriculture etc,"* and E11 emphasising that "*collaboration between the rubber and construction industries could mutually benefit both sectors and enhance their carbon performance.*" Circular public procurement was recognised as a critical policy driver, with E3 suggesting "*a regulation required to insist on certain minimum percentage of reclaimed content*," and E6 highlighting that "*public procurement guidelines can include mandatory LCA requirement for certain type of projects including public sector projects,"* thereby supporting sustainable timber utilisation.

Stakeholder education and awareness were also identified as essential enabling factors for implementing circular timber strategies. Experts emphasised the need to improve knowledge among designers, contractors, and clients regarding timber properties and reuse practices. As noted by E1, *"It is necessary to educate and improve the awareness*

*of all the stake holders across different strata."* Similarly, E11 highlighted that *"Dislike of people of using reclaimed material, sometimes backed by customary myths, hindered the circular use of timber. Therefore, an effective social awareness campaign is required."* Digital traceability platforms were also identified as important tools for improving supply chain transparency and material tracking. Experts highlighted that digital systems could integrate material passports and documentation processes throughout the supply chain. As explained by E5, *"A streamlined digital documentation system with a material passport that accumulates information throughout the supply chain would benefit both the primary and secondary use of timber."* E7 also highlighted the role of BIM platforms in improving supply chain collaboration, stating, *"Using platforms like BIM allows early detailing and better supply chain collaboration, which is key to efficiently using timber in construction."* The regeneration of timber resources through plantation forestry was also emphasised as an essential strategy in the Sri Lankan context. Experts highlighted that sustainable timber utilisation requires continuous regeneration of forest resources. As noted by E4, *"forest conservation department encourage the private sector investments manmade forest plantation and commercial tree plantations."* However, experts also noted several challenges associated with plantation forestry. For example, E2 stated that *"Commercial timber plantations are vital, but limited land is a major challenge."* Experts also highlighted the importance of preservation and treatment in extending the lifespan of timber materials. As explained by E3, *"There is a huge stock of old building being unattended without been maintained. Old buildings are material banks."* Proper preservation techniques can therefore facilitate the reclamation of timber from existing buildings. E12 emphasised that *"Timber is a sustainable material but consume a substantial time for regeneration. Therefore, it is important to improve the durability and prolong the use to keep up with the regeneration pace."* E12 further highlighted the need to address environmental impacts associated with preservation methods. Finally, experts also emphasised the potential of engineered timber technologies in overcoming structural limitations associated with natural timber. As noted by E8, *"Although timber is highly sustainable material it comes with lot of inherent challenges as it prone to defects. Engineered timber can help address these issues and support greater circular use."* Experts also highlighted that engineered timber technologies remain relatively underdeveloped in Sri Lanka, indicating opportunities for technological advancement within the sector. Overall, the findings demonstrate that integrating circular economy strategies across design, material utilisation, supply chains, and resource regeneration can significantly improve sustainable timber utilisation within the Sri Lankan construction industry.

## 5. DISCUSSION

The findings of this study demonstrate strong alignment with existing literature on circular economy implementation in the built environment while also reflecting several contextual nuances specific to the Sri Lankan construction sector. The identified strategies such as design for disassembly, prefabricated construction, modular thinking, and the use of reclaimed materials correspond closely with circular construction strategies widely discussed in previous studies (Timm et al., 2023). Although Product as a Service (PaaS) was identified in the literature (Foster, 2020; Massari & Giannoccaro, 2023; Anastasiades et al., 2022), it was excluded from the final list of strategies, as experts highlighted its limited applicability to construction, being more suitable for furniture and temporary interior elements rather than structural timber applications. These strategies

emphasise extending material lifecycles, improving resource efficiency, and enabling reuse through design and production innovations. Similarly, the emphasis on lifecycle assessment and material traceability reflects the increasing importance of lifecycle thinking and digital information systems in supporting circular material flows within construction supply chains (Chen et al., 2022; Schroeder et al., 2018). The findings also reinforce prior research highlighting the potential of timber as a sustainable construction material due to its renewable nature and favourable environmental performance (Ramage et al., 2017; Koca, 2018). However, the results indicate that the effective implementation of circular timber strategies requires additional enabling conditions within the Sri Lankan context. Strategies such as stakeholder education, circular public procurement, and plantation regeneration highlight the importance of institutional support, industry awareness, and resource governance in facilitating circular timber utilisation. These findings therefore suggest that while global circular construction strategies are applicable within Sri Lanka, their successful implementation depends on addressing local supply chain constraints, policy mechanisms, and industry knowledge gaps.

## 6. CONCLUSIONS

This study examined how circular economy strategies can be integrated to support sustainable timber usage in the Sri Lankan construction industry. The findings indicate that improving timber sustainability requires the integration of circular practices across design, material utilisation, supply chains, and resource regeneration. The convergence of these strategies can enhance timber lifecycle performance, improve resource efficiency, and reduce pressure on virgin timber resources within construction activities. The study highlights that advancing circular timber utilisation in Sri Lanka requires both improved industry practices and supportive institutional mechanisms. Circular design approaches that facilitate reuse and adaptability, together with improved material recovery and traceability practices, can strengthen the efficiency of timber utilisation within construction projects.

This study contributes to research by contextualising circular economy strategies for sustainable timber utilisation within the Sri Lankan construction industry, an area that has received limited academic attention. The study advances existing knowledge by identifying circular strategies for timber use and demonstrating how circular economy concepts can be applied within a developing construction context. The interview findings were triangulated with existing literature to strengthen the credibility, interpretation, and contextual relevance of the findings.. From an industry perspective, the findings provide practical guidance in improving timber utilisation practices by integrating circular approaches into design, material management, and supply chains. The identified strategies support improved resource efficiency, promote reclaimed timber utilisation, emphasise commercial plantations and encourage more sustainable timber practices within the construction sector. Future studies may examine the environmental and economic performance of different timber species. This study is limited to qualitative insights derived from 12 expert interviews within the Sri Lankan construction industry. To mitigate the limitations of relying solely on expert perspectives in the Sri Lankan construction industry, data triangulation was employed by integrating literature findings with expert feedback and validation.

# 7. REFERENCES


Amudjie, J., Agyekum, K., Adinyira, E., Amos-Abanyie, S., & Botchway, E. A. (2023). Implementing the principles of circular economy in the construction industry: Exploratory and confirmatory factor analyses of strategies. *Construction Innovation*, 25 (3), 761–786. https://doi.org/10.1108/CI-10-2022-0270

Anastasiades, K., Lambrechts, T., Mennes, J., Audenaert, A., & Blom, J. (2022). Formalising the R of reduce in a circular economy oriented design methodology for pedestrian and cycling bridges. J — Multidisciplinary Scientific Journal, 5(1), 35–51. https://doi.org/10.3390/j5010003

Benachio, G. L. F., Freitas, M. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production, 260*, Article 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Bilal, M., Khan, K. I. A., Thaheem, M. J., & Nasir, A. R. (2020). Current state and barriers to the circular economy in the building sector: Towards a mitigation framework. *Journal of Cleaner Production, 276*, Article 123250. https://doi.org/10.1016/j.jclepro.2020.123250

Buliga, B., & Nichiforel, L. (2018). Voluntary forest certification vs. stringent legal frameworks: Romania as a case study. *Journal of Cleaner Production*, 207, 329–342. https://doi.org/10.1016/j.jclepro.2018.10.021

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., & Walker, K. (2020). Purposive sampling: Complex or simple? Research case examples. *Journal of Research in Nursing, 25*, 652–661. https://doi.org/10.1177/1744987120927206

Cancela, B. L, Santos, C, and Coelho, A. (2026). "Green strategies for circular economy and sustainable supply chains." *Corporate Social Responsibility and Environmental Management* 33, no. 1: 675-693. https://doi.org/10.1002/csr.70195

Chen, Q., Feng, H., & Garcia de Soto, B. (2022). Revamping construction supply chain processes with circular economy strategies: A systematic literature review. *Journal of Cleaner Production, 335*, 130240. https://doi.org/10.1016/j.jclepro.2021.130240

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Sage Publications.

Das, T. K., Jesionek, M., Ali, M. D., Ganguly, S., & Poater, A. (2026). Advancing sustainability: circular economy strategies for fibrous polymer composites. *Cleaner Materials*, (*19*), 100381.https://doi.org/10.1016/j.clema.2026.100381

Eppich, W. J., Gormley, G. J., & Teunissen, P. W. (2019). In-depth interviews. In *Healthcare simulation research* (pp. 85–91). Springer. https://doi.org/10.1007/978-3-030-26837-4_12

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American Journal of Theoretical and Applied Statistics, 5*(1), 1–4. https://doi.org/10.11648/j.ajtas.20160501.11

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production, 143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghobadi, M., & Sepasgozar, S. (2026). Optimizing sustainable timber projects and asset management through AI-powered circular economy systems. *Built Environment Project and Asset Management*, *16*(1), 92-108. https://doi.org/10.1108/BEPAM-02-2025-0060

Ghufran, M., Khan, K. I. A., Ullah, F., Nasir, A. R., Al Alahmadi, A. A., Alzaed, A. N., & Alwetaishi, M. (2022). Circular economy in the construction industry: A step towards sustainable development. *Buildings, 12*(7), Article 1004. https://doi.org/10.3390/buildings12071004

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: Interviews and focus groups. *British Dental Journal, 204*(6), 291–295. https://doi.org/10.1038/bdj.2008.192

Islam, A. M. S., Barua, A., & Alam, M. R. (2026). Sustainable timber-concrete composite housing for the coastal region of Bangladesh: a comparative study. *Journal of Building Pathology and Rehabilitation*, *11*(1), 23. https://doi.org/10.1007/s41024-025-00699-1

Ibáñez-Forés, V., Alejandrino, C., Bovea, M. D., & Mercante, I. (2023). Prioritising organisational circular economy strategies by applying the partial order set theory: Tool and case study. *Journal of Cleaner Production*, *406*, 136727. https://doi.org/10.1016/j.jclepro.2023.136727

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation & Recycling, 127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kirchherr, J., Yang, N. H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): An analysis of 221 definitions. *Resources, Conservation & Recycling, 194*, Article 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Koca, G. (2018). Ecological properties of wooden building materials. *Turkish Journal of Forestry, 19*(1), 9–14..

Kulah, A. S., Blay, A. V. K., & Opoku, A. (2022). Strategies to reduce the impact of resource consumption in the Ghanaian construction industry. *International Journal of Real Estate Studies, 16*(1), 51–59. https://doi.org/10.11113/intrest.v16n1.88

Leavy, P. (2022). *Research design: Quantitative, qualitative, mixed methods, arts-based, and community-based participatory research approaches* (2nd ed.). Guilford Press.

Mosly, I. (2025). Carbon footprint of global construction industries: A cross-country analysis of emissions, drivers, and the Construction Carbon Sustainability Index (1990–2023). Sustainability, 17, 9274. https://doi.org/10.3390/su17209274

Massari, G. F., & Giannoccaro, I. (2023). Adopting GRI standards for the Circular Economy strategies disclosure: The case of Italy. *Sustainability Accounting, Management and Policy Journal, 14*(4), 660–698. https://doi.org/10.1108/SAMPJ-07-2021-0284

Merli, R., Preziosi, M., & Acampora, A. (2018). How do scholars approach the circular economy? A systematic literature review. *Journal of Cleaner Production, 178*, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). The ecodesign methodologies to achieve buildings' deconstruction: A review and framework. *Buildings, 10*(11), 183. https://doi.org/10.3390/buildings10110183

Ogunmakinde, O. E., Egbelakin, T., & Sher, W. (2022). Contributions of the circular economy to the UN sustainable development goals through sustainable construction. *Resources, Conservation & Recycling, 178*, 106023. https://doi.org/10.1016/j.resconrec.2021.106023

Probodha, H., De Silva, S., De Silva, S., & Subashi, D. (2017). Application of non class timber in construction industry. In *Proceedings of the International Conference on Structural Engineering and Construction Management (ICSECM 2017)*. University of Ruhuna, Sri Lanka

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings—From theory to practice. *Applied System Innovation, 4*(2), 26. https://doi.org/10.3390/asi4020026

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., & Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews, 68*, 333–359. https://doi.org/10.1016/j.rser.2016.09.107

Ravinder, B. (2025). Assessing the environmental impact of the construction industry: Insights for environmental science and sustainable development. *International Journal of Environmental Sciences, 11*(21), 2248–2260. https://doi.org/10.64252/km0nnc24

Ruwanpathirana, N. (2012). *Sustainable utilization of timber resources in Sri Lanka*. State Timber Corporation. Sri Lanka

Schroeder, P., Anggraeni, K., & Weber, U. (2018). The relevance of circular economy practices to the sustainable development goals. *Journal of Industrial Ecology, 23*(1), 77–95. https://doi.org/10.1111/jiec.12732

Schukoske, J. (2009). Enforcing environmental laws in Sri Lanka through fundamental rights litigation. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1427323

Sudeshika, D. M. P., Mendis, M. S., & Halwatura, R. U. (2019). A study on most abundantly utilized timber for structural application in Sri Lanka. In S. Samarawickrama et al. (Eds.), *Re evaluating space across disciplines: Proceedings of the 12th International Conference of the Faculty of Architecture Research Unit (FARU)* (pp. 107–114). Faculty of Architecture Research Unit, University of Moratuwa.

Thormark, C. (2007). Motives for design for disassembly in building construction. Portugal SB 2007 - *Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, June*, 607–611.

Timm, J. F. G., Maciel, V. G., & Passuello, A. (2023). Towards sustainable construction: A systematic review of circular economy strategies and ecodesign in the built environment. *Buildings, 13*(8), 2059. https://doi.org/10.3390/buildings13082059

Wikramanayake, E., Pfeiffer, D. U., Magouras, I., Conan, A., Ziegler, S., Bonebrake, T. C., & Olson, D. (2021). A tool for rapid assessment of wildlife markets in the Asia-Pacific Region for risk of future zoonotic disease outbreaks. *One Health*, 13, 100279. https://doi.org/10.1016/j.onehlt.2021.100279

World Green Building Council. (2023). *The circular built environment playbook*. World Green Building Council

Zhang, C., Behrens, P., & Myers, R. J. (2026). Aligning circular economy and low-carbon economy for a sustainable built environment. *Cell Reports Sustainability*.

Udayangani, M.A.A., Ramachandra, T. and Piranavan, S., 2026. Cost impacts of circular applications to construction activities: A case of Sri lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 485-498. DOI: https://doi.org/10.31705/WCS.2026.36. Available from: https://ciobwcs.com/papers/

# COST IMPACTS OF CIRCULAR APPLICATIONS TO CONSTRUCTION ACTIVITIES: A CASE OF SRI LANKA

**M.A.A. Udayangani[1], T. Ramachandra[2] and S. Piranavan[3]**

## *ABSTRACT*

*The need to transition towards a circular economy (CE) paradigm has increased due to the growing environmental burden associated with rising resource consumption and waste generation in the construction industry. Although the construction phase constitutes a relatively small proportion of the overall building life cycle, it exerts a disproportionately high environmental impact due to the extensive use of virgin materials. Nevertheless, the implementation of CE during this phase is constrained by the lack of awareness of its economic incentives. Therefore, this study seeks to assess the cost impacts of integrating CE into construction activities within the Sri Lankan context. Using a multiple case study approach, the research evaluates the cost implications of CE practices in construction of two multi-storied buildings. Data were gathered through semi-structured interviews and review of documents, including Bills of Quantities and as-built records. The findings demonstrate that CE applications are currently concentrated within eight (out of forty-one) major activities, including excavation, concrete and masonry, primarily operationalised through basic 3R (Reduce, Recycle, Reuse) principles. This limited applications of CE yielded total cost savings of approximately 2% to 4% of the contract value. Notably, of the two buildings, the green building exhibited higher savings (4.39%) compared to the non-green building (1.89%). By providing empirical evidence of economic cost savings resulting from CE applications, the study contributes to enhancing the adoption of CE in the construction sector. These findings highlight that the greater integration of CE practices during construction stage would enhance the sustainability of the construction projects.*

***Keywords:*** *Circular Economy; Construction Activities; Cost Implications; R – Principles; Sri Lanka.*

## 1. INTRODUCTION

According to the United Nations, it is projected that the world population will reach up to 8.5 billion in 2030 (United Nations, 2021). Population growth and urbanization are identified as coupled factors which increase resource consumption in the built environment (Pullen et al., 2012). This intensive use of resources ultimately leads to a significant amount of construction waste. According to Tafesse et al. (2022), the building sector consumes 40% of raw materials and produces approximately 35% of total waste to

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, udayanganimaa@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, thanujar@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sivasothypiranavan27@gmail.com

the environment, which represents one third of global waste. Moreover, the higher resource consumption increases the embodied carbon emission (Palomar-Torres et al., 2025). Addressing this environmental burden has urged shifting from the linear take-make-dispose based economy to circular economy (CE) (Çimen, 2021).

The CE is widely defined as a system in which materials are continuously cycled, minimizing waste while supporting and regenerating natural systems through reduced resource extraction and closed loop flows (Akhimien et al., 2021). In practice, CE is often operationalized through hierarchical R-principles that aim to transform construction processes into regenerative closed loop systems (Ghisellini & Ulgiati, 2020). The R Frameworks demonstrate conceptual maturity and adaptability of CE in its implementation across building lifecycle. Based on a proactive cradle-to-cradle framework Akhimien et al. (2021) emphasized that circularity must be integrated throughout the entire building lifecycle from design and planning, construction, operation, maintenance to deconstruction phases (Pomponi & Moncaster, 2016). On a slightly different note, Charef et al. (2021) have concluded that the limited attention on cost impacts as one of the significant barriers in adopting CE to the design and end-of-life management stages of a construction project.

Although the construction phase represents a relatively small portion of the building life cycle, Fagone et al. (2023) highlighted that it has a significant influence on environmental impacts. Furthermore, the review of CE applications during the construction phase indicates that existing studies are largely limited to the qualitative identification of techniques for utilizing recovered components obtained through building deconstruction and incorporating recycled materials into construction projects (Rahla et al., 2021). In another recent study, Fagone et al. (2023) have formulated a circular construction site methodology to monitor the circularity process, using green certification protocols and KPIs. However, the study fails a quantitative assessment of cost effects of CE implementation. With regards to CE implementation in overall lifecycle, Charef et al. (2021) state that it is impeded by multiple barriers spanning across organisational, economical, technical, environmental, political, and societal dimensions. Furthermore, Adams et al. (2017) have stressed the importance of studying cost benefit of CE implementation due to the associated higher upfront costs in construction.

Green concept aims to promote efficient resource use in the production process and consumption, by reducing waste generation which aligns with definition of circular economy (UN environment programme, 2018). Further, the World Green Building Council states that ‘resources and circularity’ is one of areas which they are focusing on in the process of transforming the construction sector to a more sustainable and healthier built environment (World Green Building Council, n.d.). In another recent study, Li et al. (2025) have identified that the circular economy implementation is contributing to maturation of green building research by aligning construction workflows with global carbon reduction targets and science driven sustainability efforts. Building on these insights, Moustafa et al., (2025) stated that integrating CE strategies into green buildings would enable a sustainable and efficient built environment.

In this context, the current study aims to assess the cost impacts of integrating CE principles into construction activities by considering both a green building and a non-green building.

## 2. CE PRINCIPLES AND APPLICATIONS OF CIRCULAR ECONOMY PRINCIPLES TO CONSTRUCTION ACTIVITIES

"R-principles" (or R-imperatives) are used to operationalise the circularity. While 3R (Reduce, Recycle, Reuse) model is widely recognised as the foundational framework, there are notable evolution of the principles to include multiple iterations including 4R, 5R, 9R, and 10R (Reike et al., 2022). Charef (2024) specifically identifies transition to a 4R model through inclusion of Recovery, highlighting the need of prevent the energy or value being lost to the system, while Mrad and Ribeiro (2022) have assessed a comprehensive 10R framework comprising Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Reduce, Rethink and Refuse, to evaluate the impacts throughout the whole building lifecycle as part of circularity. Expanding this hierarchy further, Kochanski et al. (2024) analysed material use and costs based on 11R principles as effective CE implementation. In another recent study, Uvarova et al. (2023) has introduced 60R principles in broad general context classified into major four groups of Reduce, Reuse, Recycle and Reverse logistics. However, Zhu and Feng (2026) have analysed multiple R-principles and stated that 3R principles remain central to all the variations. Collectively, these variations of R-principles demonstrate the evolving and increasingly comprehensive approach to operationalise circularity across different contexts, still maintaining the basic emphasis on resource efficiency and waste minimisation. Pearlmutter et al. (2019) found that green buildings are one of the nature-based solutions contributing to circularity, especially through transforming the urban built environment into circular cities. CE implementation in green building construction enables effective resource utilisation and cost savings in construction phase (Giorgi et al., 2022).

Although construction phase is relatively shorter in entire building lifecycle, it is the point of highest material flow and waste generation (Fagone et al., 2023). Gamage et al. (2024) studied the relationship between the CE practices and lifecycle stages of construction projects and concluded that the practices in construction stage including use of offsite construction, reducing waste generation, optimising the resource usage, and prioritising reuse and recycled materials into the process. Phear and Fraser (2024) have focused on developing a new standard for sustainable earthworks especially through the practices of reducing use of natural resources, adopting regenerative solutions and reuse of existing waste materials in earthworks. Yet, there are several further applications of CE practices, especially during the construction phase, as summarised in Table 1.

*Table 1: Construction activities and CE applications*

| Construction Activities | | CE Applications | CE Principle | Sources |
|---|---|---|---|---|
| Preliminary work | Site selection | Soft re-use of brownfield sites | Reuse<br>Retrofit | (Bardos et al., 2016) |
| | Provide temporary utilities | Use of harvested rainwater for potable water requirements | Rethink | (Diehl de Souza & Ghisi, 2020) |

| Construction Activities | | CE Applications | CE Principle | Sources |
|---|---|---|---|---|
| Excavation and filling | Filling obtained from excavated material | Collaborate on techniques to reduce labour and fuel requirements in the cut-and-fill procedure | Reuse<br>Recycle<br>Reduce | (Phear & Fraser, 2024) |
| | | Reuse of excavated soil | | |
| Concrete work | In-situ concrete work | Use of fly ash mixed concrete by reducing cement content | Reduce | (Abushanab & Alnahhal, 2023) |
| | | Reuse of excavated soil as fine aggregate in cement mortar | Recycle | (Priyadharshini et al., 2018) |
| | | Recycling plastic and using it as aggregates | Recycle<br>Reduce<br>Repurpose | (Alqahtani et al., 2021) |
| | | Use of recycled concrete waste as aggregates | Recycle<br>Reduce | (Akbulut et al., 2025) |
| | Formwork | Reusable formwork | Reuse | (Balasbaneh et al., 2024) |
| | Precast work | Use of precast concrete columns, and beams | Reduce | (De Silva & Vithana, 2008) |
| Masonry work | Brick and block work | Reuse of demountable walls | Reuse | (Buyle et al., 2019) |
| | Brick work | Mix of organic waste in clay brick production | Reduce | (Lozano-Miralles et al., 2018) |
| | Block work | Block production by utilizing fly ash | Reduce<br>Replace | (Shi et al., 2019) |
| Carpentry | Woodwork | Use of wood residue applications, such as MDF | Recycle | (Vamza et al., 2021) |
| Off-site manufactured components | Prefabricated structures | Reuse of concrete elements | Reuse<br>Refurbish | (Kromoser et al., 2025) |
| | | Reversible use of dismantled steel for prefabricated elements | Reverse | (Rahla et al., 2021) |
| | | Waste reduction with the use of prefabricated elements | Reduce | (Tam et al., 2005) |
| | | Reuse of prefabricated timber frames | Reuse | (Lisco & Aulin, 2024) |
| | Prefabricated buildings | Disassembly and reusing | Reuse | (Minunno et al., 2018) |
| Partitioning | | Recycling of gypsum plasterboard | Recycle<br>Repurpose | (Jiménez Rivero et al., 2016) |

| Construction Activities | | CE Applications | CE Principle | Sources |
|---|---|---|---|---|
| Composite flooring | Composite concrete work | Use of GLT- concrete slab as a sustainable and reusable solution | Reduce<br>Rethink<br>Reuse | (Balasbaneh et al., 2022) |
| | | Reuse at the end of a lifecycle by using demountable steel-concrete floor | Reuse | (Brambilla et al., 2019) |

As seen from Table 1, the CE applications are limited to eight major construction activities. In terms of CE principles, Reduce, Recycle and Reuse are mostly implemented, with the minimal application of Retrofit, Repurpose, Refurbish, Reverse, and Rethink.

## 3. RESEARCH METHODS

A multiple-case study approach was used to explore the CE implementation in construction activities and to quantify the related cost implications. Two educational building projects of different profile were selected as presented in Table 2. Although the case selection was not intended to target a specific building function or green-certified project, the projects were chosen based on their accessibility and the availability of cost data. Nevertheless, the inclusion of a green-certified case enabled an examination of the influence of green certification on construction circularity, while the functional similarity of the projects enhanced the comparability of the study findings. Data were gathered through semi-structured interviews with project managers, with over 10 years of work experience engaged in the construction-phase of the selected buildings and from BOQs, as-built drawings, and cost records maintained at the site. The project managers of each project were selected as the sole participants representing their respective projects due to their comprehensive knowledge and understanding of the subject, as well as their familiarity with the selected projects. The New Rules of Measurement 2 (NRM2) work sequence was considered to identify the CE applicable activities systematically and to be consistent across the selected cases. Cost implications due to CE integration were calculated using BOQ rates, and cost records maintained at the site. The cost impact of each activity was calculated as cost per Gross Internal Floor Area (GIFA) basis. The methods used to derive the cost impacts of CE applications along with respective cost impacts are presented in Table 3.

*Table 2: Summary profile of the selected educational buildings*

| Information | Green Building - GB | Non-Green Building - NGB |
|---|---|---|
| Contract value (LKR) | 3.03 Bn | 0.72 Bn |
| GIFA | 27,781 m² | 3,258 m² |
| Current status | In operation | In operation |
| Green certification | Platinum – GREENSL, UDA Blue Green | Not certified |
| Number of buildings | Five buildings with varying number of storeys – single to 10 | Single building with six storeys |
| Structure | Concrete; Brick and block work; slab roof | Concrete; Brick and block work; Prefabricated steel roof |

As seen from Table 2, though the selected buildings differ in contract value and GIFA, the cost impact due to CE applications for each activity were normalised by calculating 'cost per GIFA' and then presenting the value as a percentage of the total contract value, thereby reducing the effect of variation. , However, it is expected that the number of buildings available within the project and the green certification could influence the CE applications and the cost effects while, building function could have less/no effects on the results.

# 4. RESULTS AND DISCUSSION

This section presents the analysis of CE principles applicable to construction activities and the respective cost impacts.

## 4.1 CIRCULAR ECONOMY POTENTIAL IN CONSTRUCTION ACTIVITIES

The participants' views were sought on the CE applicable construction activities, by referring to NRM2 work sequence and CE principles derived from the literature. The results of the collated views are presented in Table 3. Of the forty NRM 2 based work sections, CE applications are found only in eight work sections. Aligning with literary findings, CE applications have been practiced in preliminary work, excavation and filling, concrete, masonry, and partitioning works in the selected buildings. However, the specific CE measures varied within some of these sections. For example, the preliminary works section exhibited only two CE applications in the literature review, but four applications emerged from case-study analysis. Regardless of these differences in implementation, similar observation is noted in terms of applicable CE principles as well, mostly revolving around the basic 3Rs. Worth still, that green building context has promoted the application of Recycling while non-green building has used the Reduce concept in most of the activities. This distinction suggests that green building projects tend to incorporate material recovery and recycling-oriented approaches, such as the use of recycled aggregates or industrial by-products, whereas conventional construction practices primarily focus on resource efficiency and waste minimization measures, such as reducing material use or improving operational efficiency on site.

Apart from conventional construction activities, green building construction has promoted certain circular applications. For example, the advanced CE principles; Retrofit and Rethink have been applied in green buildings through the selection of brownfield sites and the use of harvested rainwater, respectively. However, the use of recycled materials has been promoted in concrete, masonry and structural metal work of both green and non-green buildings. Besides, building characteristics and quality requirements have induced CE applications. Reuse of existing adjacent access path was enabled as the building contains multiple structures within the given project. Similarly, excavated soil was reused for backfilling as the soil quality was good.

## 4.2 COST IMPLICATIONS OF CIRCULAR ECONOMY APPLICATIONS

As evidenced above, although the construction activities have greater potential for incorporating various R principles, the practical applications may be hindered by the cost implications of implementing them. The cost impact of CE applications assessed through case study analysis are presented in Table 3.

Of the eight, six work sections contribute to around 1-13% of cost saving in individual construction activities. Excavation & earth filling and doors are activities with exceptionally large percentage of cost savings. A 34% saving is obtained due to reduction of total cost of excavation and backfilling with the use of brownfield site instead of green field. On other hand, repurpose of solid plywood doors contributed negatively to around 80% of cost saving in the total door cost. Amongst the six work sections, concrete has the greater potential for Reduce, Reuse and Recycle and thereby contributes around 11% saving on average to the total cost of concrete. Similarly, use of offsite manufactured, prefabricated steel roof structure result in 7% saving on the total cost of the element via Reduce of on-site labour, material, and time waste. Comparatively, an increased saving is observed in green building over the non-green due to compliance to green requirement. Especially, the activities like use of brown field, rainwater harvesting, recycled and reused materials contributed additional saving in green building context. However, cost savings were calculated solely on the basis of reduced consumption of virgin materials. For instance, in the excavation and backfilling section, savings associated with avoiding transport of excavated soil for disposal and subsequent import of fill material (due to on-site reuse) were not included. Consequently, the present analysis captures only a portion of the total potential cost savings.

*Table 3: CE Applications and cost impact*

| | Construction Activity | CE Application | CE Principle | Cost Impact (Rs. per GIFA) | | Derivation of Cost Impact |
|---|---|---|---|---|---|---|
| | | | | GB | NGB | |
| Preliminary work | Site selection | Selecting a brownfield site instead of a greenfield site | Repurpose<br>Retrofit | No cost record | N/A | N/A |
| | Provide site access path | Reuse of the access path which was used during the construction of adjacent project | Reuse | 253 | N/A | Adjust the past cost data using pro-rata method |
| | Facilitating temporary site offices for the staff | Reuse of materials which are used to erect site offices in previous projects | Reuse | 510 | 547 | Percentage of cost of site office as per BOQ |
| | Provide temporary utility facilities (non-potable water) | Use of harvested rainwater for non-potable water requirements | Rethink<br>Reduce | 14 | N/A | Quantity of collected rainwater x price per unit of NWS&DB |
| | Total cost saving on preliminary work | | | 777 | 547 | N/A |
| | Total cost of preliminary work | | | 12,675 | 25,477 | N/A |
| | Cost saving as a % of total cost of preliminary work | | | 6.13% | 2.15% | N/A |
| Excavation & filling | Site clearing and excavation | Ensuring efficient fuel usage by comparing the work done and fuel consumption monthly | Reduce | No cost record | No cost record | N/A |
| | Imported filling | Optimizing excavated soil for backfilling | Reuse | N/A | 156 | Cost difference of imported and excavated soil |
| | | Use of quarry dust obtained from rock blasting | Recycle | 173 | N/A | Cost difference of quarry dust filling and sand filling |
| | Total cost saving on excavation & filling | | | 173 | 156 | N/A |
| | Total cost of excavation & filling | | | 507 | 6,890 | N/A |

| | | Construction Activity | CE Application | CE Principle | Cost Impact (Rs. per GIFA) GB | Cost Impact (Rs. per GIFA) NGB | Derivation of Cost Impact |
|---|---|---|---|---|---|---|---|
| | | Cost saving as a % of total cost of excavation & filling | | | 34.10% | 2.26% | N/A |
| Concrete work | In-situ concrete work | Plain In-situ concrete – Mass concreting | Use of waste concrete as aggregates in screeds | Recycle | 1.35 | 117 | Cost of concrete screed |
| | | Reinforced In-situ concrete – Horizontal concreting - slab | Use of fly ash mixed cement in concreting | Recycle | 254 | 114 | Price difference of fly ash mixed and ordinary Portland cement |
| | | Formwork | Repetitive use of formwork | Reuse | 3,500 | 3,022 | Cost of new formwork |
| | | Reinforcement | Use of recycled reinforcement | Recycle | No cost record | N/A | N/A |
| | Precast work | Precast concrete goods | Use of precast concrete blocks | Reduce | No Significant Saving | No Significant Saving | N/A |
| | | | Use of concrete paving blocks produced by recycled materials | Reduce<br>Recycle | No cost record | N/A | N/A |
| | | Total cost saving on concrete work | | | 3,756 | 3,252 | N/A |
| | | Total cost of concrete work | | | 28,126 | 38,210 | N/A |
| | | Cost saving as a % of total concrete work | | | 13.35% | 8.51% | N/A |
| Masonry work | | Block walls | Use of hollow blocks instead of solid blocks | Reduce | 268 | 45 | Rate difference of hollow block and solid block |
| | | | Use of blocks produced using recycled materials | Recycle | No cost record | N/A | N/A |
| | | Total cost saving on masonry work | | | 268 | 45 | N/A |
| | | Total cost of masonry work | | | 4,530 | 4,811 | N/A |
| | | Cost saving as a % of total cost of masonry work | | | 5.92% | 0.93% | N/A |

| | Construction Activity | CE Application | CE Principle | Cost Impact (Rs. per GIFA) | | Derivation of Cost Impact |
|---|---|---|---|---|---|---|
| | | | | GB | NGB | |
| Structural metal work | Isolated structural members | Use of structural steel produced using recycled materials | Recycle | No cost record | N/A | N/A |
| | Total cost saving on structural metal work | | | No cost record | - | N/A |
| Partitioning | Partitioning system to walls | Use of timber panels produced by mixing rice straw | Repurpose | 19 | 46 | Cost difference of timber rice straw mixed partitions |
| | Total cost saving on partitioning | | | 19 | 46 | N/A |
| | Total cost of partitioning | | | 1,023 | 6,254 | N/A |
| | Cost saving as a % of total cost of partitioning | | | 1.84% | 0.73% | N/A |
| Doors | Doors | Use of solid plywood doors instead of timber doors | Repurpose | (203) | (62) | Cost difference of timber and solid plywood doors |
| | Total cost saving on door fixing | | | (203) | (62) | N/A |
| | Total cost of door fixing | | | 254 | 1,237 | N/A |
| | Cost saving as a % of total cost of door fixing | | | (80%) | (5%) | N/A |
| Off-site manufactured components | Use of prefabricated structures | Use of prefabricated steel roof | Reduce | N/A | 168 | Cost difference of on-site roof and prefabricated roof |
| | Total cost saving on off-site components | | | - | 168 | N/A |
| | Total cost of off-site components | | | - | 2,556 | N/A |
| | Cost saving as a % of total cost of off-site manufactured components | | | - | 7.46% | N/A |
| Total cost saving as a % of contract value | | | | 4.39% | 1.89% | N/A |

## 5. CONCLUSIONS

The main focus of the study was to assess the cost impacts due to CE implementations in the construction activities. The analysis of selected cases reveal that CE applications are seen in limited construction activities. The CE applications are mainly in the form of Reduce and Recycle of waste materials, and Reuse of existing access path, excavated soil, and formwork. The major CE based construction activities include preliminary work, excavation and filling, concrete, masonry, structural metal, partition, doors, and off-site manufactured components. Collectively, CE applications contributed cost savings of approximately 2-4% of the total contract value. However, these savings cannot be readily generalized owing to the inconsistent application of CE principles across the two building contexts. However, there are many other work sections where non-availability of cost data has restricted the assessment of cost impact. Further, the cost impact was based on initial cost, not on the life cycle cost where the impact could be higher due to CE applications during operation and maintenance as well as end of life phases. Moreover, there can be potential CE strategies in the work sections which are not identified through this study due to the limitation of the site conditions. Therefore, the actual cost impact could be greater.

The comparison of the selected two cases in the current study indicates that although there was potential for CE applications in some activities, it has not been incorporated. For example, use of harvested rainwater for non-potable water requirements, use of blocks, and structural steel produced using recycled materials are seen only in green building where it has contributed to additional cost saving. It is worthy to note that the use of strategies like use of brownfield instead of greenfield site has contributed significantly to the cost saving, 34% of cost of excavation & filling. This evidences that green buildings provide more pathways to integration of circularity. The study therefore recommends that professionals responsible should carefully examine the potential CE applications, in compliance with green requirements where possible and thereby assess the cost impact. This would result in significant environmental benefits such as waste, energy and emission reduction, and reduce resource consumption. The limited CE application could be due to lack of knowledge and awareness about the CE applications, and its environmental and economic implications. Therefore, it is recommended that the further study to examine the above in detail. From the practical implementation perspective, the study recommends that there could be design-level interventions, technological integration, or reverse logistics systems that need to be embedded within current construction practices.

## 6. REFERENCES

Abushanab, A., & Alnahhal, W. (2023). Life cycle cost analysis of sustainable reinforced concrete buildings with treated wastewater, recycled concrete aggregates, and fly ash. *Results in Engineering*, *20*, 101565. https://doi.org/10.1016/j.rineng.2023.101565

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Akbulut, Z. F., Guler, S., Yavuz, D., & Avcı, M. S. (2025). Toward sustainable construction: A critical review of recycled aggregate concrete properties and future opportunities. *Case Studies in Construction Materials*, *23*, e05133. https://doi.org/10.1016/j.cscm.2025.e05133

Akhimien, N. G., Latif, E., & Hou, S. S. (2021). Application of circular economy principles in buildings: A systematic review. *Journal of Building Engineering*, *38*, 102041. https://doi.org/10.1016/J.JOBE.2020.102041

Alqahtani, F. K., Abotaleb, I. S., & ElMenshawy, M. (2021). Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates. *Journal of Building Engineering*, *40*, 102670. https://doi.org/10.1016/j.jobe.2021.102670

Balasbaneh, A. T., Sher, W., & Haziman Wan Ibrahim, M. (2024). Life cycle assessment and economic analysis of reusable formwork materials considering the circular economy. *Ain Shams Engineering Journal*, *15*(4), 102585. https://doi.org/10.1016/j.asej.2023.102585

Balasbaneh, A. T., Sher, W., Yeoh, D., & Koushfar, K. (2022). LCA & LCC analysis of hybrid glued laminated timber–concrete composite floor slab system. *Journal of Building Engineering*, *49*, 104005. https://doi.org/10.1016/j.jobe.2022.104005

Bardos, R. P., Jones, S., Stephenson, I., Menger, P., Beumer, V., Neonato, F., Maring, L., Ferber, U., Track, T., & Wendler, K. (2016). Optimising value from the soft re-use of brownfield sites. *Science of The Total Environment*, *563–564*, 769–782. https://doi.org/10.1016/j.scitotenv.2015.12.002

Brambilla, G., Lavagna, M., Vasdravellis, G., & Castiglioni, C. A. (2019). Environmental benefits arising from demountable steel-concrete composite floor systems in buildings. *Resources, Conservation and Recycling*, *141*, 133–142. https://doi.org/10.1016/j.resconrec.2018.10.014

Buyle, M., Galle, W., Debacker, W., & Audenaert, A. (2019). Sustainability assessment of circular building alternatives: Consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. *Journal of Cleaner Production*, *218*, 141–156. https://doi.org/10.1016/j.jclepro.2019.01.306

Charef, R. (2024). A digital framework for the implementation of the circular economy in the construction sector: Expert opinions. *Sustainability*, *16*(14), 5849. https://doi.org/10.3390/su16145849

Charef, R., Morel, J., & Rakhshan, K. (2021). Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability*, *13*(23), 12989. https://doi.org/10.3390/su132312989

Çimen, Ö. (2021). Construction and built environment in circular economy: A comprehensive literature review. *Journal of Cleaner Production*, *305*, 127180. https://doi.org/10.1016/j.jclepro.2021.127180

De Silva, N., & Vithana, S. B. K. H. (2008). Use of PC elements for waste minimization in the Sri Lankan construction industry. *Structural Survey*, *26*(3), 188–198. https://doi.org/10.1108/02630800810887081

Diehl de Souza, T., & Ghisi, E. (2020). Harvesting rainwater from scaffolding platforms and walls to reduce potable water consumption at buildings construction sites. *Journal of Cleaner Production*, *258*, 120909. https://doi.org/10.1016/j.jclepro.2020.120909

Fagone, C., Santamicone, M., & Villa, V. (2023). Architecture engineering and construction industrial framework for circular economy: Development of a circular construction site methodology. *Sustainability*, *15*(3), 1813. https://doi.org/10.3390/su15031813

Gamage, I., Senaratne, S., Perera, S., & Jin, X. (2024). Implementing circular economy throughout the construction project life cycle: A Review on potential practices and relationships. *Buildings*, *14*(3), 653. https://doi.org/10.3390/buildings14030653

Ghisellini, P., & Ulgiati, S. (2020). Circular economy transition in Italy. Achievements, perspectives and constraints. *Journal of Cleaner Production*, *243*, 118360. https://doi.org/10.1016/j.jclepro.2019.118360

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five European countries policies and practices. *Journal of Cleaner Production*, *336*, 130395. https://doi.org/10.1016/j.jclepro.2022.130395

Jiménez Rivero, A., Sathre, R., & García Navarro, J. (2016). Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. *Resources, Conservation and Recycling*, *108*, 171–181. https://doi.org/10.1016/j.resconrec.2016.01.014

Kochanski, M., Lotz, M. T., & Korczak, K. (2024). Benchmarking circular economy measures in buildings along the 11R framework: A systematic review of quantified impacts on material use, energy consumption, GHG emissions, and costs. *Journal of Cleaner Production*, *485*, 144337. https://doi.org/10.1016/j.jclepro.2024.144337

Kromoser, B., Gappmaier, P., Ahmed, I., & Reichenbach, S. (2025). Circular economy in concrete construction through modular construction, automated design and production of structurally optimised reusable concrete building components. *Case Studies in Construction Materials*, *23*, e05139. https://doi.org/10.1016/j.cscm.2025.e05139

Li, X., Xu, J., & Su, Y. (2025). Research status and emerging trends in green building materials based on bibliometric network analysis. *Buildings, 15*(6), 884. https://doi.org/10.3390/buildings15060884

Lisco, M., & Aulin, R. (2024). Taxonomy supporting design strategies for reuse of building parts in timber-based construction. *Construction Innovation*, *24*(1), 221–241. https://doi.org/10.1108/CI-11-2022-0293

Lozano-Miralles, J. A., Hermoso-Orzáez, M. J., Martínez-García, C., & Rojas-Sola, J. I. (2018). Comparative study on the environmental impact of traditional clay bricks mixed with organic waste using life cycle analysis. *Sustainability*, *10*(8), 2917. https://doi.org/10.3390/su10082917

Minunno, R., O'Grady, T., Morrison, G. M., Gruner, R. L., & Colling, M. (2018). Strategies for applying the circular economy to prefabricated buildings. *Buildings*, *8*(9), 125. https://doi.org/10.3390/buildings8090125

Moustafa, Z., Asif, M., & Wuni, I. Y. (2025). Circular economy in the building sector: a systematic review of environmental, economic, and social dimensions. *Sustainable Futures, 9*, 100690. https://doi.org/10.1016/j.sftr.2025.100690

Mrad, C., & Ribeiro, L. F. (2022). A review of Europe's circular economy in the building sector. *Sustainability*, *14*(21), 14211. https://doi.org/10.3390/su142114211

Palomar-Torres, A., Rey-Hernández, J. M., Rey-Hernández, A., & Rey-Martínez, F. J. (2025). Decarbonizing near-zero-energy buildings to zero-emission buildings: A holistic life cycle approach to minimize embodied and operational emissions through circular economy strategies. *Applied Sciences*, *15*(5), 2670. https://doi.org/10.3390/app15052670

Pearlmutter, D., Theochari, D., Nehls, T., Pinho, P., Piro, P., Korolova, A., Papaefthimiou, S., Mateo, M. C. G., Calheiros, C., Zluwa, I., Pitha, U., Schosseler, P., Florentin, Y., Ouannou, S., Gal, E., Aicher, A., Arnold, K., Igondová, E., & Pucher, B. (2019). Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. *Blue-Green Systems*, *2*(1), 46–72. https://doi.org/10.2166/bgs.2019.928

Phear, A., & Fraser, N. (2024). Developing a new European standard for sustainable earthworks. In D. G. Toll & M. G. Winter (Eds.), *Geo-resilience 2023 conference* (pp. 1-9). British Geotechnical Association, London. https://doi.org/10.53243/Geo-Resilience-2023-2-6

Pomponi, F., & Moncaster, A. (2016). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Priyadharshini, P., Ramamurthy, K., & Robinson, R. G. (2018). Sustainable reuse of excavation soil in cementitious composites. *Journal of Cleaner Production*, *176*, 999–1011. https://doi.org/10.1016/j.jclepro.2017.11.256

Pullen, S., Chiveralls, K., Zillante, G., Palmer, J. S., Wilson, L., & Zuo, J. (2012, January). *Minimising the impact of resource consumption in the design and construction of buildings*. Australian and New Zealand Architectural Science Association, Brisbane. https://www.researchgate.net/publication/266376260

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings—from theory to practice. *Applied System Innovation*, *4*(2), 26. https://doi.org/10.3390/asi4020026

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2022). Conceptualization of circular economy 3.0: Synthesizing the 10R hierarchy of value retention options. In A. Alvarez-Risco, M. A. Rosen, & S. Del-Aguila-Arcentales, (Eds.), *Towards a circular economy* (pp. 47–69). Springer, Cham. https://doi.org/10.1007/978-3-030-94293-9_3

Shi, Y., Li, Y., Tang, Y., Yuan, X., Wang, Q., Hong, J., & Zuo, J. (2019). Life cycle assessment of autoclaved aerated fly ash and concrete block production: A case study in China. *Environmental Science and Pollution Research*, *26*(25), 25432–25444. https://doi.org/10.1007/s11356-019-05708-8

Tam, C. M., Tam, V. W. Y., Chan, J. K. W., & Ng, W. C. Y. (2005). Use of prefabrication to minimize construction waste - A case study approach. *International Journal of Construction Management*, *5*(1), 91–101. https://doi.org/10.1080/15623599.2005.10773069

Tafesse, S., Girma, Y. E., & Dessalegn, E. (2022). Analysis of the socio-economic and environmental impacts of construction waste and management practices. *Heliyon*, *8*(3), e09169. https://doi.org/10.1016/j.heliyon.2022.e09169

UN Environment Programme. (2018, January 23). *Green economy*. Retrieved February 11, 2026, from https://www.unep.org/regions/asia-and-pacific/regional-initiatives/supporting-resource-efficiency/green-economy

United Nations. (2021). *Global population growth and sustainable development*. https://desapublications.un.org/publications/global-population-growth-and-sustainable-development

Uvarova, I., Atstaja, D., Volkova, T., Grasis, J., & Ozolina-Ozola, I. (2023). The typology of 60R circular economy principles and strategic orientation of their application in business. *Journal of Cleaner Production*, *409*, 137189. https://doi.org/10.1016/j.jclepro.2023.137189

Vamza, I., Valters, K., Luksta, I., Resnais, P., & Blumberga, D. (2021). Complete circularity in cross-laminated timber production. *Environmental and Climate Technologies*, *25*(1), 1101–1113. https://doi.org/10.2478/rtuect-2021-0083

World Green Building Council. (n.d.). *Our mission.* Retrieved February 11, 2026, from https://worldgbc.org/about-us/our-mission/

Zhu, S., & Feng, H. (2026). Construction and demolition waste circulation and its sustainability performance in the building sector: Current trend and future directions. *Engineering, Construction and Architectural Management*, *33*(5), 4119–4148. https://doi.org/10.1108/ECAM-05-2024-0678

Uduwage, D.N.L.S., Thiruchelvam, K., Hemantha H.H.A.P. and Panuwatwanich, K., 2026. Critical criteria influencing the selection of bid evaluation mechanism under the Most Economically Advantageous Tender (MEAT). In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 499-512. DOI: https://doi.org/10.31705/WCS.2026.37. Available from: https://ciobwcs.com/papers/

# CRITICAL CRITERIA INFLUENCING THE SELECTION OF BID EVALUATION MECHANISM UNDER THE MOST ECONOMICALLY ADVANTAGEOUS TENDER (MEAT)

**D.N.L.S. Uduwage[1], K. Thiruchelvam[2], H.H.A.P. Hemantha[3] and K. Panuwatwanich[4]**

## *ABSTRACT*

*Most Economically Advantageous Tender (MEAT) is widely adopted in the European Union, where multiple criteria are considered in contract awarding. Although studies have highlighted the potential benefits of adopting MEAT in Sri Lanka, limited attention has been given to the selection of an appropriate bid evaluation mechanism under MEAT, namely price to quality or quality to price, despite its influence on bid evaluation outcomes and contractor behaviour. This study aims to identify the critical criteria influencing the selection of bid evaluation mechanisms under MEAT in the Sri Lankan construction industry. A quantitative method was adopted. Initially, a comprehensive literature review and a preliminary survey were conducted to identify and validate the relevant criteria to Sri Lanka. Subsequently, a questionnaire survey was administered among architects, engineers, and quantity surveyors involved in public construction procurement. The Kruskal-Wallis test was used to examine differences among professional groups, while mean ranking was applied to identify critical criteria. The findings indicate that professional groups hold statistically similar views regarding the influence of the identified criteria. Six out of seven criteria were identified as critical, with the degree of measuring project-specific criteria and the reliability of data used to develop scoring formulas emerging as the most critical. The study contributes to the MEAT implementation in Sri Lanka by providing a structured basis for selecting bid evaluation mechanisms. The findings may assist practitioners in developing evaluation frameworks that better align with project requirements and support the effective adoption of MEAT in the construction industry.*

***Keywords:*** *Bid Evaluation Mechanism; Construction Industry; Most Economically Advantageous Tender (MEAT); Value for Money.*

[1] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, hemanthahhap.26@uom.lk
[4] Professor, Sirindhorn International Institute of Technology, Thammasat University, Thailand, kriengsak@siit.tu.ac.th

# 1. INTRODUCTION

Government is the primary and most influential client in the construction industry particularly in relation to infrastructure projects such as roads, dams, and irrigation works (Uduwage et al., 2026). The selection of a suitable contractor is essential for ensuring the timely delivery and overall success of construction projects (Nemec et al., 2021). The contractor selection process typically consists of two main stages namely prequalification and contract awarding (Acheamfour et al., 2021). During the prequalification stage, contractors are shortlisted based on their technical, financial, and managerial capabilities (Rashvand et al., 2015). Subsequently, the shortlisted contractors are evaluated based on predefined awarding criteria, which is referred to as the contract awarding process (CAP) (Uduwage et al., 2024).

There are two main contract awarding criteria used in CAP, namely bid price and the Most Economically advantageous Tender (MEAT) (Ballesteros-Pérez et al., 2015). The bid price is commonly used contract awarding criterion where the contractor is selected solely based on the bid price, without considering other parameters such as time, safety, and environmental aspects (Chileshe et al., 2020). In contrast, MEAT has emerged as a widely adopted alternative in several regions, including the European Union (EU) (Lehtonen & Virtanen, 2022), the United Kingdom (UK) (Rees et al., 2023), Canada (Trade Commissioner Service, 2025), and Visegrad Group countries (Nemec et al., 2021). MEAT enables procuring entities to assess bids by incorporating qualitative, environmental, and social factors alongside price considerations (Organisation for Economic Co-operation and Development [OECD], 2021). The bid evaluation mechanism under each contract awarding criterion differs. Under the bid price criterion, bids are typically evaluated using the lowest bid price (LBP) or average bid price methods (Uduwage et al., 2026; Ioannou & Awwad, 2010). Under MEAT, bids are evaluated using either the price to quality or quality to price evaluation mechanisms (Stilger et al., 2017). The price to quality mechanism converts the bid price into a score and combines it with quality scores to determine the highest ranked bidder. In contrast, the quality to price mechanism converts quality attributes into monetary values, resulting in a quality adjusted price, where the bidder with the lowest adjusted price is selected (Stilger et al., 2017).

The adoption of MEAT provides several benefits compared to the traditional bid price approach (Abdelrahman et al., 2008). It enables the selection of contractors based on value for money, improves quality performance, and enhances long-term project outcomes by considering multiple evaluation criteria rather than focusing solely on price (Lehtonen & Virtanen, 2022). Therefore, MEAT is considered more suitable for complex construction projects where quality and performance play a significant role (Uduwage et al., 2023). However, under MEAT, the selection of the appropriate evaluation mechanism, either price to quality or quality to price is critical, as it directly influences bid outcomes, contractor pricing strategies, and overall project performance (Rees et al., 2023). Based on the selected evaluation mechanism, the ranking of bidders may vary. Therefore, clearly defining the evaluation mechanism in the bidding documents is essential to ensure transparency and to enable contractors to align their pricing strategies with project requirements.

In Sri Lanka, given that public funds are utilised in government projects, ensuring transparency and accountability in contractor selection is of critical importance (Wu et

al., 2016). Sri Lanka follows the guidelines and manuals issued by the National Procurement Commission (NPC) for contractor selection in public sector projects (Hasantha et al., 2024). According to these guidelines, contract awarding primarily prioritises the lowest bid price (LBP), provided that the requirements specified in the bidding documents are satisfied (Uduwage et al., 2024), which falls under the bid price-based awarding criterion. However, reliance on the LBP method may not be appropriate for all types of construction projects, as it does not necessarily ensure successful project delivery in terms of cost, time, and quality performance (Baldi et al., 2016). Even though NPC guidelines do not explicitly mention the use of MEAT as an awarding criterion (Dinesh et al., 2026; Uduwage et al., 2024), the concept of MEAT and its evaluation mechanisms are reflected in Standard Bidding Document (SBD) 4 published by the Construction Industry Development Authority (CIDA) and Standard Bidding Document, Procurement of General Goods (NPA/Goods/SBD 01), where evaluation can extend beyond price to include factors such as delivery schedule, operating costs, design parameters, and quality (Dinesh et al., 2026; Uduwage et al., 2024; Uduwage et al., 2026).

Although previous studies have highlighted the potential applicability of MEAT to the Sri Lankan construction industry (Uduwage et al., 2026), limited attention has been given to how procuring entities should select the most appropriate bid evaluation mechanism under MEAT. In the absence of structured basis, the selection of the evaluation mechanism is largely based on subjective judgement (Dinesh et al., 2026), which may lead to inappropriate bid evaluation mechanism selection and consequently affect the effectiveness of contractor selection (Uduwage et al., 2026). Therefore, identifying the critical criteria influencing the selection of the appropriate evaluation mechanism is essential. Accordingly, this study aims to identify the critical criteria for selecting appropriate bid evaluation mechanism (quality to price or price to quality) under the MEAT in the Sri Lankan construction industry. To achieve the aim, following objectives were formulated.

1. To identify the criteria influencing the selection of suitable bid evaluation mechanism under MEAT.
2. To examine the statistical differences among construction professionals regarding the criteria for selecting appropriate bid evaluation mechanism under MEAT.
3. To extract the critical criteria influencing the selection of suitable bid evaluation mechanism under MEAT.

# 2. LITERATURE REVIEW

## 2.1 CONTRACT AWARDING PROCESS IN SRI LANKA

The development of physical infrastructure is a crucial factor for the economic expansion of any country (Abdullahi & Sieng, 2023). As a country investing public funds in infrastructure, Sri Lanka emphasises transparency and accountability in contractor selection for public sector projects (Abdullahi & Sieng, 2023). Therefore, the Sri Lankan government follows the Procurement Guidelines published by the National Procurement Commission (NPC) for contractor selection to achieve value for money, optimum use of budgetary resources, competitiveness, and enhanced stakeholder trust (National Procurement Commission [NPC], 2024). These guidelines emphasise the selection of the substantially responsive lowest bid for contract award, where the decision is primarily

determined based on bid price after ensuring compliance with technical and qualification requirements. In practice, the contract awarding process in Sri Lanka mainly follows the Lowest Bid Price (LBP) method under bid price-based awarding (Uduwage et al., 2024).

Although NPC guidelines do not explicitly mention the use of multi-criteria evaluation methods, the concept of the Most Economically Advantageous Tender (MEAT) and its bid evaluation mechanisms are reflected in Standard Bidding Document (SBD) 4 and Standard Bidding Document for Procurement of General Goods (NPA/Goods/SBD 01). SBD 04, which is designed for design and build contracts, evaluates bids based on design along with bid price, while NPA/Goods/SBD 01 evaluates bids based on delivery schedule, operating costs, functional performance, and quality (Uduwage et al., 2026). This indicates that MEAT is not a new concept in Sri Lanka. However, due to the dominance of the LBP method, contractor selection based on MEAT has not gained significant attention.

MEAT allows procuring entities to evaluate bids not only based on price but also by considering qualitative, environmental, and social criteria (OECD, 2021). Compared to bid price-based awarding, which primarily focuses on bid price, MEAT enables the incorporation of project specific criteria, improves value for money, and enhances long-term project performance (Abdelrahman et al., 2008; Lehtonen & Virtanen, 2022). Despite these advantages, the effectiveness of MEAT largely depends on selecting an appropriate bid evaluation mechanism, as different mechanisms may lead to different contractor selection outcomes.

## 2.2 BID EVALUATION MECHANISMS UNDER MEAT

The bids submitted under MEAT can be evaluated under two main mechanisms, namely price to quality and quality to price (Stilger et al., 2015). The selection between these mechanisms is critical, as it directly influences bid evaluation outcomes, contractor behaviour, and overall project performance (Rees et al., 2023).

### 2.2.1 Price to Quality

In the price to quality evaluation mechanism, the price is transformed into a score and combined with the quality score, making the bid a price adjusted highest quality bid (Bergman & Lundberg, 2013). Here, the term quality refers to project specific attributes such as time for completion, technical merit, overall value and environmental performance (Stilger et al., 2017). The price score is typically derived by normalising the submitted bid price against the lowest submitted bid. The resulting price score is then weighted according to a predetermined price-quality ratio and combined with the quality score (Parikka-Alhola & Nissinen, 2012). The bid achieving the highest composite score is often selected for contract award (Bergman & Lundberg, 2013). Several formulas are used depending on project specific requirements. For instance, Dimitri et al. (2006) used Equation 1 to assess the quality align with the price.

$$Score_i = \frac{P_{Best}}{P_i} W_{price} + Q_i W_{Quality} \qquad (01)$$

where, $i$= individual bid, $P_{Best}$= lowest price of all bids, $P_i$ = price of each individual bid, $W_{Price}$ = weight of price, $Q_i$ = quality of each individual bid and $W_{Quality}$ = weight of quality

Similarly, Waara and Bröchner (2006) proposed Equation 2 to assess the quality align with the price.

$$Score_{\ i} = \frac{P_i - P_{Max}}{P_{Max} - P_{Best}} W_{Price} + Q_i W_{Quality} \qquad (02)$$

where, $i$= individual bid, $P_{Best}$ = lowest price of all bids, $P_i$ = price of each individual bid, $P_{Max}$ = highest price of all bids, $W_{Price}$= weight of price, $Q_i$= quality of each individual bid and $W_{Quality}$= weight of quality

Hence, the formula used varies depending on project characteristics, and the selected formula should be clearly stated in the bidding documents.

### 2.2.2 Quality to Price

In the quality to price evaluation mechanism, quality measures are converted into monetary values and combined with the submitted bid price, making the bid a quality adjusted lowest price bid (Uduwage et al., 2024). In contrast to the price to quality mechanism, where price is transformed into a score and aggregated with quality scores, in the quality to price mechanism, quality attributes such as completion time, sustainably and experience are assigned monetary values and added to the bid price (Bergman & Lundberg, 2013). The bid with the lowest aggregated price is often selected for contract award (Uduwage et al., 2024). For instance, McFarland et al. (1994) proposed Equation 3 to combine project cost and completion time.

$$TCB = ECC + (DRUC \times EPD) \qquad (03)$$

where, $TCB$ = total combined bid, $ECC$ = estimated construction cost for the project, $DRUC$ = daily road user cost and $EPD$ = estimated project duration for project completion.

DRUC represents the estimated economic cost incurred by road users per day due to construction-related disruptions, such as travel time delays, vehicle operating costs, and other user impacts (McFarland et al., 1994).

Overall, the two mechanisms follow different evaluation procedures and require different types of information in the bidding documents. In the price to quality mechanism, the weightage assigned to price and quality attributes and the scoring formula must be specified (Parikka-Alhola & Nissinen, 2012). In the quality to price mechanism, the method used to convert quality attributes into monetary values must be clearly defined (Bergman & Lundberg, 2013). Furthermore, the choice of evaluation mechanism and scoring formula can affect bidder rankings and, consequently, the contract award decision (Uduwage et al., 2026). Different formulae place varying emphasis on price and quality, meaning that the same set of bids may be ranked differently under different evaluation approaches (Dinesh et al., 2026). Therefore, the selected method should be consistent with the procurement objectives and the intended balance between cost and quality (Uduwage et al., 2026). Therefore, prior to preparing bid documents under MEAT, selecting an appropriate bid evaluation mechanism is essential to ensure transparency, consistency in evaluation, and accurate pricing by bidders.

## 2.3 CRITERIA INFLUENCING THE SELECTION OF BID EVALUATION MECHANISM UNDER MEAT

To facilitate the selection of a suitable bid evaluation mechanism under MEAT, several criteria have been discussed in the literature. A summary of the criteria influencing the selection of the bid evaluation mechanism is presented in Table 1.

*Table 1: Criteria influencing the selection of bid evaluation mechanism under MEAT*

| Criteria code | Criteria | Explanation | Sources |
|---|---|---|---|
| C1 | Subjective evaluation | The weighting factors to transform price to quality scoring or quality scoring to price originate from the judgements or the opinions of the experts. | [1], [3], [4], [5], [6], [7], [9], [10], [11], [12], [13], [14] |
| C2 | Simplicity in the evaluation process | Ease of handling the contractor selection process | [2], [3], [4], [7], [9], [11] |
| C3 | Degree of measuring project specific criteria | The extent to which project-specific evaluation criteria can be objectively measured, quantified, and assessed during the bid evaluation process. | [1], [2], [3], [4], [5], [6], [7], [9], [10], [12], [13], [14] |
| C4 | Speed of evaluation process | Expedited contractor selection process | [1], [9] |
| C5 | Efficiency | Ability to evaluate with a minimum of effort, expense or resources | [5], [6], [9] |
| C6 | Reliability of the data used to develop a scoring formula | Accuracy of the data used to develop the weights of the scoring formula (price to quality or quality to price scoring) | [3], [4], [5], [6], [7], [9], [11], [13], [14] |
| C7 | Practicability of the method | Degree of feasibility to apply the selected method on a specific type of project | [5], [6], [7], [11] |

[1] Abdelrahman et al. (2008); [2] Parikka-Alhola et al. (2006); [3] Asker and Cantillon (2006); [4] Asker and Cantillon (2008); [5] Ballesteros-Pérez et al. (2015); [6] Ballesteros-Pérez et al. (2016); [7] Dimitri et al. (2006); [8] Idrees et al. (2023); [9] Ioannou and Awwad (2010); [10] Khan (2015); [11] Lahdenperä (2013); [12] Lambropoulos (2013); [13] Lundberg and Bergman (2011); [14] Lundberg and Marklund (2011)

The criteria summarised in Table 1 are extracted from the literature and are not contextualised to the Sri Lankan construction industry. Since bid evaluation mechanisms are influenced by country-specific procurement regulations, market conditions, and stakeholder practices, the relevance and significance of these criteria may vary across different contexts (Uduwage et al., 2026). Further, rather than providing equal attention to all the identified criteria, it is more practical to identify the critical criteria and then focus on those specific criteria in the selection of the bid evaluation mechanism. Focusing on these critical criteria would enable a more structured and context specific approach to selecting the appropriate bid evaluation mechanism under MEAT, thereby improving the effectiveness of contractor selection.

# 3. RESEARCH METHODOLOGY

The study adopted a quantitative research approach to statistically analyse and extract the critical criteria influencing the selection of the bid evaluation mechanism under MEAT. The target population of the study consists of construction industry professionals, namely Engineers, Architects, and Quantity Surveyors (QS), who are registered as "qualified persons" in the Construction Industry Development Authority (CIDA). For the sampling frame, qualified persons with a minimum of 6 years of experience and involvement in public construction procurement at the precontract stage were considered. To determine the sample size from the target population, the formula developed by Krejcie and Morgan (1970) was used, where the required sample size for the study was derived as 365 (see Equation 4).

$$S = \frac{X^2 N\ P\ (1-P)}{d^2(N-1) + X^2 P(1-P)} \qquad (04)$$

Where, $S$ = required sample size, $X^2$ = Chi-square value for 1 degree of freedom at the desired confidence level, $N$ = population size, $P$ = population proportion and $d$ = margin of error

A purposive sampling method was used to select respondents due to its ability to gather data from individuals who possess relevant knowledge related to the study objectives (Thiruchelvam & Uduwage, 2025). Figure 1 illustrates the research design of the study.

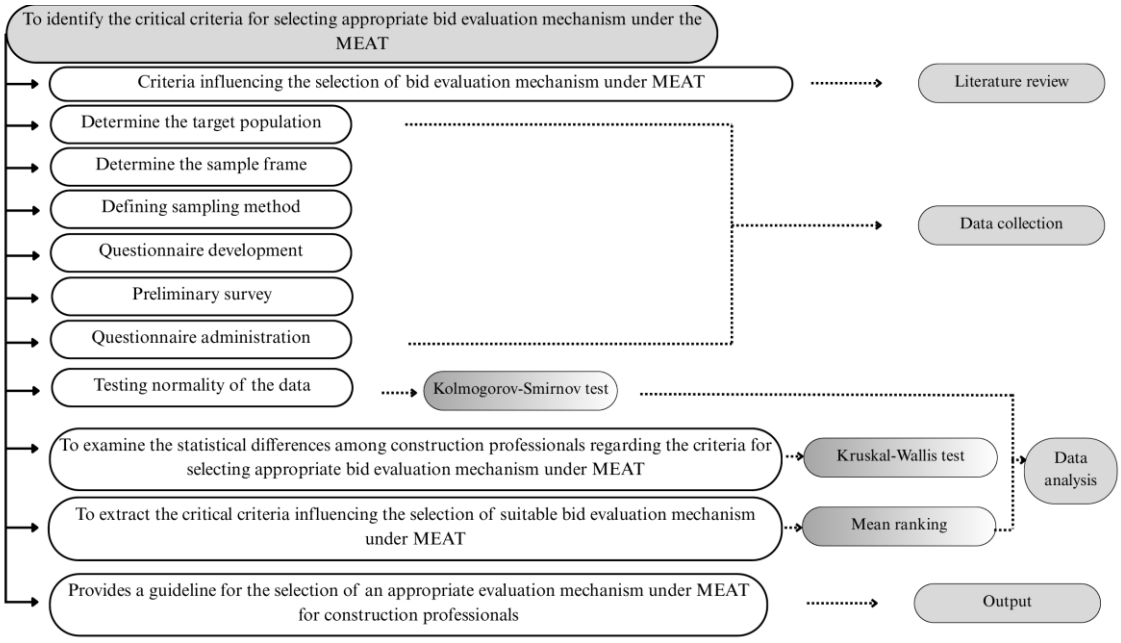



*Figure 1: Research design*

Initially, a comprehensive literature review was conducted to identify the criteria influencing the selection of the bid evaluation mechanism under MEAT. Subsequently, a preliminary survey was conducted with 10 respondents aligned with the sample frame to validate the literature findings in the Sri Lankan construction industry context. Based on this, a questionnaire survey was developed and distributed to 400 construction

professionals aligned with the sample frame via online platforms such as email, LinkedIn, and WhatsApp to facilitate easy access for respondents.

The questionnaire consisted of three sections. The first section provided the research background and general instructions to the respondents. The second section gathered respondents' demographic information. In the final section, respondents were requested to rate the identified criteria influencing the selection of the bid evaluation mechanism under MEAT based on their level of influence using a five-point Likert scale (1 - negligible, 2 - low, 3 - moderate, 4 - high and 5 - extremely high).

The collected data were then tested for normality using the Kolmogorov-Smirnov test. The hypotheses of the Kolmogorov-Smirnov test are as follows:

- Null hypothesis ($H_0$): Data follows a normal distribution.
- Alternative hypothesis ($H_1$): Data does not follow a normal distribution.

If $p > 0.05$ the null hypothesis was not rejected. Otherwise, the null hypothesis is rejected. To achieve Objective 2, the Kruskal-Wallis test was conducted to determine whether there are statistically significant differences among the responses of Engineers, Architects, and Quantity Surveyors regarding the influence of the identified criteria, at a significance level of 0.05 with a 95% confidence level. The hypotheses of the Kruskal-Wallis test are as follows:

- Null hypothesis ($H_0$): There is no statistically significant discrepancies between the responses of Engineers, Architects and Quantity Surveyors.
- Alternative hypothesis ($H_1$): There is a statistically significant discrepancies between the responses of Engineers, Architects and Quantity Surveyors.

If $p > 0.05$ the null hypothesis was not rejected. Otherwise, the null hypothesis is rejected. To achieve Objective 3, mean values were calculated for each criterion based on the responses. A criterion was considered critical or significant if its overall mean ($\bar{X}$), is greater than 3.50, while criteria with a mean less than or equal to 3.50 were considered insignificant (Aghimien et al., 2021). Where two or more criteria have the same overall mean ($\bar{X}$), the one with the lowest standard deviation was assigned the higher importance ranking (Chileshe et al., 2020).

# 4. RESULTS AND DISCUSSION

## 4.1 RESPONDENTS' DEMOGRAPHIC INFORMATION

The preliminary survey was conducted with 10 construction professionals who are align with the sample frame. Based on the preliminary survey, all seven criteria identified through the literature review were validated as relevant to the Sri Lankan construction industry. Subsequently, a questionnaire survey was developed and distributed to 400 construction professionals aligned with the sample frame. According to Krejcie and Morgan (1970), the required sample size for the study was calculated as 365. However, out of the 400 distributed questionnaires, only 122 were returned with valid responses, resulting in a 30.5% response rate. James (2001) stated that achieving the required sample size is not always practical due to constraints such as budget, time, and resources. In such cases, 100 responses are considered the minimum threshold for obtaining meaningful results in questionnaire surveys (Memon et al., 2020). As the number of responses

collected in this study exceeds this minimum threshold, the sample size can be considered adequate.

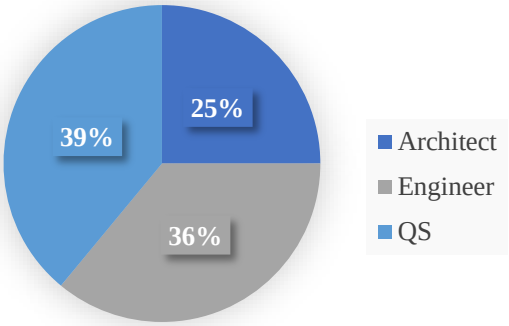



*Figure 2: Respondents' profession*

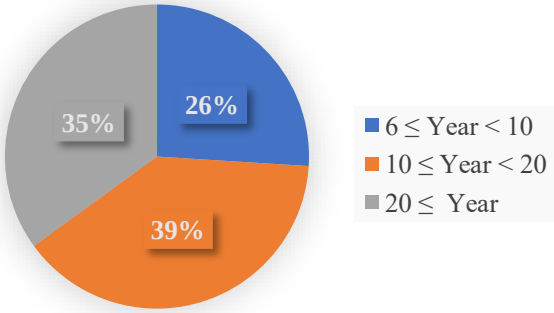



*Figure 3: Respondents' experience*

As illustrated in Figure 2, data were collected from three professional groups, namely architects, engineers, and quantity surveyors (QS), with proportions of 25%, 36%, and 39%, respectively. The majority of respondents were quantity surveyors, which is justifiable given that QS professionals are more actively involved in the tendering process compared to architects and engineers. In terms of years of experience, as presented in Figure 3, 26% of respondents have 6 - 10 years of experience, 39% have 10 - 20 years of experience, and 35% have more than 20 years of experience. The average years of working experience among respondents was calculated as 16.5 years. This indicates that the respondents possess considerable industry experience. Furthermore, regarding the highest academic qualifications, 65% of respondents hold postgraduate degrees, 32% hold bachelor's degrees, while 2% and 1% hold doctorate and national diploma qualifications, respectively. Overall, the demographic analysis indicates that the respondents possess substantial knowledge of the construction industry, supported by both their academic qualifications and extensive professional experience.

## 4.2 CRITICAL CRITERIA INFLUENCING THE SELECTION OF BID EVALUATION MECHANISM UNDER MEAT

The collected data first underwent the Kolmogorov-Smirnov (K-S) test to evaluate the normality of the data and to determine the appropriate type of data analysis to be conducted. The results of the K-S test are presented in Table 2. As per the results, all p-values at the 0.05 significance level with a 95% confidence level were less than 0.05 ($p < 0.05$). Thus, the null hypothesis was rejected, indicating that the data do not follow a normal distribution. Therefore, to determine whether there are statistically significant differences among the responses of Engineers, Architects, and QS regarding the influence of the identified criteria, the Kruskal-Wallis (K-W) test, a non-parametric test, was performed. The K-W test results presented in Table 2 indicate that there is no statistically significant difference in the responses of the respondents at the 0.05 significance level with a 95% confidence level.

*Table 2: Critical criteria influence the selection of bid evaluation mechanism under MEAT*

| Criteria code | Architect | | Engineer | | QS | | Overall | | K-S Significant at 5% level | K-W P Value | K-W Significant at 5% level |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{x}$ | R | $\bar{x}$ | R | $\bar{x}$ | R | $\bar{X}$ | R | | | |
| C3 | 4.16 | 1 | 3.98 | 2 | 3.98 | 1 | 4.02 | 1 | <0.05 | 0.528 | No |
| C6 | 3.94 | 3 | 4.00 | 1 | 3.91 | 2 | 3.95 | 2 | <0.05 | 0.765 | No |
| C5 | 4.00 | 2 | 3.75 | 4 | 3.74 | 5 | 3.81 | 3 | <0.05 | 0.814 | No |
| C7 | 3.90 | 4 | 3.77 | 3 | 3.79 | 4 | 3.81 | 4 | <0.05 | 0.273 | No |
| C1 | 3.68 | 5 | 3.64 | 5 | 3.87 | 3 | 3.74 | 5 | <0.05 | 0.291 | No |
| C4 | 3.68 | 6 | 3.41 | 6 | 3.66 | 6 | 3.57 | 6 | <0.05 | 0.314 | No |
| C2 | The criterion is not critical ($\bar{X}$ < 3.5). Therefore, $\bar{x}$ values were not mentioned | | | | | | 3.48 | This criterion is not critical ($\bar{X}$ < 3.5). Therefore, K-S, K-W values and significant status were not mentioned | | | |

*Notes: $\bar{X}$ = Overall Mean; $\bar{x}$ = Mean of each profession; R = Rank; K-S = Kolmogorov-Smirnov test; K-W = Kruskal-Wallis test*

As shown in Table 2, criteria C3, C6, C5, C7, C1, and C4 recorded mean values above 3.5 and were therefore considered as critical criteria influencing the selection of the bid evaluation mechanism under MEAT. The degree of measuring project specific criteria (C3) received the highest ranking and indicates that the ability to measure project specific criteria plays a dominant role in selecting the appropriate bid evaluation mechanism under MEAT. When projects involve significant variation in quality attributes such as technical performance, project duration, and environmental considerations, the selection of the bid evaluation mechanism depends on how effectively these attributes can be incorporated, either through price to quality or quality to price transformation. As stated by Bergman and Lundberg (2013), in the quality to price mechanism, quality attributes need to be converted into monetary values. Therefore, depending on the nature of the project specific attributes and the feasibility of assigning monetary values to them, the selection between price to quality and quality to price mechanisms may vary. Hence, respondents may have ranked C3 as the most critical criterion. This finding is particularly relevant to the Sri Lankan construction industry, where public sector projects vary considerably in terms of complexity, technical requirements, and performance expectations (Uduwage et al., 2026).

Reliability of the data used to develop a scoring formula (C6) was ranked as the second most critical criterion influencing the selection of the bid evaluation mechanism. The scoring formula for both price to quality and quality to price mechanisms is developed based on the weightage assigned to price and quality attributes (Bergman & Lundberg, 2013). For instance, in the price to quality mechanism, price is converted into a score based on assigned weights, making it particularly sensitive to inaccuracies (Parikka-Alhola & Nissinen, 2012). If the underlying data is unreliable, the transformation of price into quality scores may produce misleading results. Similarly, in the quality to price mechanism, unreliable data may affect the accuracy of monetary values assigned to quality attributes. Therefore, respondents may have given higher priority to C6 due to its direct influence on the accuracy and reliability of both evaluation mechanisms. This

finding may reflect practitioners' concerns regarding the availability and quality of project and market data required to support objective decision making, particularly when introducing relatively new evaluation approaches such as MEAT into the Sri Lankan procurement environment.

Efficiency (C5) was ranked as the third critical criterion. In practice, the price to quality mechanism is relatively simpler, as it often involves predefined formulas and requires less effort and resources (Parikka-Alhola & Nissinen, 2012). In contrast, in the quality to price mechanism, quality attributes need to be converted into monetary values during the evaluation stage, which may require additional time and resources. Therefore, respondents may have considered efficiency as an important factor when selecting between the two mechanisms. Practicability of the method (C7) also received the same mean value as C5 ($\bar{X}$ =3.81) and was ranked as the fourth critical criterion based on its standard deviation. Since the conversion of quality attributes into monetary values is relatively complex and requires expert judgment during the evaluation stage, respondents may perceive the quality to price mechanism as less practical in certain contexts. Therefore, respondents may have considered C7 as an important criterion influencing the selection of the evaluation mechanism.

Subjective evaluation (C1) and speed of the evaluation process (C4) were also identified as critical factors. However, they received the lowest rankings among the critical criteria. Since both price to quality and quality to price mechanisms involve a certain degree of subjectivity in assigning weights and evaluating quality attributes, respondents may not have given high importance to C1. With regard to the speed of the evaluation process, the lower ranking indicates that respondents are more concerned with the quality and accuracy of the decision rather than the time taken for evaluation. Notably, simplicity (C2) recorded a mean value below 3.5 and was therefore considered a non-critical criterion influencing the selection of the bid evaluation mechanism under MEAT. This implies that construction professionals are willing to adopt more complex evaluation mechanisms when they provide more reliable and project-specific evaluation outcomes.

Moreover, the results indicate that the selection of the bid evaluation mechanism under MEAT is primarily influenced by the ability to accurately represent project specific requirements and ensure data reliability, while factors such as simplicity and speed are given comparatively less importance. This suggests that construction professionals are more concerned with achieving accurate and project-appropriate contractor selection outcomes than minimising the effort associated with the evaluation process.

## 5. CONCLUSIONS

Contract awarding for public sector projects in Sri Lanka currently follows procurement guidelines published by the National Procurement Commission (NPC), which primarily emphasise bid price-based awarding, particularly the Lowest Bid Method (LBM). Although the explicit adoption of the Most Economically Advantageous Tender (MEAT) is limited, concept of MEAT and its evaluation mechanisms are reflected in standard bidding documents such as SBD 4 and NPA/Goods/SBD 01. In recent years, research attention on the applicability of MEAT within the Sri Lankan construction industry has increased due to its potential to enhance value for money, quality performance, and long-term project outcomes compared to the Lowest Bid Method (LBM). For effective implementation of MEAT, bid documents need to clearly specify the bid evaluation

mechanism to be adopted, as the choice between price to quality and quality to price mechanisms can influence evaluation outcomes and contractor behaviour. Accordingly, this study identified the criteria influencing the selection of bid evaluation mechanisms under MEAT.

The study initially examined the differences in responses among engineers, architects, and quantity surveyors using the Kruskal-Wallis test, and the findings indicated no statistically significant differences among the professional groups. Subsequently, seven criteria identified through the literature review were analysed using mean ranking, of which six were identified as critical. Among these, the degree of measuring project-specific criteria (C3) and the reliability of data used to develop scoring formulas (C6) were identified as the most critical criteria, ranked first and second, respectively.

The findings provide a basis for industry practitioners and procurement authorities to consider project characteristics and data reliability when selecting suitable evaluation mechanisms under MEAT during procurement planning and bid document preparation. Furthermore, policymakers may consider incorporating guidance on MEAT implementation within existing procurement frameworks to support transparent and structured contractor selection processes. Future research may focus on developing a decision-support framework to assist practitioners in selecting the most appropriate evaluation mechanism under MEAT. The findings of this study may also benefit developing countries with evolving procurement practices, where selecting appropriate evaluation mechanisms based on project characteristics can enhance transparency, reduce inefficiencies, and improve value for money in public projects.

## 6. REFERENCES

Abdelrahman, M., Zayed, T., Hietpas, J. J., & Elyamany, A. (2008). Rational best-value model based on expected performance. *Transportation Research Record Journal of the Transportation Research Board*, *2081*(1), 46–55. https://doi.org/10.3141/2081-05

Abdullahi, A., & Sieng, L. W. (2023). The effect of infrastructure development on economic growth: The case of sub-Saharan Africa. *Journal of Infrastructure Policy and Development*, *7*(2), 1994. https://doi.org/10.24294/jipd.v7i2.1994

Acheamfour, V. K., Adjei-Kumi, T., & Kissi, E. (2021). Contractor selection: A review of qualification and pre-qualification systems. *International Journal of Construction Management*, *23*(2), 338–348. https://doi.org/10.1080/15623599.2020.1868092

Aghimien, D., Aigbavboa, C., Meno, T., & Ikuabe, M. (2021). Unravelling the risks of construction digitalisation in developing countries. *Construction Innovation*, *21*(3), 456–475. https://doi.org/10.1108/ci-02-2020-0026

Asker, & Cantillon, E. (2006). *Procurement when price and quality matter*. SSRN. https://doi.org/10.2139/ssrn.804224

Asker, J., & Cantillon, E. (2008). Properties of scoring auctions. *The RAND Journal of Economics*, *39*(1), 69–85. https://doi.org/10.1111/j.0741-6261.2008.00004.x

Baldi, S., Bottasso, A., Conti, M., & Piccardo, C. (2016). To bid or not to bid: That is the question: Public procurement, project complexity and corruption. *European Journal of Political Economy*, *43*, 89–106. https://doi.org/10.1016/j.ejpoleco.2016.04.002

Ballesteros-Pérez, P., Skitmore, M., Pellicer, E., & González-Cruz, M. C. (2015). Scoring rules and abnormally low bids criteria in construction tenders: A taxonomic review. *Construction Management and Economics*, *33*(4), 259–278. https://doi.org/10.1080/01446193.2015.1059951

Ballesteros-Pérez, P., Skitmore, M., Pellicer, E., & Zhang, X. (2016). Scoring rules and competitive behavior in best-value construction auctions. *Journal of Construction Engineering and Management*, *142*(9). https://doi.org/10.1061/(asce)co.1943-7862.0001144

Bergman, M. A., & Lundberg, S. (2013). Tender evaluation and supplier selection methods in public procurement. *Journal of Purchasing and Supply Management*, *19*(2), 73–83. https://doi.org/10.1016/j.pursup.2013.02.003

Chileshe, N., Kavishe, N., & Edwards, D. J. (2020). Critical factors influencing the bid or no-bid decision of the indigenous small building contractors in Tanzania. *Construction Innovation*, *21*(2), 182–202. https://doi.org/10.1108/ci-09-2019-0098

Dimitri, N., Piga, G., & Spagnolo, G. (Eds.). (2006). *Handbook of procurement*. Cambridge: Cambridge University Press. https://doi.org/10.1017/cbo9780511492556

Dinesh, K. L. S., Liyanage, U. P., & Wijeyaratne, W. M. D. N. (2026, February 18). A framework to value sustainability of procurement in Sri Lanka's health sector, integrating the EUMEAT concept to the E-GP platform. In *6th International conference on advanced research in computing (ICARC)* (pp. 1-6). IEEE. https://ieeexplore.ieee.org/document/11454074

Hasantha, M. L., Waidyasekara, A. S., & Victar, H. C. (2024). Evaluation of time allocated for bid preparation in national competitive bidding in the Sri Lankan construction industry. *Engineering Construction & Architectural Management*, *32*(7), 4310–4337. https://doi.org/10.1108/ecam-11-2023-1151

Idrees, S. M., Eid, M. S., & Awwad, R. (2023). Impact of altering the bid selection method to below-average method: An agent-based modeling approach. *Journal of Management in Engineering*, *39*(3), 5084. https://doi.org/10.1061/jmenea.meeng-5084

Ioannou, P. G., & Awwad, R. E. (2010). Below-average bidding method. *Journal of Construction Engineering and Management*, *136*(9), 936–946. https://doi.org/10.1061/(asce)co.1943-7862.0000202

James, E. B. (2001). Organizational research: Determining appropriate sample size in survey research. *Information Technology, Learning, and Performance Journal*, *19*(1), 43–50. http://api.ning.com/files/dDaMclZ3KnGUTT6nb2fPTHLljun-LLZEfrgdcoswcvTsB60CmiaZ93cmYBLFd1wUyFBUK4H9eT767qY8mUR7PWj88cc1Xw6h/SampleSizeDetermination.pdf

Khan, T. H. (2015). Effects of lowest bidding bid awarding system in public sector construction projects in Pakistan. *Developing Country Studies*, *15*(1), 132–146. https://www.iiste.org/Journals/index.php/DCS/article/download/19650/20118

Krejcie, R. V., & Morgan, D. W. (1970). Determining sample size for research activities. *Educational and Psychological Measurement*, *30*(3), 607–610. https://doi.org/10.1177/001316447003000308

Lahdenperä, P. (2013). Determining 'the most economically advantageous tender' based on capability and fee-percentage criteria. *Journal of Public Procurement*, *13*(4), 409–446. https://doi.org/10.1108/jopp-13-04-2013-b001

Lambropoulos, S. (2013). Objective construction contract award using cost, time and durability utility. *Procedia - Social and Behavioral Sciences*, *74*, 123–133. https://doi.org/10.1016/j.sbspro.2013.03.052

Lehtonen, J., & Virtanen, K. (2022). Choosing the most economically advantageous tender using a multi-criteria decision analysis approach. *Journal of Public Procurement*, *22*(2), 164–179. https://doi.org/10.1108/jopp-06-2021-0040

Lundberg, S., & Bergman, M. A. (2011). *Tender evaluation and award methodologies in public procurement*. SSRN. https://doi.org/10.2139/ssrn.1831143

Lundberg, S., & Marklund, P. (2011). The Pivotal nature of award methods in green public procurement. *SHILAP Revista De Lepidopterología*. *2*(3), 64-73. https://doaj.org/article/b02df015139c4913b79eaa9458efbad2

McFarland, W. F., Kabat, R. J., & Krammes, R. A. (1994). *Comparison of contracting strategies for reducing project construction time*. https://trid.trb.org/view.aspx?id=1170742

Memon, M. A., Ting, H., Cheah, J., Thurasamy, R., Chuah, F., & Cham, T. H. (2020). Sample size for survey research: Review and recommendations. *Journal of Applied Structural Equation Modeling*, *4*(2), i–xx. https://doi.org/10.47263/jasem.4(2)01

Nemec, P., Kubak, M., & Dzupka, P. (2021). The transition of the Visegrad countries toward sustainable public procurement. *Eastern European Economics*, *59*(5), 487–512. https://doi.org/10.1080/00128775.2021.1956973

Organisation for Economic Co-operation and Development. (2021). S*trengthening value for money in the public procurement system of the Slovak Republic: Towards a strategy to use adequate award criteria*. https://www.oecd.org/content/dam/oecd/en/publications/reports/2021/12/strengthening-value-for-money-in-the-public-procurement-system-of-the-slovak-republic_caef030b/9b4deebd-en.pdf

Parikka-Alhola, K., Ekroos, A., & Ekroos, A. (2006). Green award criteria in the most economically advantageous tender in public purchasing. In Thai K.V. & Piga G. (Eds.) *Advancing public procurement* (pp. 257–279). Academic Press. https://www.researchgate.net/publication/237714849_Green_Award_Criteria_in_the_Most_Economically_Advantageous_Tender_in_Public_Purchasing

Parikka-Alhola, K., & Nissinen, A. (2012). Environmental impacts and the most economically advantageous tender in public procurement. *Journal of Public Procurement*, *12*(1), 43–80. https://doi.org/10.1108/jopp-12-01-2012-b002

National Procurement Commission. (2024). *The procurement manual – 2024 for goods, works, and non-consulting services*. https://nprocom.gov.lk/elementor-913/

Rashvand, P., Majid, M. Z. A., Baniahmadi, M., & Ghavamirad, F. (2015). Contractor selection at prequalification stage: Current evaluation and shortcomings. *Jurnal Teknologi*, *77*(16), 81-89. https://doi.org/10.11113/jt.v77.6403

Rees, M., Al-Nabahani, K., Forrester, L., Sabbarton, R., Wiseman, A., & Williams, G. (2023). *Lessons learned: Competition in public procurement*. Victoria, United Kingdom: National Audit Office.

Stilger, P. S., Siderius, J., & Van Raaij, E. M. (2015). *A comparative study of formulas for choosing the economically most advantageous tender*. SSRN. https://doi.org/10.2139/ssrn.2626934

Stilger, P. S., Siderius, J., & Van Raaij, E. M. (2017). A comparative study of formulas for choosing the economically most advantageous tender. *Journal of Public Procurement*, *17*(1), 89–125. https://doi.org/10.1108/jopp-17-01-2017-b004

Thiruchelvam, K., & Uduwage, D.N.L.S (2025). Assessing SDG 7 performance: identifying relevant KPIs for the Sri Lankan construction industry. In Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 13th World Construction Symposium* (pp. 203–215). CIOB & BEMRU. https://doi.org/10.31705/wcs.2025.16

Trade Commissioner Service. (2025, June 3). European Union government procurement guide for Canadian business. Tradecommissioner.gc.ca. https://www.tradecommissioner.gc.ca/en/market-industry-info/search-country-region/region/canada-europe-export/european-union-government-procurement-guide-canadian-business.html

Uduwage, D.N. L. S., Hadiwattage, C., & Panuwatwanich, K. (2023). Enhancing the responsiveness of bids in public procurement: The case of Sri Lanka. *Public Works Management & Policy*, *29*(3), 332–363. https://doi.org/10.1177/1087724x231191724

Uduwage, D.N.L.S., Panuwatwanich, K., & Waidyasekara, K. (2024). Multicriteria selection practices in public tender evaluation process: The case of Sri Lanka. *Built Environment Project and Asset Management*, *15*(3), 733–751. https://doi.org/10.1108/bepam-12-2023-0220

Uduwage, D.N.L.S., Perera, B. A. K. S., & Panuwatwanich, K. (2026). Critical factors influencing the contract award criteria in public construction Projects: A Confirmatory Factor Analysis approach. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *18*(2), 1445. https://doi.org/10.1061/jladah.ladr-1445

Waara, F., & Bröchner, J. (2006). Price and nonprice criteria for contractor selection. *Journal of Construction Engineering and Management*, *132*(8), 797–804. https://doi.org/10.1061/(asce)0733-9364(2006)132:8(797)

Wu, J., Liu, J., Jin, X., & Sing, M. C. (2016). Government accountability within infrastructure public–private partnerships. *International Journal of Project Management*, *34*(8), 1471–1478. https://doi.org/10.1016/j.ijproman.2016.08.003

Nawarathna, H.G.G., Jayasena, H.S. and Piranavan, S., 2026. Data requirements for a material passport in the Sri Lankan construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 513-526. DOI: https://doi.org/10.31705/WCS.2026.38. Available from: https://ciobwcs.com/papers/

# DATA REQUIREMENTS FOR A MATERIAL PASSPORT IN THE SRI LANKAN CONSTRUCTION INDUSTRY

**H.G.G. Nawarathna[1], H.S. Jayasena[2] and S. Piranavan[3]**

## *ABSTRACT*

*Material Passports have emerged as an effective digital tool enabling systematic documentation of material information throughout the building lifecycle, supporting Circular Economy principles in the Built Environment. However, the concept of Material Passport is relatively new to the Sri Lankan context, and there is currently a lack of a standardized template specifying the data requirements necessary for their implementation. Therefore, this study aims to identify the data requirements needed to develop a standardized MP template for the Sri Lankan BE. A qualitative research approach was adopted for this study. Initially, a comprehensive literature review was conducted to identify commonly used MP data categories reported in previous studies. Subsequently, semi-structured interviews were conducted with key stakeholders in the building lifecycle. The collected data were analysed using thematic analysis with predefined coding categories. The findings revealed that while categories like product features, composition, and maintenance are applicable, environmental impact and end-of-life deconstruction details are currently lacking in local practice. As an intermediate solution, it is proposed to retain these as descriptive open fields accompanied by guidance notes. Structuring these fields requires careful consideration to ensure backward compatibility and support a future transition toward dynamic material passports, with green building rating systems potentially serving as market-based catalysts to incentivize their use. This study provides a foundation for developing a context-specific MP template for Sri Lanka, which can enhance material traceability, improve lifecycle information management, and support gradual transition towards CE practices within the BE in Sri Lanka.*

***Keywords:*** *Built Environment; Circular Economy; Data Requirements; Material Passport; Sri Lanka.*

## 1. INTRODUCTION

The construction industry is a major contributor to global material consumption and environmental impact throughout a building's lifecycle (Lokuge et al., 2025). Notably, more than 30% of natural resources extraction and 25% of global solid waste generation are attributable to the construction sector. This is largely due to the fact that the

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, Gayasri.hg@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sivasothypiranavan27@gmail.com

construction industry still adopts a linear economic model based on "take-make-dispose" approach (Benachio et al., 2020). Therefore, the Circular Economy (CE) model is increasingly recognized as a feasible solution to the problems associated with these linear economic models (Blomsma et al., 2023). By adopting CE practices, the industry can reduce waste, enhance the utilization of recycled materials and create markets for recycled and repurposed resources (Lakshan et al., 2025).

Furthermore, the integration of digital technologies into the CE concept aims to ensure better use of fewer resources, reduce energy consumption, utilize capacity and logistics routes more effectively, and enable open access to information about the resources used by products. This enables optimization of product life cycles (Antikainen et al., 2018; Chi et al., 2023). Consequently, the Material Passport (MP) is considered an essential and reliable technology to identify the circular and sustainability values of systems and materials within the Built Environment (BE) (Blomsma et al., 2023). MP encourages the use of sustainable, circular, and healthful building materials by enabling project stakeholders to systematically evaluate material performance and lifecycle considerations when making design and construction decisions (Cagno et al., 2021).

As a developing country, Sri Lanka is increasingly suffering from environmental challenges resulting from unsustainable development practices, high material usage, and high waste generation (Athapaththu et al., 2016). This occurs as the Sri Lankan BE predominantly follows the "take-make-dispose" linear economic paradigm, promoting a necessary shift towards CE practices to mitigate these impacts (Weerakoon et al., 2023). As a solution for this significant environmental impact, the Sri Lankan construction industry is leaning away from linear economy practices towards CE (Weerakoon et al., 2023). While international studies advocate for comprehensive MP frameworks, their direct implementation in the local context is hindered by distinct differences in industry practices, regulatory maturity, digital infrastructure and availability of lifecycle data (Jayawardane et al., 2023). Specially, Jayawardane et al. (2023) identified that a lack of continuous information flows, insufficient experimental applications, and widespread ambiguity regarding how to define and implement MP acts as primary barriers within the Sri Lankan industry. Furthermore, limited stakeholder awareness, and the absence of standardised lifecycle information management systems severely restrict the adoption of internationally developed MP templates (Hernandez, 2024). Building directly upon these findings, this study addresses the implementation barrier by defining the foundational data requirements necessary to establish these missing information flows. Because international templates often rely on advanced digital integration and established circular supply chains that do not yet exist locally, a context-specific, standardized data template is essential to bridge the gap between theoretical CE concepts and practical local application.

Accordingly, this research aims to identify the key data requirements necessary to develop a standardized MP suitable for the Sri Lankan BE. The primary objectives are:

01. Identify the key requirements for a comprehensive MP.
02. Develop a standardized MP data template based on these requirements for the Sri Lankan context.

# 2. LITERATURE REVIEW

Digitalization can boost the transformation from linear economy to the CE by providing accurate product information, enabling efficient processes, minimizing waste, promoting product longevity, and reducing transaction costs, thus closing the material loop and enhancing resource efficiency (Antikainen et al., 2018). Consequently, MP serves as essential enablers of the CE acting as digital repositories that track and record the circularity characteristics of materials to systematically support end-of-life recovery, recycling, refurbishment, and reuse (Qazi et al., 2026). Therefore, the MP can be defined as a critical digital technology that enables circularity throughout the life cycle of the building in the BE (Çetin et al., 2022; Markou et al., 2025).

## 2.1 OVERVIEW OF MATERIAL PASSPORT

A MP is a tool that can be used for material information management (Munaro et al., 2019; KC et al., 2025). According to the Markou et al. (2025), a MP can be defined as digital records that provide details about the physical characteristics of the materials and the components that are utilized in various products or systems. Some other authors emphasize that an MP can be identified as a digital tool that encompasses details related to materials and their environmental impact (Atta et al., 2021; Göswein et al., 2022; Honic et al., 2019). Çetin et al. (2023) mentioned that few purposes of having MP in CE such as recovering value through recycling and reuse, calculate the economic value of products, optimisation of design, measure the circularity level of a building, and management of life cycle data. However, some similar terminologies can be identified alongside the MP such as Digital Product Passports (DPPs) and Digital Building Logbooks (DBLs) (Markou et al., 2025). These passport instruments vary according to the industries in which they are implemented, the scope and backbone principles on which they are established, yet these passport instruments are all designed to enable circularity (Çetin et al., 2023).

| | Digital Product Passports | Material Passports | Digital Building Logbooks |
|---|---|---|---|
| Scale | Product | Area; Complex; Building; Element; Product; Material; Raw material | Building |
| Industry | Cross-industry | (Mainly) Built environment | Built environment |
| Regulation | EU Ecodesign Directive | - | EU-wide Framework for a Digital Building Logbook |

*Figure 1: Differences and similarities between digital product passports, material passports, and digital building logbooks (Source çetin et al., 2023)*

Considering that the MP and DPP both provide details regarding material quantities, capabilities of reuse, and the potential to dissemble products, the main difference is their scope: MP is tailored for the BE, whereas DPP is cross-industry tools applied across a wide range of sectors, including textiles, electronics, and industrial batteries, under regulations like the EU's Eco-design for Sustainable Products Regulations (Ahmadi et al., 2026; Qazi et al., 2026). Furthermore, considering the MP and DBL, while both are involved in digital information management, DBL is primarily utilised as centralised

repositories for activities, energy efficiency, and emission tracking during a building's operational and renovation stages (Ahmadi et al., 2026; Qazi et al., 2026). In contrast, the MP encompassed detailed material data covering the entire life cycle of a building (Markou et al., 2025; Çetin et al., 2023).

These distinctions are particularly impactful for the Sri Lankan context. Because the local industry predominantly struggles with high material waste and the linear "take-make-dispose" paradigm rather than advanced operational energy tracking, the MP, with its specific focus on material recovery and lifecycle traceability, is the most urgent and contextually appropriate tool to introduce first, as summarised in Figure 1.

## 2.2 KEY REQUIREMENTS FOR A COMPREHENSIVE MATERIAL PASSPORT

Some studies have identified key requirements that should be included in a comprehensive MP template. Initially, there should be general information regarding the building such as the name, type, and location of the building, the year the building was constructed, the gross floor area, and the number of floors (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022; Çetin et al., 2022). Moreover, product features such as details of the manufacturer, the product registration number, the unique ID of the materials, and a material photo must be included in the MP (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022). Çetin et al. (2023) and Markou et al. (2025) explained that there should be product composition details in the MP, under this category, detailed information on materials and components used should be included by mentioning quantities, weight, volume, physical properties and the composition of materials.

Additionally, there should be quality standards for materials including performance characteristics, the durability status of the materials, and relevant certifications (Markou et al., 2025). Çetin et al. (2023) mentioned that there must be a quality assessment as an essential data requirement in the MP. On the other hand, Marsh et al. (2022) argued that omitting the quality of material category from the MP will undermine the effectiveness of the tool. Moreover, without incorporating quality standards into the MP, it would not be possible to enable the reuse of reclaimed materials efficiently or secure the cradle-to-cradle concept in the BE (Honic et al., 2021).

In addition, there should be details about the quantity of the materials in the MP and under this category, there is a need to include quantitative data on the amounts of material used expressed in weight (Markou et al., 2025). Çetin et al. (2023) and Göswein et al. (2022) also emphasized that the quantity of materials must be included in the MP as a data requirement category. The ability to deconstruct is another category to be included in the MP, under this category, it should be mentioned how a product can be dismantled easily for recycling or reuse purposes at the end of its life (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022). However, Çetin et al. (2023) argued that ability to deconstruct data is not always readily available and requires an effort to obtain.

On the other hand, there should be an environmental impact category in the MP (Markou et al., 2025). Çetin et al. (2023) emphasized that under this category, there should be details about recycled or reused materials, the renewable or non-renewable content of the materials, details about whether materials are untreated or treated, and life cycle assessment details. These environmental impact details facilitate the CE concept by offering a systematic framework for evaluating material circularity performance in the BE (Senarathne et al., 2025). Furthermore, there should be details regarding product

safety features (Markou et al., 2025). Under this category, one should identify the hazardous substances used in the product, provide guidelines for the handling and disposal of those substances, and include the product safety data sheet (Çetin et al., 2023).

Moreover, there should be a category regarding product operational aspects. Under this category, this includes maintenance instructions, the maintenance log, maintenance contractor information, the availability of spare parts, and the expected service life (Çetin et al., 2023; Senarathne et al., 2025). Markou et al. (2025) expressed that under this category, proper recommendations for maintenance and care should be provided. Under the expected life data point, details of the duration for which the materials can be used under the normal conditions should be provided. Table 1 illustrates the summary of data requirements for a comprehensive MP.

*Table 1: Summary table of required data to create MP template*

| Data Requirement Category | Sub Category | Illustrative Reference(s) |
|---|---|---|
| Building General Information | Name of the building | |
| | Type of the building | |
| | Location of the building | [A], [B], [E], [F] |
| | Year of building constructed | |
| | Gross Floor Area | |
| | Number of floors | |
| Product Features | Details of manufacturer | |
| | Product registration number | [A], [B], [E] |
| | Unique ID of the materials | |
| | Material photo | |
| Product Composition | Weight | |
| | Quantity | |
| | Volume | [A], [B] |
| | Physical properties | |
| | Composition of materials | |
| Quality of Materials | Durability | |
| | Performance characteristics | [A], [B], [C], [D] |
| | Certifications | |
| Quantity of Materials | Quantity of each material type | [A], [B], [E] |
| Ability to Deconstruct | Details of dismantle process | |
| | Details of recycling process | [A], [B], [E] |
| | Details of reusing process | |
| Environmental Impact | Details of recycle & reuse materials | |
| | Renewable or non-renewable content of materials | [A], [B], [G] |

| Data Requirement Category | Sub Category | Illustrative Reference(s) |
|---|---|---|
| | Details about untreated or treated materials | |
| | Life cycle assessment details | |
| Product safety features | Hazardous substances | |
| | Manuals for hazardous substances | [A], [B] |
| | Product safety data sheet | |
| Product operations aspects | Maintenance aspects | |
| | Maintenance log | |
| | Maintenance contractor information | [A], [B], [G] |
| | Availability of spare parts | |
| | Expected service life time | |

[A]-Çetin et al., 2023; [B]- Markou et al., 2025; [C]- Marsh et al., 2022; [D]- Honic et al., 2021; [E]- Göswein et al., 2022; [F]- Çetin et al., 2022; [G]- Senarathne et al., 2025

## 3. RESEARCH METHODOLOGY

A literature review was conducted to identify the key data requirements needed for the MP. The MP is a very new concept to the Sri Lankan BE. Consequently, a quantitative approach was deemed unsuitable to collect data due to the lack of awareness of the concept within the BE, making it challenging to select a reliable and large sample. Qualitative research focuses on the quality of the data and aims to comprehend the explanations and motivations behind acts, as well as the way people perceive their experience and the environment around them (Ghanad, 2023), while facilitating the active participation of researchers in data collection (Creswell, 2017). Hence, a qualitative research approach was selected for this study to collect data using semi-structured interviews with stakeholders of the BE having knowledge of material specification and potential future users of MP.

Given that MP is a relatively new concept in the Sri Lankan BE, a specific interview protocol was established to ensure validity and reliability of the data. Initially, each interviewee's baseline understanding of MP was assessed. Subsequently, the interviewer, having extensively researched the domain, provided a comprehensive briefing on MP concepts, data structure, and lifecycle applications. During this briefing, literature-based MP data categories and explanatory examples from studies conducted in other countries were used to guide the semi-structured interview discussions, assisting respondents in evaluating the relevance of the MP requirements in the Sri Lankan context. This ensured that all respondents possessed a clear, unified understanding before providing their expert evaluations.

The interviewees were selected based on purposive sampling focusing on various stakeholders who would ideally be responsible for maintaining the MP throughout a building life cycle, such as civil engineers, quantity surveyors, architects, project managers, and facility managers(Senarathne et al., 2025). (refer Table 2). These participants were explicitly chosen because they have considerable knowledge of material

specifications, project coordination, construction documentation, facility management, and decision making in the context of a material's lifecycle. Given its qualitative exploratory nature and data collection continued until data saturation was achieved.

*Table 2: Selection criteria of interviewed experts*

| Code | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|
| **Designation** | **Civil Engineer** | **Quantity Surveyor** | **Architect** | **Civil Engineer** | **Project Manager** | **Facility Manager** | **Quantity Surveyor** | **Architect** |
| Having more than 5-year experience | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Involvement in building projects | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Exposure to Material Specifications | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lifecycle phase experience | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Thematic analysis was employed to systematically identify and analyse patterns within the interview responses. The process followed a structured deductive approach (Braun & Clarke, 2008), utilising predefined codes derived from the literature review. Interview transcripts were first carefully reviewed for familiarisation. Subsequently, data segments were manually coded using text-based software and transferred into a spreadsheet matrix. This matrix allowed the data to be systematically filtered and cross-referenced according to the predefined MP data requirement categories, ensuring a rigorous synthesis of the insights of practitioners. Findings from the literature and data analysis were then discussed to achieve the research aim and objectives.

## 4. RESEARCH FINDINGS AND DISCUSSION

Initially, pre-defined codes were developed based on the findings of the literature review and date collected from the respondents. These codes encompassed categories such as building and element identification, material specifications, composition, quality and durability, design parameters, sources, manufacturer details, installation records, maintenance and operation, environmental impact, recycle ability, and-end-of life deconstruction. Each interview transcript was carefully reviewed and statements from respondents were assigned to the appropriate codes to identify the most critical MP data requirements for the Sri Lankan context.

*Table 3: Respondents summary*

| Category | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|
| Building and element identification data | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Material identification and specifications | | ✓ | | ✓ | ✓ | ✓ | | |
| Material composition and quantities | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| Category | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 |
|---|---|---|---|---|---|---|---|---|
| Quality and durability data | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Design related parameters | ✓ | | | | | | | ✓ |
| Details of sources | ✓ | | | | | | | |
| Manufacturer details | ✓ | ✓ | | ✓ | ✓ | | | |
| Installation records | ✓ | | | ✓ | | ✓ | | ✓ |
| Maintenance and operational data | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Environmental impact indicators | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Recycling ability | | | ✓ | | | | | |
| End of life deconstruction | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

## 4.1 BUILDING AND ELEMENT IDENTIFICATION DATA

According to Çetin et al. (2023), Markou et al. (2025), Göswein et al. (2022) and Çetin et al. (2022b), there should be general information about the building in an MP. This includes the name of the building, type of building, location, year constructed, gross floor area, and the number of floors. By including this data category, one can easily identify basic project details, and stakeholders can get an idea about project information. Additionally, R1, R3, R4, R5, R6, R7, and R8 commented that there should be building and element identification data. Specifically, R7 mentioned that "*it should include general building information, such as project name, location, building type, and construction year. It helps users understand the context of the project and identify the building easily*". These kinds of data requirements are highly accessible through the internal database of the relevant project.

## 4.2 PRODUCT FEATURES/MATERIAL IDENTIFICATION AND SPECIFICATIONS

Existing literature strongly supports the inclusion of product features such as manufacturer information, product registration numbers, unique material IDs, and material photos to ensure the traceability and transparency of building materials (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022). The responses obtained from the industry practitioners further validate this requirement within the Sri Lankan BE. Specifically, respondents R1, R2, R4, and R5 emphasised the importance of manufacturer details in the MP template. The suggestion made by R1 regarding code-based manufacturer identification, *"code-based manufacturer details. For example, when we are going to use concrete if we can code the batching plant as a reference, then we can track the quality of the concrete"* highlights the potential for integrating systematic tracking mechanisms within MPs to monitor material quality and performance.

Furthermore, several respondents commented on the importance of having material identification and specifications data for the MP template when considering the Sri Lankan context. In this context, this requirement becomes important due to the diversity

of materials used in construction and the need for reliable documentation of specifications that are often dispersed across different project documents.

### 4.3 MATERIAL COMPOSITION AND QUANTITIES

Çetin et al. (2023) and Markou et al. (2025) emphasized that there should be product composition details in the MP. Under the product composition data requirement category, there should be included detailed material information and components used by mentioning quantities, weight, volume, physical properties and the composition of materials. Such information enables a comprehensive understanding of material traceability and lifecycle management within the BE. The responses from the industry practitioners in the study strongly support these arguments, as the majority of respondents (except R1) commented on the importance of including material composition and quantity details when developing an MP template tailored to the Sri Lankan context.

The practical implementation of this data category may present challenges within the Sri Lankan BE. This is because in many construction projects, detailed information regarding material composition and quantities is often dispersed across various documents such as BOQs, material specifications, and supplier records rather than being systematically centralized. R4 specifically mentioned that *"there should be material composition and quantities details. Quantities can be tracked with the BOQ but composition details tracking may be limited by supplier transparency".* Therefore, it will be critical to collect data for the MP template under this data requirement category.

### 4.4 QUALITY AND DURABILITY DATA

The inclusion of quality standards for materials, including durability, performance characteristics, and relevant certifications is considered an essential requirement for the development of an MP template (Çetin et al., 2023; Markou et al., 2025; Marsh et al., 2022; Honic et al., 2021). These types of information enable stakeholders to evaluate the reliability and long-term performance of materials utilized in construction projects. Consistent with existing literature, the data collection findings indicated that almost all respondents (except R2) highlighted the necessity of integrating quality-related information into the Sri Lankan MP template. Among them R7 explicitly emphasized the importance of documenting detailed quality verification information, stating *"There should be details to evaluate the quality of the material or product including warranties, inspection reports or test reports".* Consequently, systematically incorporating this quality-related data into the MP can significantly enhance reliability, transparency, and lifecycle management of building materials in the local BE.

### 4.5 END OF LIFE DECONSTRUCTION

According to Çetin et al. (2023), Markou et al. (2025), and Göswein et al. (2022) MPs should include details regarding the deconstruction ability of the construction project at the end of its expected lifetime, encompassing. The disassembly process, recoverability, and the feasibility of reusing or recycling building elements. However, findings indicate that the inclusion of end-of-life data currently has limited practical applicability within the Sri Lankan context. During the interview process, all respondents indicated that end-of-life deconstruction details are rarely considered in the current construction process in Sri Lanka. In particular, R8 commented that such details are not valid for Sri Lanka, most of the projects don't consider the end-of-life part. A sentiment echoed by R2.

Therefore, while deconstruction-related data are frequently suggested in international MPs, they are not yet mainstream in the local BE.

## 4.6 MAINTENANCE AND OPERATIONAL DATA

An MP should also incorporate product operation aspects including maintenance instructions, logs, contractor details, and availability of spare parts (Çetin et al., 2023; Markou et al., 2025; Senarathne et al., 2025). Such information enables building owners and facility managers to efficiently maintain building components and ensure their best performance over their service life. Except for R1, all respondents agreed that the inclusion of maintenance and operational data is highly applicable to the Sri Lankan context. R6 provided a detailed explanation, stating, "*there should be details regarding the maintenance and operational data including maintenance procedures, inspection schedules, repair guidelines, and previous maintenance history*". Furthermore, R1, R4, R6, and R8 recommended incorporating installation records under this category. R6 emphasized recording installation dates, responsible contractors, and installation methods because installation conditions may affect performance. Therefore, recording installation-related information within the MP can support improved lifecycle management of materials.

## 4.7 ENVIRONMENTAL IMPACT INDICATORS

Previous studies emphasized the importance of including environmental impact data within the MP template, such as renewable content, treatment details, lifecycle assessments, and recycled material usage (Çetin et al., 2023; Markou et al., 2025; Senarathne et al., 2025). These indicators are crucial for evaluating the sustainability and promoting CE practices in the BE.

During the data collection, all other respondents except for R2 commented on these indicators. Agreeing they could enhance sustainable practices; however, they noted that practical implementation remains limited locally. R1 highlighted this stating, *"in Sri Lanka we do not strictly focus on the environmental impact data such as the renewable or non-renewable ability of materials, and Life cycle assessment details"*. This suggests that while widely recommended in international MPs, the practical integration of environmental indicators into the Sri Lankan BE is currently constrained due to limited awareness, data unavailability, and insufficient regulatory requirements.

## 4.8 CONTEXTUAL ADAPTATION AND FINALIZATION OF MP DATA REQUIREMENTS FOR THE SRI LANKAN BE

Comparing the literature review insights with practitioners data, Figure 2 summarises the finalise MP data requirements for the Sri Lankan context categories such as building general information, product features, product composition, quality of materials, maintenance and operational details, and design related parameters were found to be highly applicable and ready for immediate implementation (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022). Conversely, while end-of-life/deconstruction and environmental impact details are critical components of international MP template (Çetin et al., 2023; Markou et al., 2025; Göswein et al., 2022; Senarathne et al., 2025), respondents indicated these are rarely practiced in Sri Lanka. In the Figure 2 red color text indicated the collected data categories during the data collection process and black color text indicated the collected data categories through literature review. However,

completely excluding these categories would undermine the MP's primary objective of facilitating the transition from a linear to a circular economy. As an intermediate solution, these categories should be retained in the template as descriptive open fields accompanied by guidance notes.

Defining the MP structure requires careful consideration because buildings have long lifecycles; maintaining these open fields alongside strictly structured data points ensures the template's backward compatibility and support the eventual transition from static data models to dynamic MPs that can be continuously updated across all lifecycle stages (Ahmadi et al., 2026; Qazi et al., 2026). To address the current lack of utilisation, explanatory notes can provide an initial incentive for practitioners to continually improve their data recording practices as awareness grows. Ultimately, realising the full benefits of material passports requires supportive regulations and policy incentives (Senarathne et al., 2025). Furthermore, private sector initiatives, such as green building rating systems and certifications, can drive this adoption by introducing scoring criteria that reward projects for documenting end-of-life material pathways and environmental impacts (Ahmadi et al., 2026). This actively incentivises practitioners to populate these open fields, encouraging a market-based approach to broader CE adoption much like green building certifications did for energy efficiency (Ahmadi et al., 2026).

Ultimately, standardizing these data formats from the outset will enable the development of structured decision support systems, facilitating better material selection, maintenance planning, and long-term resource management among project stakeholders.

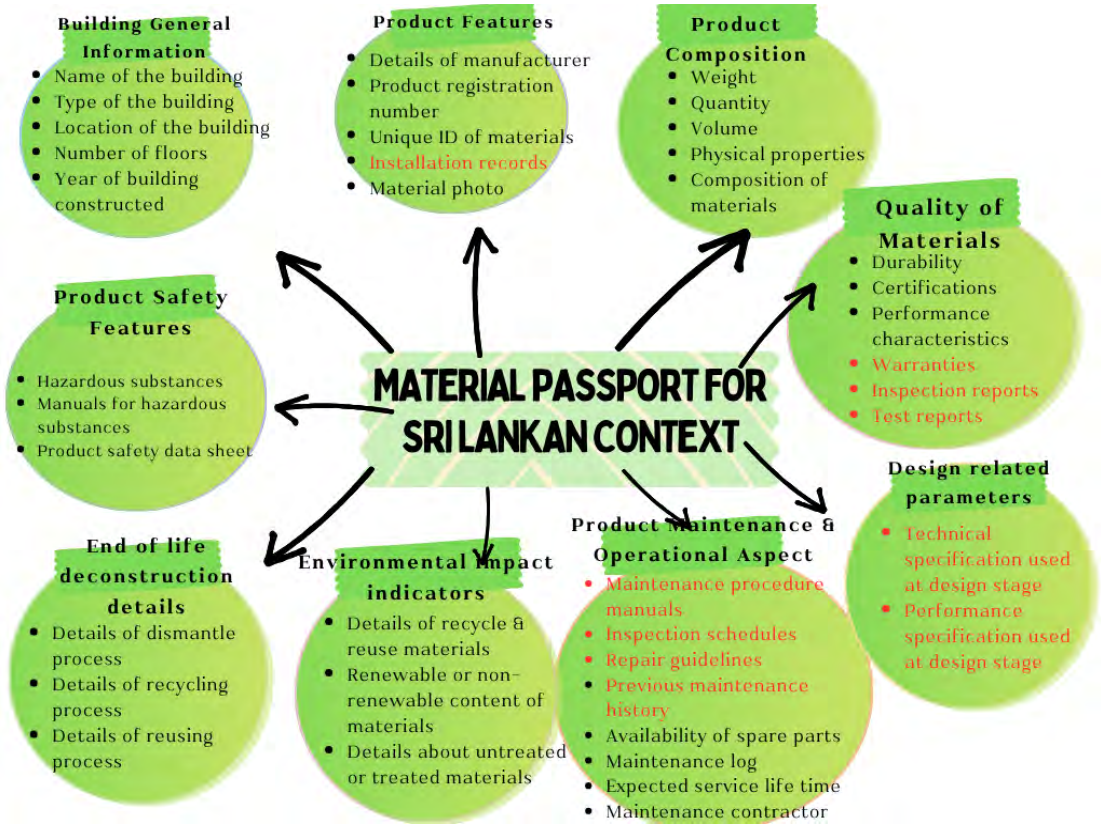



*Figure 2:MP summary diagram for the Sri Lankan context*

### 4.9 IMPLICATION OF THE RESEARCH

The findings provide a practical foundation for developing a standardized MP template suitable for the Sri Lankan BE. The identified data requirements can help construction stakeholders systematically document material information throughout the building lifecycle. Consequently, the adoption of MP could enhance material traceability, quality verification, and the lifecycle management of building components. The inclusion of information such as manufacturer details, material specifications, installation records, and maintenance data can enhance the more efficiency facility management and decision-making regarding maintenance aspects. Therefore, findings of this research study support industry practitioners, policymakers, and project stakeholders in developing a more transparent and information driven construction practice.

Additionally, this study contributes to the growing body of knowledge on MP and circular construction. It provides context-specific insights for the Sri Lankan BE, which is currently underrepresented in existing MP research. On the other hand, these findings contribute to the theoretical development of an MP template by illustrating the importance of adapting internationally proposed models to suit local industry practices and conditions.

## 5. CONCLUSIONS

This study concludes that the development of MP is a valuable strategy for enhancing the representation of material information in the BE. MP enhances the efficiency of tracking and assessing material attributes by enabling clearer communication between stakeholders. Accordingly, this research highlights MP as a practical tool for a border information management system. To develop a standardized MP template suitable for the Sri Lankan context, this research identified key data requirements including building general information, product features, material composition, quality, and maintenance aspects. Due to its qualitative exploratory nature, with eight industry practitioners, the findings may not be generalizable to the entire Sri Lankan BE. Data collection, however, continued until saturation was reached, that is, no new substantial insights arose from further interviews, to ensure the reliability and depth of the findings within the scope of the study.

However, because end-of-life deconstruction and environmental impact data are currently lacking in local practice, it is recommended to leave these as descriptive open fields for the moment. Consequently, an intermediate guidance note should be provided to allow stakeholders to include whatever data they currently have regarding material circularity. Moreover, defining the current MP must be done very carefully because buildings have a long lifecycle and the same MP will be used many years later. Because of this, the structure of the other defined fields must also be carefully chosen for consistency in revisions for backward compatibility. Once environmental and deconstruction data become practical, revised versions of the MP can be issued with proper revision notes, while maintaining the other fields to ensure no data is lost over time. By structuring material data, MP supports evidence-based decision-making. This illustrates how a structured MP template can enable the effective assessment mechanisms by facilitating CE practices and enhancing sustainability outcomes. As a qualitative research study conducted with stakeholders in the BE, the findings may have limited generalizability. Based on the findings of this paper, further studies can adopt the development of a fully

operational MP template for the Sri Lankan BE and explore the integration of MPs with digital platforms such as Building Information Modelling to facilitate more effective material data management and support the transition towards a circular and digitally enabled BE in Sri Lanka.

# 6. REFERNCES


Ahmadi, L., Bilal, M., Olumo, A., Mollaei, A., Jalaei, F., Ebrahimi, N., Mozaffari, H., Kim, J., & Haas, C. (2026). Enhancing circularity in the building industry: A review of material passports and digital twin technologies. *Journal of Construction Engineering and Management*, *152*(2). https://doi.org/10.1061/JCEMD4.COENG-16899

Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. *Procedia CIRP*, *73*(2018), 45–49. https://doi.org/10.1016/j.procir.2018.04.027

Athapaththu, K. I., Karunasena, G., & Ekanayake, E. M. A. C. (2016). Sustainable construction practices of Sri Lankan contractors. *In Proceedings of the 5th World Construction Symposium* (pp. 1-9). http://dl.lib.mrt.ac.lk/handle/123/11992

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, *43*, 103233. https://doi.org/10.1016/j.jobe.2021.103233

Benachio, G. L. F., Freitas, M. do C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Blomsma, F., Bauwens, T., Weissbrod, I., & Kirchherr, J. (2023). The 'need for speed': Towards circular disruption—What it is, how to make it happen and how to know it's happening. *Business Strategy and the Environment*, *32*(3), 1010–1031. https://doi.org/10.1002/bse.3106

Braun, V., & Clarke, V. (2008). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Cagno, E., Neri, A., Negri, M., Bassani, C. A., Lampertico, T., & Carvalho, A. (2021). The role of digital technologies in operationalizing the circular economy transition: A systematic literature review. *Applied Sciences*, *11*(8), 3328. https://doi.org/10.3390/app11083328

Çetin, S., Gruis, V., & Straub, A. (2022a). Digitalization for a circular economy in the building industry: Multiple-case study of dutch social housing organizations. *Resources, Conservation & Recycling Advances*, *15*(2022), 200110. https://doi.org/10.1016/j.rcradv.2022.200110

Çetin, S., Gruis, V., & Straub, A. (2022b). *How Can Digital Technologies Support the Circular Transition of Social Housing Organizations? Empirical Evidence from Two Cases*. https://www.researchgate.net/publication/359602837

Çetin, S., Raghu, D., Honic, M., Straub, A., & Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Production and Consumption*, *40*(2023), 422–437. https://doi.org/10.1016/j.spc.2023.07.011

Chi, Z., Liu, Z., Wang, F., & Osmani, M. (2023). Driving circular economy through digital technologies: Current research status and future directions. *Sustainability*, *15*(24), 16608. https://doi.org/10.3390/su152416608

Creswell, J. W. (2017). *Research design: qualitative, quantitative, and mixed methods approaches*. SAGE. https://books.google.lk/books/about/Research_Design.html?id=KGNADwAAQBAJ&redir_esc=y

Ghanad, A. (2023). An overview of quantitative research methods. *International Journal of Multidisciplinary Research and Analysis*, *06*(08). https://doi.org/10.47191/ijmra/v6-i8-52

Göswein, V., Carvalho, S., Cerqueira, C., & Lorena, A. (2022). Circular material passports for buildings - Providing a robust methodology for promoting circular buildings. *IOP Conference Series: Earth and Environmental Science*, *1122*(1), 012049. https://doi.org/10.1088/1755-1315/1122/1/012049

Hernandez, J. (2024). Development of a roadmap for materials passport creation (Publication No. URN:NBN:fi:amk-2024051311359) [Master's thesis, Metropolia University of Applied Sciences]. Theseus. https://urn.fi/URN:NBN:fi:amk-2024051311359

Honic, M., Kovacic, I., Aschenbrenner, P., & Ragossnig, A. (2021). Material passports for the end-of-life stage of buildings: Challenges and potentials. *Journal of Cleaner Production*, *319*(2021), 128702. https://doi.org/10.1016/j.jclepro.2021.128702

Honic, M., Kovacic, I., & Rechberger, H. (2019). Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. *Journal of Cleaner Production*, *217*, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212

Jayawardane, J. M. P. M., Chathuranga, I. H. N., Siriwardana, C. S. A., & Shahzad, W. (2023). The integration of circular economy principles with BIM-enabled material passports for sustainable construction. In Proceedings of the 14th International Conference on Sustainable Built Environment 2023 (ICSBE 2023) (pp. 1162-1171).

KC, A., Senaratne, S., Perera, S., & Nanayakkara, S. (2025). Review of material passports and their application in industrialised construction: Enhancing material circularity in construction. *Sustainability*, *17*(12), 5661. https://doi.org/10.3390/su17125661

Lakshan, S. D. V., Wijekoon, W. M. C. L. K., & Buddhini, P. H. Y. (2025). Towards a circular economy: Evaluating effective implementation strategies for recycling and reuse programmes in Sri Lanka's construction industry. In Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (Eds). *The 13th World Construction Symposium 2025.* (pp. 1369–1383). Ceylon Institute of Builders (CIOB) Sri Lanka. https://doi.org/10.31705/WCS.2025.102

Lokuge, A., Anuradha Tennakoon, G., & Kulatunga, U. (2025). A review on circular economy and its synergy with industrial symbiosis. In Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (Eds). *The 13th World Construction Symposium 2025*. (pp. 56–68). Ceylon Institute of Builders (CIOB) Sri Lanka. https://doi.org/10.31705/WCS.2025.5

Markou, I., Sinnott, D., & Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. *Case Studies in Construction Materials*, *22*(2025). https://doi.org/10.1016/j.cscm.2025.e04267

Marsh, A. T. M., Velenturf, A. P. M., & Bernal, S. A. (2022). Circular economy strategies for concrete: implementation and integration. In *Journal of Cleaner Production*, *362*, 132486. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2022.132486

Munaro, M. R., Fischer, A. C., Azevedo, N. C., & Tavares, S. F. (2019). Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil. *IOP Conference Series: Earth and Environmental Science*, *225*(1), 012018. https://doi.org/10.1088/1755-1315/225/1/012018

Qazi, Z., Wuni, I. Y., & Akinkuowo, F. (2026). Material passports for circular economy in the construction industry: state-of-art-review. *International Journal of Construction Management*, 1–20. https://doi.org/10.1080/15623599.2026.2642423

Senarathne, H. N. Y., Weerasinghe, N. P., & Zhang, G. (2025). Developing a standardized materials passport framework to unlock the full circular potential in the construction industry. *Sustainability*, *17*(14), 6337. https://doi.org/10.3390/su17146337

Weerakoon, P., Thayaparan, M., & Siriwardena, M. (2023). Analyzing the contribution of green buildings towards circular economy in Sri Lanka. *International Conference on Industrial Engineering and Operations Management Manila, Philippines*. https://doi.org/10.31705/WCS.2023.14

Weerakoon, T. G., Wimalasena, S., & Zvirgzdins, J. (2023). Assessment of implementation of circular economy framework in the Sri Lankan construction sector. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1), 133–152. https://doi.org/10.2478/bjreecm-2023-0009

Bhattarai, A., Shiwakoti, R.K. and Uduwage, D.N.L.S., 2026. Deep learning-based flood mapping in monsoon climates using sentinel-1 sar. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 527-538. DOI: https://doi.org/10.31705/WCS.2026.39. Available from: https://ciobwcs.com/papers/

# DEEP LEARNING-BASED FLOOD MAPPING IN MONSOON CLIMATES USING SENTINEL-1 SAR

**Amit Bhattarai[1], Ranju Kumari Siwakoti[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Monsoon floods pose significant disaster management challenges due to persistent cloud cover, which renders optical remote sensing ineffective for rapid response. To overcome this limitation, this study proposes a computationally efficient, all-weather flood mapping framework that integrates Sentinel-1 Synthetic Aperture Radar (SAR) data with Height Above Nearest Drainage (HAND) topographic constraints within a deep learning pipeline. Three model architectures were compared systematically: a baseline U-Net, a U-Net with spatial augmentation (UNet_Aug), and a U-Net++ with Focal-Tversky loss (UNetPP_TMA). Bi-temporal Sentinel-1 scenes (VV and VH polarisations) from the 2024 Nawalpur flood event in Nepal were combined with a hydrologically corrected 30 m SRTM DEM, utilizing Sentinel-2 imagery and field data as high-fidelity ground truth. Models were trained using patch-based sampling to ensure computational efficiency. Quantitative results demonstrated that while UNet_Aug achieved the highest overall balance of metrics (IoU of 0.6101, F1-Score of 0.7578, Precision of 0.7496, and AUC-ROC of 0.9901), UNetPP_TMA achieved the highest recall of 0.7704. Overall, UNet_Aug is recommended as the most suitable operational model because it provided the best balance across IoU, F1-score, Kappa, accuracy, and AUC, while UNetPP_TMA remains useful as a high-recall option for safety-critical screening. This study contributes a reliable flood delineation approach for cloud-obscured monsoon conditions and provides an open-source pipeline and dataset that can serve as a reproducible benchmark for future disaster management in data-scarce regions.*

***Keywords:*** *Change Detection, Deep Learning, Flooding Mapping; Sentinel-1, Synthetic Aperture Radar (SAR).*

## 1. INTRODUCTION

Flooding is one of the most destructive natural hazards globally, causing severe financial losses and damage to critical infrastructure such as roads, houses, and schools (Amitrano et al., 2024). Nepal ranks tenth on the Global Climate Risk Index due to unpredictable weather, complex topography, and limited institutional resilience (World Bank, 2024). Hydro-meteorological events account for more than 80% of disasters in Nepal, and climate change has increased both their frequency and severity (Bhandari, 2025). Extreme

[1] Student, Department of Electronics and Computer Engineering, Institute of Engineering – Pulchowk Campus. Tribhuvan University, Nepal, 080msdsa003.amit@pcampus.edu.np
[2] Assistant Professor, Department of Electronics and Computer Engineering, Institute of Engineering – Pulchowk Campus. Tribhuvan University, Nepal, ranju.shiwakoti@ioe.edu.np
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

rainfall from September 26-28, 2024, triggered intense floods and landslides, marking the highest level since 1970. This intense rainfall resulted in the deaths of 250 individuals, 18 missing, and 178 injured. The destruction amounted to NPR 46 billion, affecting 302 telecommunication projects, 26 hydropower plants, 1,639 water supply systems, and 146 bridges (National Disaster Risk Reduction and Management Authority [NDRRMA], 2024). Rainfall exceeded 300 mm in different locations within Kathmandu Valley within three days, producing unprecedented levels of water. To reduce loss of life, infrastructure damage and enhance community resilience against increasingly extreme monsoon climates, accurate weather forecasting and robust early warning systems becomes beneficial.

Historically, flood monitoring primarily relied on in-situ methods, manual rain gauges and community-based watch and warn system (Macherera & Chimbari, 2016). In Nepal, local volunteers were utilised to monitor water level manually which only limited to lead of two to three hours (Budimir et al., 2020). These foundational systems have since evolved through advancements in satellite-based Earth Observation and automated telemetry, enabling real-time, broad-scale monitoring (Peng et al., 2025). While modern systems combine complex probabilistic forecasting, previous manual approaches established the essential framework for today's sophisticated disaster risk management (Budimir et al., 2020; Smith et al., 2017).

Flood monitoring has improved from early manual community gauge monitoring and simple hydrological models. Now it uses sophisticated satellite-based early warning systems (Smith et al., 2017; Revilla-Romero et al., 2014). HAND metrics are topography-based metrics highly effective for rapid prediction of flood inundation. HAND normalises the height of the terrain to the nearest drainage network using only digital elevation model, which allows the topography to be mapped efficiently (Nobre et al., 2011). Despite these technological innovations enhancing flood forecasting capabilities, Nepal's early warning systems continue to face major limitations, similar to those worldwide. These stem from weak government-wide strategies, lack of coordination, unclear institutional roles, and poor dissemination of alerts to vulnerable communities (Bhandari, 2025). Due to these persistent gaps and the urgent need for reliable, all-weather mapping during the cloud-prone monsoon season, this study compares baseline U-Net, UNet_Aug, and UNetPP_TMA using multi-temporal Sentinel-1 SAR imagery and HAND topographic guidance for Nepal’s conditions.

## 2. LITERATURE REVIEW

Flood detection in Nepal is currently a critical priority because of the increasing frequency of monsoon flooding, which continues to threaten agricultural stability, infrastructure, and livelihoods across the Terai lowlands and high-relief river basins (Bhandari, 2025; Kumar et al., 2026). Historically, flood detection was done manually or using simple automated thresholding, e.g. the Otsu method on SAR images. Nevertheless, these conventional methods were compromised by the phenomenon of surface confusion, when the shadow and wet soil resemble the water signature and the natural speckle noise of the SAR data (Amitrano et al., 2024; Pech-May et al., 2023). Subsequently, SAR has transitioned toward achieving rapid, all-weather situational awareness, overcoming the limitations of optical sensors (e.g., Sentinel-2 and Landsat), which are frequently rendered ineffective by persistent cloud cover during the peak monsoon (Kulk et al., 2023; Tarpanelli et al., 2022). Consequently, operational systems e.g. UNOSAT and

Sentinel Asia have increasingly prioritised SAR-based monitoring. These platforms provide essential rapid mappings; they exhibit systemic limitations in Nepal's environments. Specifically, they suffer from inaccuracies, due to complex terrain, vegetation, and a failure to incorporate hydrological constraints in the West Rapti basin (Poudel et al., 2025; United Nations Satellite Centre [UNOSAT], 2024).

Deep Learning (DL) has significantly advanced automated delineation, with architectures such as U-Net consistently outperforming thresholding methods by learning complex spatial hierarchies (Bentivoglio et al., 2022; Vongkusolkit et al., 2023). Regardless of these advantages, standard U-Net architectures often lack the multi-scale contextual understanding required to reliably distinguish transient floodwater from permanent water bodies in speckle-affected mountainous topography, leading to high false-positive rates (Huang et al., 2024). Recent studies have independently tested the HAND index and bi-temporal change detection to mitigate this limitation. However, a key gap remains: the comparative integration of bi-temporal SAR signals with HAND-based hydrological guidance in a single deep learning framework remains underexplored in the flood-mapping literature (Huang et al., 2024; Tupas et al., 2023).

Standard U-Net uses direct skip connections, but these can leave a semantic gap between encoder and decoder features and limit fine-scale spatial learning in flood segmentation (Zhou et al., 2018). U-Net++ reduces this gap through nested skip pathways, which improve feature refinement, boundary delineation, and discrimination between floodwater and spectrally similar dark surfaces such as terrain shadows and dense vegetation in noisy SAR imagery (Zhou et al., 2018; Melgar-García et al., 2023). For the class-imbalance problem common in flood mapping, Focal-Tversky loss gives more weight to hard-to-classify pixels and helps the model detect small, fragmented flood patches more effectively (Abraham & Khan, 2019). While recent cloud-based studies have started combining Sentinel-1 SAR and HAND topographic data for flood mapping, the comparative use of bi-temporal SAR signals with HAND-based hydrological guidance in complex monsoon settings remains underexplored (Tian et al., 2026; Tupas et al., 2023).

## 3. METHODOLOGY

This study compares baseline U-Net, UNet_Aug, and UNetPP_TMA using multi-temporal Sentinel-1 SAR imagery and the terrain-derived HAND index. By integrating bi-temporal change detection with hydrological conditioning, the flood mapping process have become faster and highly reliable.

This approach helps address common issues with SAR, such as speckle noise and spectral confusion. As a result, flood predictions stay consistent with the actual topography of the area (Huang et al., 2024; Tupas et al., 2023). This means flood mapping can be both computationally efficient and geophysical reliable. Figure 1 shows the entire workflow, covering complete workflow from data collection and preprocessing to model inference and performance evaluation.

To accurately capture the flooding and bi-temporal change detection, Sentinel-1 Synthetic Aperture Radar (SAR) images for the study area was used. The pre-flood image was captured on August 3, 2024, while the post-flood image was captured on October 2, 2024. These images helped to map surface water and identify temporary flood features.

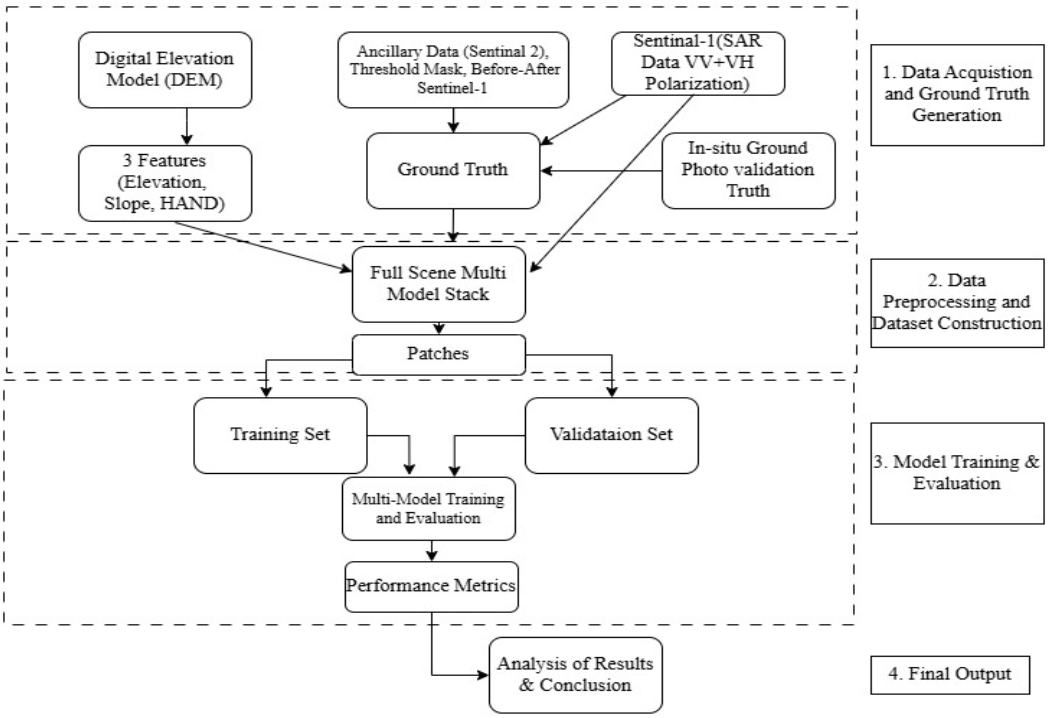



*Figure 1: Methodology of the proposed deep learning framework.*

The methodology to develop proposed model is illustrated in Figure 1, which outlines the comprehensive pipeline for disaster mapping using multi-source geospatial data. The methodology is structured into four distinct functional phases.

## 3.1 PHASE 1: DATA ACQUISITION AND GROUND TRUTH GENERATION

The flooded data collection area covers Nawalpur district of Nepal, with a focus on flood event. Multi-source data were integrated for model training and evaluation. Sentinel-1 SAR imagery (VV,VH polarisations) was acquired for pre- and post-flood dates. Sentinel-2 optical data, threshold masks, and bi-temporal SAR comparisons were fused to generate a ground mask. These masks were further refined using in-situ ground photographs to ensure high fidelity and representativeness of real-world flood conditions. Topographic data, including elevation, slope, and HAND indices, were derived from the NASADEM Digital Elevation Model using Google Earth Engine.

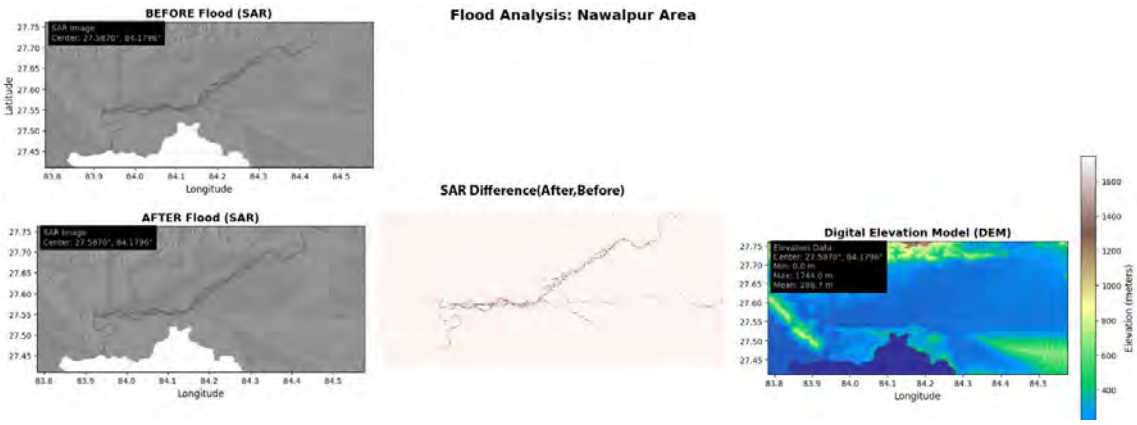



*Figure 2: Before flood, after flood, SAR difference and digital elevation model*

Figure 2 shows the study area before flood on dry season observed on July 16, 2024, of Nawalpur district, Nepal, from Sentinel-1. The post-flood image, acquired on 2nd October 2024, and pre-flood image were used to analyse surface changes on SAR Difference image. SAR imagery in VV and VH polarisations was utilised to detect changes in water extent, comparing conditions "before" and "after" the event. Digital Elevation Model (DEM) of the collected data shows elevation, slope and HAND with the goal of providing an environmental context of the Nawalpur region. The NASADEM elevation data was processed in Python with RichDEM and NumPy to compute the HAND index. Flow direction and accumulation rasters were first generated from the DEM, after which the nearest drainage network was extracted, and HAND was calculated as the vertical height of each cell above its downslope drainage path.

## 3.2 PHASE 2: DATA PREPROCESSING AND DATASET CONSTRUCTION

Raw Sentinel-1 data underwent standard preprocessing, including orbit file application, thermal noise removal, radiometric calibration to $\sigma^0$, terrain correction using the SRTM 30 m DEM, 5×5 refined Lee speckle filtering, and conversion to a decibel scale. Pre- and post-event SAR channels (VV, VH) were then combined with the normalised Height Above Nearest Drainage (HAND) index. Five channel input tensor was independently scaled between 0 and 1. A HAND threshold of 15 m was selected as a conservative, study-specific operational buffer caused by radar shadow and DEM uncertainty. Because HAND-derived flood extent is sensitive to local topography, DEM preprocessing, and drainage-network definition, the threshold was treated as a calibrated parameter rather than a universal cutoff.

Pre-processed full scene stack (3,910 × 8,851 pixels) and corresponding ground truth were divided into 128×128 pixel non overlapping 1500 patches of spatial tiles. Strict geographic split was used rather than randomly shuffling the patches to prevent spatial data leakage. Which is a critical issue in remote sensing where overlapping or adjacent patches artificially inflate validation metrics. The broader scene was spatially partitioned to ensure that training and validation patches were drawn completely distinct geographic blocks, preventing any boundary pixels from leaking across sets. The dataset was divided into 80/20 ratio, resulting in 1,200 independent training samples and 300 validation samples.

## 3.3 PHASE 3: MODEL TRAINING AND EVALUATION

Model development and training were done in Python using the TensorFlow framework to maintain computational efficiency. Deep learning model was trained on the patched dataset using the combined SAR and topographic features, where the attention mechanism focused on relevant spatial features while suppressing noise inherent in the raw Sentinel-1 data. For comparative evaluation, baseline U-Net, UNet_Aug, and UNetPP_TMA were benchmarked under identical training conditions. Following an 80/20 training and validation split, all three deep learning architectures were trained from scratch for exactly 50 epochs utilising a batch size of 16. Optimisation was performed using the Adam optimiser with an initial learning rate of 0.0001, which dynamically updated the network weights by minimising a combined binary cross-entropy and Dice loss function.

As illustrated in the third phase of Figure 1, three CNN models—baseline U-Net, UNet_Aug, and UNetPP_TMA—were implemented and compared:

1. Baseline U-Net which takes the five-channels as the input (before flood VV/VH, after flood VV/VH, and HAND).

2. U-Net with augmentation (UNet_Aug), which uses the same architecture as the baseline but trained using data augmentation, by random flips and 90-degree rotations.

3. U-Net++ with Focal-Tversky Loss (UNetPP_TMA), uses more complex U-Net++ architecture with dense skip connections to aggregate features. UNetPP_TMA uses focal-Tversky loss, which is determined by the formula: TFL= (1 - TI)^γ, where TI is Tversky Index), with α=0.7 (higher penalty on false positives to avoid over-prediction in imbalanced data), β=0.3 (lower on false negatives, as per Abraham & Khan, 2019, for small-target segmentation like floods), and γ=0.75 (equivalent to 3/4, focusing on hard examples by down weighting easy ones, as this non-linearity balances convergence without over-suppression, empirically optimal in original studies and variants for rare-class detection).

### 3.4 PHASE 4: ANALYSIS OF RESULTS AND CONCLUSION

The trained model generates flood inundation maps. Results are analysed through quantitative metrics. The quantitative assessment of the methodology, based on the final stage of Figure 1, is presented through precision, recall, and F1-score. Precision measures the reliability of positive predictions by measuring the proportion of correctly classified flooded pixels out of all pixels classified as flooded and how many are actually flooded out of all the pixels that are classified as flooded, as Precision = TP / (TP + FP), where TP and FP are the number of pixels correctly identified as flooded and the number of pixels incorrectly identified as flooded respectively.

Recall measures the completeness of the model in identifying actual flooded areas, which is Recall = TP / (TP + FN), where FN denotes false negatives and TP denotes true positive. Recall reduces errors of omission and ensures that the regions at risk of being flooded do not escape disaster management and monitoring. F1 score, a harmonic mean of the precision and recall measures, is a single-value measure of the classification performance which is more useful with class imbalance caused by the large number of non-flooded pixels in flood datasets. It is calculated with F1 = 2 (Precision * Recall)/ (Precision+ Recall). This measure is commonly cited in the deep learning flood segmentation literature as it combines both error types.

Additionally, Cohen's Kappa coefficient (κ) accounts for agreement beyond chance, formulated as $\kappa = (p_o - p_e) / (1 - p_e)$, where $p_o$ is the observed agreement and $p_e$ is the expected agreement by chance. The Area Under the Receiver Operating Characteristic Curve (ROC-AUC) evaluates threshold-independent performance by integrating the true positive rate against the false positive rate across classification thresholds, expressed as Area Under Curve.

## 4. RESULTS AND PERFORMANCE EVALUATION

Quantitative metrics, including IoU, F1-score, Precision, Recall, Cohen's Kappa, and AUC, were employed to comparatively evaluate three deep learning architectures: the baseline U-Net, U-Net with augmentation (UNet_Aug), and U-Net++ with Focal-Tversky loss (UNetPP_TMA).

*Table 1: Quantitative comparison of deep learning models for flood segmentation.*

| Model | IoU | F1-Score | Precision | Recall | Kappa | Overall Accuracy | AUC |
|---|---|---|---|---|---|---|---|
| Baseline U-Net | 0.5803 | 0.7344 | 0.7201 | 0.7493 | 0.7205 | 0.9736 | 0.9846 |
| UNet_Aug | **0.6101** | **0.7578** | **0.7496** | 0.7663 | **0.7453** | **0.9761** | **0.9901** |
| UNetPP_TMA | 0.5686 | 0.725 | 0.6846 | **0.7704** | 0.71 | 0.9715 | 0.9855 |

From Table 1, the UNet_Aug model achieved a IoU (0.6101), indicating better spatial overlap between the predicted and ground truth flood segments. In the context of semantic segmentation, IoU values within the 0.50–0.70 range are generally recognised as indicating moderate and practically useful performance. The model yielded a 3.2% increase in F1-Score over the baseline. Consistent with the data scarcity challenges outlined by Bentivoglio et al. (2022), these performance gains demonstrate that spatial augmentation effectively enhances model generalisation and robustness in complex SAR-based flood mapping. The UNet_Aug model effectively balanced Precision (0.7496) and Recall, resulting in the highest overall F1-Score and an AUC-ROC of 0.9901. This indicates excellent discriminative ability (>0.90 benchmark; Mandrekar, 2010).

Conversely, UNetPP_TMA achieved the highest Recall (0.7704), minimising omission errors, yet at a lower Precision (0.6846), increasing commission errors and reducing overall IoU and F1-Score. The Focal-Tversky Loss, with parameters $\alpha$=0.7 (penalising false negatives), $\beta$=0.3 (penalising false positives), and $\gamma$=0.75, effectively targeted the imbalanced flood class, however, compromised prediction purity (Abraham & Khan, 2019). UNet_Aug is the recommended overall model because it achieved the best balance of IoU, F1-score, precision, Kappa, overall accuracy, and AUC.

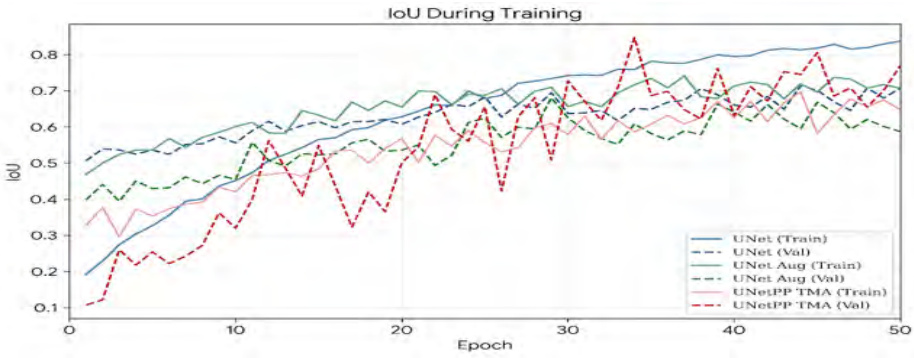



*Figure 3: Intersection over Union (IoU) of U-Net, Unet_Aug, and UnetPP_TMA*

Figure 3 illustrates the convergence of the Intersection over Union (IoU) across training epochs, representing the spatial overlap between predictions and ground truth. While the baseline U-Net displays a smooth learning curve, the UNet_Aug model demonstrates the most consistent and superior convergence, ultimately achieving the highest overall segmentation accuracy. UNetPP_TMA exhibits fluctuations in validation performance; however, it reaches competitive IoU levels in later epochs, indicating that despite initial training instability, it performs robustly by the end of the training cycle.

Figure 4 shows how precision changes over the training epochs for three models. For each model training and validation curve shows how often models are correct when it predicts a flood pixel. Higher curves show few false positive flood detections.

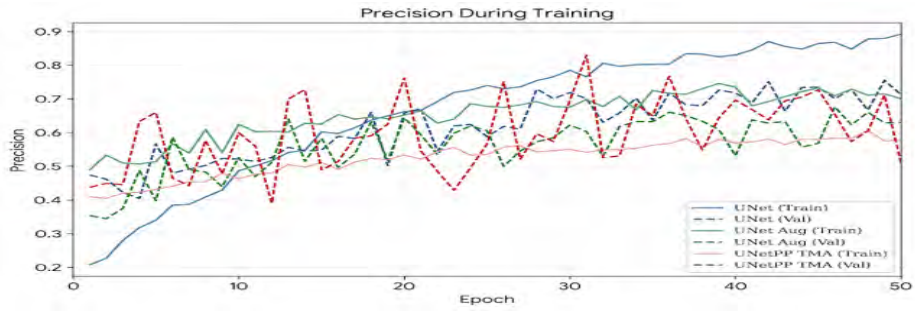



*Figure 4: Precision of U-Net, Unet_Aug, and UnetPP_TMA*

Solid lines are used for training precision, while dashed lines represent validation precision. Blue curves are for U-Net, green curves for UNet_Aug and then red curves are for UNetPP_TMA. The U-Net training curve rises steadily from a low starting point and reaches the highest final precision, which indicates the model is improving over time. UNet_Aug exhibits more consistent relationship between training and validation precision, which indicates improved generalisation and greater training stability. UNetPP_TMA displays stronger fluctuations in both curves, which shows less stable convergence. Overall, UNet_Aug shows balanced learning among the evaluated models.

All three models were able to distinguish temporary floodwater from permanent water bodies via bi-temporal change detection. Qualitative comparisons of the outputs with and without HAND integration (Figure 5) demonstrated that the topographical prior successfully eliminated implausible predictions. This effectively restricted flood extents to low-lying, drainage-adjacent areas, significantly improving physical realism for emergency response applications.

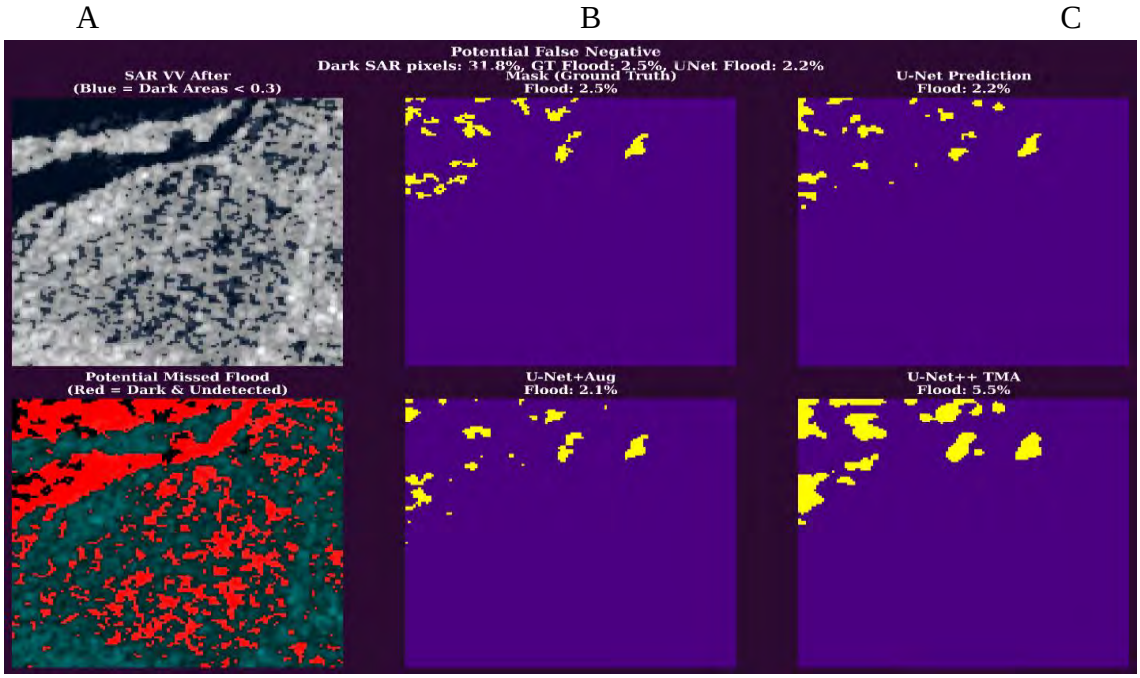



*Figure 5: Qualitative comparison of flood predictions with and without HAND-based hydrological mask.*

Figure 5 shows flood predictions from the evaluated models over a challenging patch that is prone to false negatives where HAND is used as topographic guidance. Figure 5(A) shows the post-event Sentinel-1 VV SAR image, where dark, low-backscatter areas is

less than 0.3 and cover approximately 31.8% of the pixels. The ground truth (Figure 5B) contains about 2.5% flooded pixel, the baseline U-Net (Figure 5C) contains about 2.2%, the augmented U-Net about 2.1% flooded pixel, and the UNetPP_TMA about 5.5%. Figure 5A contains extensive dark low-backscatter regions, which may represent floodwater, smooth surfaces, radar shadow, or speckle rather than flood. When compared with the ground truth, the baseline U-Net and UNet_Aug produce similar flood proportions, whereas UNetPP_TMA predicts a larger and more continuous flooded extent along drainage-connected areas. The comparison shows that HAND improves the physical realism of the predictions by constraining flood extent to low-lying terrain and reducing implausible detections outside hydrologically plausible zones.

This visual comparison confirms deep learning model was able to completely capture flood extents completely and realistically than the simple U-Net baselines. This result maps are physically consistent and well suited for emergency response.

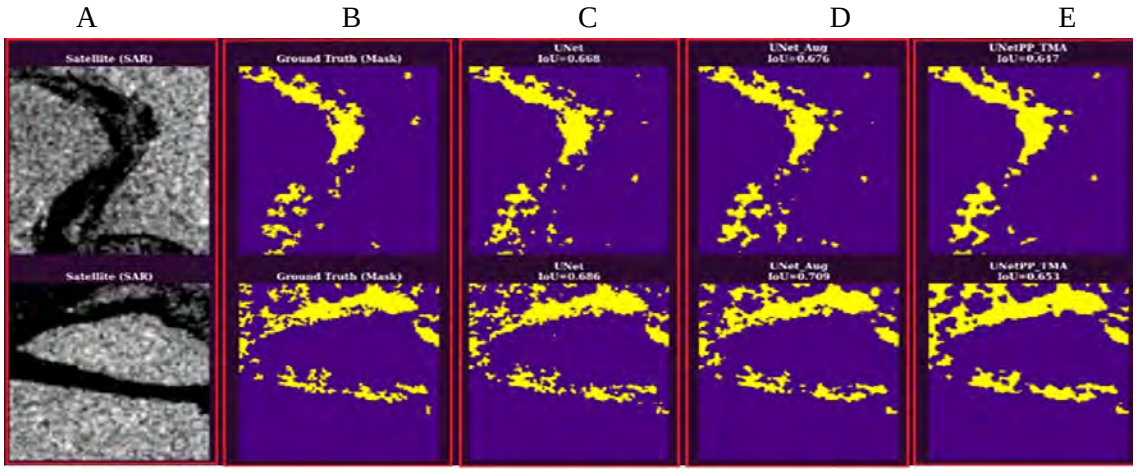



*Figure 6: Prediction of flood from 3 different model and satellite SAR image*

Figure 6 provides a visual comparison of the flood-extent predictions produced from three deep-learning models. The input SAR VV polarisation image and ground truth binary mask are shown in figures 6A and 6B, respectively. The base line model in Figure 6C tends to produce conservative flood estimation with fragmented flood patches. This might be due to limited sensitivity to subtle flood signal under SAR speckle noise. figure comprises multiple panels: input SAR VV-polarization imagery is shown in Figure 6(A), and the ground truth binary mask is shown in Figure 6B. These visualisations illustrate distinct qualitative differences in flood delineation. The simple baseline model (refer Figure 6C) often yields conservative estimates, characterised by smaller, fragmented yellow regions that may under-represent subtle inundated areas obscured by SAR speckle noise. The augmented model (refer Figure 6D) demonstrates moderate gains in generalisation and spatial extent which captures the strongest overall flood extent representation. This comparative evaluation highlights the proposed framework's ability to generate accurate, practical flood maps suitable for emergency response applications.

The bi-temporal Sentinel-1 SAR image combined with HAND in U-Net has been successfully applied to develop deep learning techniques for flood mapping in a monsoon climate. The Overall Accuracy of the UNet_Aug model was 0.9761, IoU was 0.6101 and F1-Score was 0.7578. In general, standard U-Net on complex SAR datasets without topographic constraints have IoU ranging from 0.35 to 0.48. The proposed framework

was able to tackle the complexity of the monsoon floods, by including spatial augmentation and hydrological conditioning, avoiding the large performance drop and high false-positive rate often seen in urban and topographically challenging environments (Bentivoglio et al., 2022). The model's competitive IoU is largely attributable to the successful removal of permanent water false positives via bi-temporal change detection. While these results are highly robust for complex terrains, future work could further improve boundary delineation by integrating finer-resolution Digital Elevation Models (DEMs) to reduce topographical backscatter errors, aiming for the high-resolution improvements demonstrated in advanced urban SAR fusion studies.

UNet_Aug emerges as the optimal model architecture for operational flood detection because it achieved the strongest overall performance. This framework, combining SAR robustness, hydrological physics, and efficient computation, advances reliable, all-weather flood mapping in data-scarce regions while maintaining computational practicality for real-time deployment.

## 5. CONCLUSIONS AND RECOMMENDATIONS

This study presents a robust, deep learning framework for operational flood detection in topographically complex monsoon regions, successfully validated using the 2024 Nawalpur flood event in Nepal. UNet_Aug achieved the highest overall balance of metrics (IoU = 0.6101, F1-score = 0.7578, precision = 0.7496, Kappa = 0.7453, overall accuracy = 0.9761, and AUC = 0.9901), while UNetPP_TMA achieved the highest recall (0.7704). In the context of emergency response, missing an active flood zone is unacceptable due to life-safety. Therefore, UNet_Aug emerges as the optimal operational model because it provides the strongest overall balance of flood-mapping performance.

This approach addresses critical gaps in current flood monitoring systems in disaster-prone regions. By prioritising sensitivity to inundated areas, the framework supports evidence-based emergency resource allocation, thereby enhancing regional resilience to increasing climatic hazards. This study recommends the operational deployment of UNet_Aug within Nepal’s flood early warning systems, while UNetPP_TMA may be retained as a high-recall alternative for emergency screening.

Future research should extend this framework by including DEMs from high resolution LiDAR and output from real-time hydrologic models to further enhance the topographic guidance over a variety of terrain types. Furthermore, combining multiple deep-learning architectures with uncertainty quantification techniques such as Bayesian inference would greatly improve the predictive accuracy of near-real-time operations. Finally, the scale expansion of the framework to other natural hazards, such as landslides and wildfires, and for future global SAR missions (e.g., NASA-ISRO Synthetic Aperture Radar) will help to foster broader adoption of this important tool in data-sparse developing contexts.

## 6. REFERENCES

Abraham, N., & Khan, N. M. (2019). A novel focal Tversky loss function with improved attention U-Net for lesion segmentation. In *2019 IEEE 16th International Symposium on Biomedical Imaging (ISBI 2019)* (pp. 683–687). IEEE. https://doi.org/10.1109/ISBI.2019.8759329

Amitrano, D., Di Martino, G., Iodice, A., Riccio, D., & Ruello, G. (2024). Flood detection with SAR: A review of techniques and datasets. *Remote Sensing, 16*(4), 656. https://doi.org/10.3390/rs16040656

Bentivoglio, R., Isufi, E., Jonkman, S. N., & Taormina, R. (2022). Deep learning methods for flood mapping: A review of existing applications and future research directions. *Hydrology and Earth System Sciences*, *26*(16), 4345–4378. https://doi.org/10.5194/hess-26-4345-2022

Bhandari, D. (2025). Challenges and opportunities in Nepal's early warning communication. *International Journal of Disaster Risk Reduction*, *119*, 105318. https://doi.org/10.1016/j.ijdrr.2025.105318

Budimir, M., Donovan, A., Brown, S., Shakya, P., Gautam, D., Uprety, M., Cranston, M., Sneddon, A., Smith, P., & Dugar, S. (2020). Communicating complex forecasts: An analysis of the approach in Nepal's flood early warning system. *Geoscience Communication*, *3*(1), 49–70. https://doi.org/10.5194/gc-3-49-2020

Dantas, A. A. R., & Paz, A. R. (2021). Use of HAND terrain descriptor for estimating flood-prone areas in river basins. *Revista Brasileira de Ciências Ambientais*, *56(3)*, 501–516. https://doi.org/10.5327/z21769478892

Huang, B., Li, P., Lu, H., Yin, J., Li, Z., & Wang, H. (2024). WaterDetectionNet: A new deep learning method for flood mapping with SAR image convolutional neural network. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *17*, 14471–14485. https://doi.org/10.1109/JSTARS.2024.3440995

Kumar, A., Pandey, G., & Kale, R. V. (2026). Ensemble machine learning and deep learning framework for flood susceptibility mapping in the transboundary Rapti River Basin. *Environmental Earth Sciences*, *85*, 168. https://doi.org/10.1007/s12665-026-12912-6

Macherera, M., & Chimbari, M. J. (2016). A review of studies on community based early warning systems. *Jàmbá: Journal of Disaster Risk Studies*, *8*(1), a206. https://doi.org/10.4102/jamba.v8i1.206

Mandrekar, J. N. (2010). Receiver operating characteristic curve in diagnostic test assessment. *Journal of Thoracic Oncology*, *5*(9), 1315–1316. https://doi.org/10.1097/JTO.0b013e3181ec173d

Melgar-García, L., Martínez-Álvarez, F., Tien Bui, D., & Troncoso, A. (2023). A novel semantic segmentation approach based on U-Net, WU-Net, and U-Net++ deep learning for predicting areas sensitive to pluvial flood at tropical area. *International Journal of Digital Earth*, *16*(1), 3661–3679. https://doi.org/10.1080/17538947.2023.2252401

National Disaster Risk Reduction and Management Authority. (2024). *Nepal: 2024 September floods and landslides situation report #4 as of 16 October 2024*. ReliefWeb. https://reliefweb.int/report/nepal/nepal-2024-september-floods-and-landslides-situation-report-4-16-october-2024

Nobre, A. D., Cuartas, L. A., Hodnett, M., Rennó, C. D., Rodrigues, G., Silveira, A., Waterloo, M., & Saleska, S. (2011). Height above the nearest drainage – a hydrologically relevant new terrain model. *Journal of Hydrology*, *404*(1-2), 13–29. https://doi.org/10.1016/j.jhydrol.2011.03.051

Pech-May, F., Aquino-Santos, R., & Delgadillo-Partida, J. (2023). Sentinel-1 SAR images and deep learning for water body mapping. *Remote Sensing*, *15*(12), 3009. https://doi.org/10.3390/rs15123009

Peng, X., Chen, S., Miao, Z., Xu, Y., Ye, M., & Lu, P. (2025). Automatic flood monitoring method with SAR and optical data using Google Earth Engine. *Water*, *17*(2), 177. https://doi.org/10.3390/w17020177

Poudel, P., Pokhrel, P., & Thapa, S. (2025). Hazard modeling using Sentinel data for risk assessment and management of Tsho Rolpa Glacier, Nepal. In *Proceedings of the International Conference on Remote Sensing* (pp. 1–8). SCITEPRESS. https://www.scitepress.org/Papers/2025/132887/132887.pdf

Revilla-Romero, B., Thielen, J., Salamon, P., De Groeve, T., & Brakenridge, G. R. (2014). Evaluation of the satellite-based global flood detection system for measuring river discharge: Influence of local factors. *Hydrology and Earth System Sciences*, *18*(11), 4467–4484. https://doi.org/10.5194/hess-18-4467-2014

Smith, P. J., Brown, S., & Dugar, S. (2017). Community-based early warning systems for flood risk mitigation in Nepal. *Natural Hazards and Earth System Sciences*, *17*(3), 423–437. https://doi.org/10.5194/nhess-17-423-2017

Tarpanelli, A., Mondini, A. C., & Camici, S. (2022). Effectiveness of Sentinel-1 and Sentinel-2 for flood detection assessment in Europe. *Natural Hazards and Earth System Sciences*, *22*(8), 2473–2489. https://doi.org/10.5194/nhess-22-2473-2022

Thomas, J., Mohan, S., Mallik, S., Oommen, T., Xue, P., Meadows, G., Thalakkottukara, N. T., & Williams, R. (2025). Development of a HAND-based flood risk assessment tool in Google Earth Engine for a data-scarce region in the US. *Journal of Great Lakes Research*, 102510. https://doi.org/10.1016/j.jglr.2025.102510

Tian, D., Wang, L., Liu, H., Cohen, S., & Shu, S. (2026). DeepSAR Flood Mapper: global flood mapping on Google Earth Engine cloud platform using MLP deep learning model with Sentinel-1 SAR imagery and HAND topographic data. *GIScience & Remote Sensing*, *63*(1), Article 2612306. https://doi.org/10.1080/15481603.2025.2612306

Tupas, M. E., Roth, F., Bauer-Marschallinger, B., & Wagner, W. (2023). Improving Sentinel-1 flood maps using a topographic index as prior in Bayesian inference. *Water*, *15*(23), 4034. https://doi.org/10.3390/w15234034

United Nations Satellite Centre (UNOSAT). (2024, October 2). *Satellite detected water extent Koshi and Madhesh Provinces, Nepal as of 01 October 2024*. United Nations. https://unosat.org/products/3990

Vongkusolkit, J., Peng, B., Wu, M., Huang, Q., & Andresen, C. G. (2023). Near real-time flood mapping with weakly supervised machine learning. *Remote Sensing*, *15*(13), 3263. https://doi.org/10.3390/rs15133263

World Bank. (2024). *Nepal disaster resilience second DPC with Cat DDO (NDRC): Annex - Climate change technical note*. World Bank Group. https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/099511210252413915

Zhou, Z., Rahman Siddiquee, M. M., Tajbakhsh, N., & Liang, J. (2018). UNet++: A nested U-Net architecture for medical image segmentation. In D. Stoyanov, Z. Taylor, B. Kainz, G. Zheng, R. R. Shamir, V. Diaz-Pinto, P. A. Cook, Y. Hu, S. Khan, T. Arbel, M. Blaschko, G. Carneiro, & D. Samaras (Eds.), *Deep learning in medical image analysis and multimodal learning for clinical decision support* (Lecture Notes in Computer Science, Vol. 11045, pp. 3–11). Springer. https://doi.org/10.1007/978-3-030-00889-5_1

Anil, N.A. and Prabhu, P., 2026. Development of a blockchain-enabled smart contract framework for linear construction projects. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 539-551. DOI: https://doi.org/10.31705/WCS.2026.40. Available from: https://ciobwcs.com/papers/

# DEVELOPMENT OF A BLOCKCHAIN-ENABLED SMART CONTRACT FRAMEWORK FOR LINEAR CONSTRUCTION PROJECTS

**Nair Aswaty Anil[1] and P. Prabhu[2]**

## *ABSTRACT*

*Large-scale linear infrastructure projects such as high-speed rail corridors, metro systems, highways, and pipelines face major challenges in coordination, communication, material tracking, approval processes, and payment management due to their geographically distributed nature and involvement of multiple stakeholders. Conventional digital tools improve planning and monitoring but often fail to provide secure, transparent, and automated coordination across distributed project work fronts. Blockchain technology and smart contracts offer a decentralized and transparent solution for improving workflow synchronization, payment automation, material traceability, and progress verification in such projects. This paper introduces a blockchain-based smart contract implementation framework specifically designed for linear construction projects. The proposed framework deliberately avoids reliance on Building Information Modelling (BIM) and instead utilises chainage-based scheduling, integrated digital quantity and test records, and IoT/RFID-enabled logistics tracking. It adopts a seven-layer framework that segregates functions such as physical data capture, scheduling, quantity management, smart contract logic, blockchain infrastructure, user interfaces, and governance. The framework defines a segment-oriented workflow covering progress certification, material traceability, interface coordination across civil sub-zones and functional areas, and automated retention release. A schematic flowchart illustrates the end-to-end data and control sequence for a typical corridor segment. The paper further examines expected benefits—enhanced transparency, faster payment cycles, improved traceability, and better interface control—alongside key challenges in implementation, interoperability, scalability, and integration with existing construction management practises.*

***Keywords:*** *Blockchain; Linear Infrastructure; Productivity Improvement; Smart Contracts; Supply Chain.*

## 1. INTRODUCTION

Linear construction projects represent some of the most complex forms of infrastructure development due to their geographically distributed nature, repetitive construction processes, and involvement of numerous stakeholders operating simultaneously across extended corridors. Projects such as high-speed rail systems, highways, pipelines,

[1] Post Graduate Student, Department of Civil Engineering, National Institute of Technology (NIT), Tiruchirappalli, Tamil Nadu, India, aswathy.kure@gmail.com
[2] Assistant Professor, Department of Civil Engineering, National Institute of Technology (NIT), Tiruchirappalli, Tamil Nadu, India, prabu@nitt.edu

transmission corridors, and metro viaducts require continuous coordination between contractors, suppliers, consultants, subcontractors, and project authorities over long distances and multiple work fronts.

Despite advancements in project planning and construction technologies, contract administration in linear infrastructure projects continues to rely heavily on manual documentation, fragmented communication systems, and conventional approval mechanisms. Progress verification, quantity certification, material tracking, interface coordination, and payment approvals are often handled through disconnected workflows, resulting in delays, information inconsistencies, administrative inefficiencies, and contractual disputes (Ye et al., 2022; Gupta & Jha, 2024).

The complexity of these projects increases further due to repetitive segment-based construction activities that are distributed along the alignment. Activities such as pier construction, girder erection, segment installation, pavement works, utility integration, and station or depot construction frequently occur simultaneously across multiple chainages. Coordinating these activities while maintaining accurate progress records, ensuring supply chain visibility, and processing milestone-based payments presents considerable operational and contractual challenges.

Traditional contract administration systems are often inadequate for managing such large-scale distributed operations efficiently. Delays in progress certification and payment approvals can disrupt cash flow throughout the supply chain, while poor visibility over material movement and interface dependencies can lead to disputes, schedule overruns, and productivity losses. Furthermore, fragmented project documentation limits transparency and makes auditing and claims resolution more difficult (Elghaish et al., 2020).

In recent years, blockchain technology and smart contracts have emerged as promising tools for improving transparency, traceability, and automation in construction project management (Hu et al., 2020; Lima et al., 2023). Blockchain provides a decentralised and tamper-resistant ledger capable of securely recording project events, transactions, approvals, and contractual activities. Smart contracts extend this capability by enabling automated execution of predefined contractual conditions once specified criteria are satisfied (Bottoni et al., 2020; Alhanaee & Alhanaee, 2021).

Several studies have explored the integration of blockchain and smart contracts within construction management systems, particularly for payment automation, supply chain traceability, and project governance (Hamledari & Fischer, 2021; Elsharkawi et al., 2025; Song et al., 2023). Research has demonstrated the potential of blockchain-enabled systems in integrated project delivery and governance models through automated financial workflows and decentralised coordination mechanisms (Elghaish et al., 2020; Hunhevicz et al., 2022). However, many existing frameworks depend extensively on Building Information Modelling (BIM) environments and are primarily focused on building projects rather than geographically distributed linear infrastructure systems (Kamel et al., 2023). Limited research has addressed how smart contracts can be implemented effectively in long linear projects characterised by chainage-based workflows, repetitive production cycles, distributed logistics operations, and multiple functional interfaces (Ye et al., 2022, Luo et al. 2019,).

This paper addresses this gap by proposing a blockchain-enabled smart contract implementation framework specifically tailored for linear construction projects. The

framework adopts a BIM-independent approach and instead utilises chainage-based scheduling systems, digital quantity records, logistics tracking technologies, and structured workflow automation to facilitate contract administration and project coordination. The proposed model aims to improve transparency, reduce administrative delays, automate milestone-based payments, strengthen supply chain visibility, and provide a reliable digital audit trail across distributed project environments (Hamledari & Fischer, 2021; Gupta & Jha, 2024).

Accordingly, the primary aim of this study is to develop a blockchain-enabled smart contract implementation framework for improving contract administration, workflow coordination, and information management in linear construction projects. To achieve this aim, the study first investigates the major contract administration, communication, and coordination challenges commonly encountered in large-scale linear infrastructure projects. A comprehensive review of existing literature on blockchain technology and smart contract applications in construction management is then undertaken to identify current developments, implementation approaches, and research gaps. Based on these findings, a BIM-independent smart contract framework is developed by integrating chainage-based scheduling, digital quantity records, logistics tracking mechanisms, and oracle-based verification systems capable of validating field events and project progress. Building upon these components, the study proposes a seven-layer implementation framework designed to automate progress verification, payment processing, supply chain traceability, and interface management within linear construction environments. Through this framework, the research seeks to establish a structured and scalable approach for enhancing transparency, accountability, and operational efficiency in the administration of complex linear infrastructure projects.

## 2. LITERATURE REVIEW

Research increasingly explores blockchain and smart contracts in construction to address payment delays, supply chain fragmentation, and contract inefficiencies through automated milestone payments and immutable records. While early work focused on payment automation and BIM integration, recent studies examine supply chain traceability and linear infrastructure applications.

### 2.1 BLOCKCHAIN AND SMART CONTRACTS FOR CONSTRUCTION PAYMENTS

A group of papers investigates blockchain as an enabler of transparent, traceable, and tamper-resistant construction supply chains. These studies argue that fragmented information and low visibility over material flows create opportunities for fraud, quality problems, and coordination failures in complex projects, and they propose blockchain ledgers to record procurement, shipment, delivery, and payment events end-to-end (Bottoni et al., 2020; Hu et al., 2020; Gupta & Jha, 2024). Proposed frameworks typically combine smart contracts with digital documentation and tracking to ensure that only compliant, properly documented deliveries are accepted and paid, improving auditability and trust among stakeholders (Kamel et al., 2023; Hamledari & Fischer, 2021). Case applications in public works suggest benefits in terms of traceability and stakeholder confidence yet remain at a relatively high level in terms of process detail (Elghaish et al., 2020; Ye et al., 2022; Hunhevicz et al., 2022). Importantly, they seldom consider the specific logistics patterns and chainage-based material flows characteristic of large high-speed rail viaduct and segmental construction (Song et al., 2023; Lima et al., 2023).

## 2.2 SMART-CONTRACT FRAMEWORKS WITH BIM AND INDUSTRY 4.0 TECHNOLOGIES

A category of research develops integrated frameworks that embed smart contracts within broader digital ecosystems built around BIM, IoT, and other Industry 4.0 tools. In these models, BIM is usually treated as the central data environment, with 3D/4D models generating verified quantities and progress states that feed directly into blockchain-based smart contracts for payment or performance management (Kamel et al., 2023; Hamledari & Fischer, 2021). Additional work explores linking smart contracts to sensor networks, computer vision, and automated data capture to enable near real-time verification of work completion and quality before contractual actions are triggered (Hamledari & Fischer, 2021; Elsharkawi et al., 2025). Systematic reviews in this area highlight the potential of such integrated frameworks to improve coordination, reduce disputes, and provide a single source of truth for project information across the asset lifecycle (Ye et al., 2022; Gupta & Jha, 2024; Hu et al., 2020). However, their dependence on mature BIM implementations and tightly integrated digital platforms limits direct applicability in contexts where administration is primarily schedule- and quantity-driven and BIM is not fully deployed.

## 2.3 BLOCKCHAIN IN LINEAR AND INFRASTRUCTURE PROJECTS

A smaller yet increasingly relevant body of literature targets blockchain applications in infrastructure and linear projects such as highways, railways, and pipelines. These studies situate blockchain within the broader "Construction 4.0" agenda for linear assets, emphasising its potential to support distributed work fronts, long supply chains, and multi-stakeholder governance over extended corridors (Lima et al., 2023; Bottoni et al., 2020). Conceptual frameworks and pilots in transport infrastructure show how smart contracts can formalise milestone-based payments, concession obligations, and interface management between public and private actors, with all key events recorded on a shared ledger (Elghaish et al., 2020; Gupta & Jha, 2024). Some authors also note that repetitive, segment-based production processes in linear works are particularly suitable for codified smart-contract rules and standardised data flows (Hamledari & Fischer, 2021; Kamel et al., 2023). Nevertheless, existing studies rarely drill down to the level of a single, very long EPC package with detailed chainage-based segmentation, precast logistics, and segment-wise retention and defects management.

## 2.4 BLOCKCHAIN FOR CONTRACT GOVERNANCE AND DISPUTE REDUCTION IN CONSTRUCTION

Another stream of research examines blockchain as a mechanism for improving contractual governance, transparency, and dispute reduction in construction projects. Traditional contract administration in construction is often document-intensive and affected by information asymmetry, delayed certifications, and disagreements over progress verification, which frequently lead to disputes and payment conflicts. Blockchain-based systems have therefore been proposed as shared digital environments where contractual events, approvals, and performance records are stored in immutable ledgers, creating verifiable audit trails and improving trust among project stakeholders (Hunhevicz et al., 2022; Ye et al., 2022). Within such frameworks, smart contracts can encode contractual rules, verification procedures, and payment triggers hence actions such as work certification, documentation validation, and milestone-based payments are

executed automatically once predefined conditions are satisfied (Hamledari & Fischer, 2021; Kamel et al., 2023). These approaches are expected to reduce administrative delays, enhance transparency, and minimise disputes arising from unclear documentation or delayed approvals in complex projects involving multiple stakeholders and subcontractors (Gupta & Jha, 2024).

### 2.5 BLOCKCHAIN FOR CONSTRUCTION SUPPLY CHAIN AND MATERIAL TRACEABILITY MANAGEMENT

Construction projects involve extensive supply chains comprising material suppliers, manufacturers, transporters, subcontractors, and project owners. The fragmented nature of these supply chains often results in limited visibility, inefficient information sharing, material delays, and difficulties in verifying the provenance and quality of construction materials. To address these challenges, several studies have proposed blockchain-based supply chain management systems that provide secure, transparent, and immutable records of material transactions throughout the project lifecycle (Bottoni et al., 2020; Hu et al., 2020). Within these systems, blockchain ledgers are used to record procurement orders, manufacturing data, shipment events, delivery confirmations, and quality certifications, creating an auditable chain of custody for construction materials (Song et al., 2023).

Researchers have further explored the integration of smart contracts with supply chain operations to automate material acceptance procedures, inventory management, and supplier payments based on predefined delivery and quality conditions (Hamledari & Fischer, 2021; Kamel et al., 2023). Emerging studies combining blockchain with IoT technologies demonstrate how sensors, RFID tags, and GPS-enabled tracking devices can provide real-time information on material location, condition, and transportation status, thereby improving supply chain visibility and reducing risks associated with delays, losses, and counterfeit materials (Elsharkawi et al., 2025; Gupta & Jha, 2024). While these studies establish the potential of blockchain-enabled material traceability, most focus on general building construction or conceptual supply chain frameworks. Limited attention has been given to highly repetitive and geographically distributed linear infrastructure projects, where thousands of precast components must be tracked across production yards, transportation networks, and chainage-based installation locations. This gap highlights the need for dedicated blockchain frameworks tailored to segment-wise logistics and material traceability requirements in large-scale high-speed rail construction projects (Lima et al., 2023; Ye et al., 2022).

## 3. RESEARCH METHODOLOGY

This study adopts a conceptual framework development methodology to design a blockchain-enabled smart contract implementation framework for linear construction projects. The methodology was structured in four stages: literature review, problem identification, process analysis, and framework development.

### 3.1 LITERATURE REVIEW

A comprehensive review of existing literature related to blockchain technology, smart contracts, Construction 4.0, contract administration, payment automation, supply chain management, and infrastructure project governance was conducted. Research papers, journal articles, conference proceedings, and technical studies focusing on construction

blockchain applications were analysed to identify current developments, benefits, limitations, and implementation approaches. Particular attention was given to studies related to smart contract-based payment systems, BIM-integrated blockchain frameworks, logistics traceability systems, and governance mechanisms in construction projects.

The literature review helped identify key research gaps, particularly the limited focus on geographically distributed linear infrastructure projects and the overdependence of many existing frameworks on BIM environments. Existing studies were further analysed to understand the use of oracle systems, IoT technologies, RFID/GPS tracking, digital quantity verification, and automated milestone certification mechanisms.

## 3.2 ANALYSIS OF LINEAR CONSTRUCTION PROJECT CHARACTERISTICS AND CHALLENGES

The operational characteristics of large-scale linear infrastructure projects were analysed to identify challenges that distinguish them from conventional building projects. This analysis focused on geographically distributed work fronts, chainage-based project segmentation, repetitive construction activities, complex stakeholder interactions, precast component logistics, interface management, milestone-based payment structures, and fragmented information flows. The identified challenges were mapped against limitations observed in traditional contract administration practices and existing digital project management approaches. This stage established the practical problem context that the proposed framework seeks to address.

## 3.3 PROCESS MAPPING AND FUNCTIONAL REQUIREMENT IDENTIFICATION

A detailed examination of typical project workflows was undertaken to understand the flow of information and contractual actions across various project stakeholders. Key processes analysed included progress reporting, quantity verification, inspection and approval procedures, material delivery tracking, payment certification, retention management, and dispute-related documentation.

Based on this workflow analysis, the study identified critical system requirements necessary for a blockchain-enabled environment. These requirements included secure and immutable data recording, automated milestone verification, transparent audit trails, role-based access control, logistics traceability, interoperability with external data sources, and automated execution of contractual obligations through smart contracts.

## 3.4 FRAMEWORK DESIGN AND DEVELOPMENT

The proposed seven-layer smart contract framework was developed through the synthesis of findings obtained from the literature review and process analysis stages. A layered architectural approach was adopted to organise the system into distinct functional components while maintaining interoperability and scalability. Each layer was assigned specific responsibilities relating to data generation, verification, integration, contract execution, blockchain recording, stakeholder interaction, and governance oversight.

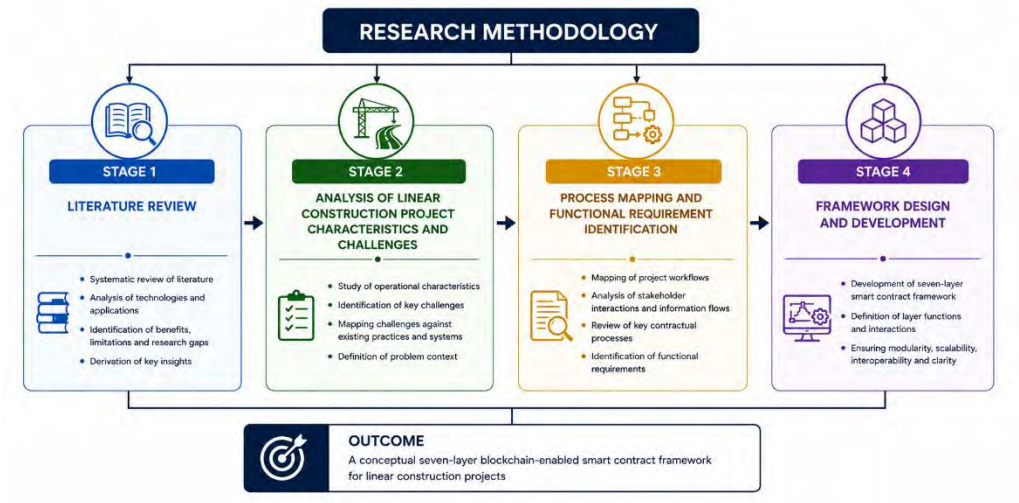



*Figure 1: Methodology flowchart*

The layered framework facilitates modular implementation while ensuring transparency, traceability, and automation across project workflows.

# 4. CHARACTERISTICS AND CHALLENGES OF LINEAR CONSTRUCTION PROJECTS

## 4.1 CHARACTERISTICS OF LINEAR INFRASTRUCTURE PROJECTS

Linear construction projects are distinguished by their elongated geographical alignment and repetitive construction processes. Unlike conventional building projects that are concentrated within a single site boundary, linear projects extend across large distances and involve multiple simultaneous work fronts (Ye et al., 2022).

Typical linear infrastructure projects include high-speed rail corridors, highways, metro viaducts, pipelines, canals, and transmission networks. These projects commonly involve repetitive structural components such as spans, piers, pavement sections, utility segments, or track systems distributed continuously along the alignment.

Construction activities are usually segmented based on chainage or location references, enabling planners to divide the project into manageable sections for scheduling, execution, monitoring, and payment administration. Due to their scale and distributed nature, these projects depend heavily on coordinated logistics systems for transporting materials, equipment, and prefabricated components across different work zones (Song et al., 2023; Bottoni et al., 2020).

## 4.2 CONTRACT ADMINISTRATION COMPLEXITY

The distributed nature of linear projects creates significant challenges in contract administration and project coordination. Progress measurement and verification must be performed across numerous locations simultaneously while ensuring consistency in quantity records and milestone certification (Ye et al., 2022; Gupta & Jha, 2024).

Material logistics management is another major challenge, particularly in projects involving precast or modular construction methods. Tracking the production, transportation, storage, and installation of structural components across long corridors

requires accurate and reliable information systems (Song et al., 2023; Bottoni et al., 2020). Interface management also becomes increasingly complex due to dependencies between multiple contractors, subcontractors, utility agencies, and functional zones. Delays in one segment or interface location can affect downstream activities and disrupt overall project schedules. Traditional manual workflows for approvals, inspections, documentation, and payment certification often result in administrative bottlenecks, reduced transparency, and delayed decision-making. These inefficiencies increase the likelihood of disputes related to progress verification, quantity measurement, payment claims, and responsibility allocation (Elghaish et al., 2020; Hunhevicz et al., 2022).

The limitations of existing contract administration systems highlight the need for digital frameworks capable of supporting distributed project environments while improving transparency, automation, and information reliability (Hamledari & Fischer, 2021; Lima et al., 2023).

# 5. SMART CONTRACT FRAMEOWRK FOR LINEAR CONSTRUCTION PROJECTS

The proposed framework introduces a blockchain-enabled smart contract system specifically designed for the operational and contractual requirements of linear construction projects. The framework focuses on automating chainage-based workflows, improving supply chain visibility, and enabling secure digital contract administration through blockchain technology.

Unlike BIM-dependent frameworks, the proposed model relies on schedule-based and quantity-based workflows supported by digital records, IoT devices, RFID systems, GPS tracking, and blockchain-enabled smart contracts. The framework transforms validated field data into automated contractual events, enabling milestone certification, payment processing, and interface coordination within a secure and transparent digital environment.

## 5.1 DESIGN PRINCIPLES

### Chainage-Based Segmentation

The framework organizes project activities based on chainage-oriented segments or location-based work packages. Each segment functions as an independent unit for tracking progress, quantities, milestones, approvals, and payments.

### BIM-Independent Data Integration

The proposed framework avoids dependence on BIM systems and instead utilizes digital schedules, measurement records, logistics data, inspection reports, and testing documentation as the primary sources for smart contract execution.

### Role-Based Access and Responsibilities

Different project stakeholders are assigned defined digital roles and permissions. Contractors, consultants, suppliers, subcontractors, and project authorities interact with the system according to predefined responsibilities for data submission, approvals, and contract execution.

**Layered System Architecture**

The framework adopts a layered architecture that separates physical data collection, validation processes, smart contract execution, blockchain infrastructure, and governance functions. This modular approach improves scalability, interoperability, and system adaptability.

## 5.2 SEVEN-LAYER FRAMEWORK

**Layer 1 – Physical Works and Data Acquisition**

This layer includes physical construction activities and all associated field-level data collection systems. Data sources may include IoT sensors, GPS-enabled equipment tracking, RFID tagged materials, digital inspection records, testing reports, mobile applications, and site measurement systems.

The objective of this layer is to continuously capture time-stamped and location-referenced information regarding construction progress, material movement, equipment usage, inspections, and quality verification.

**Layer 2 – Schedule, Quantity, and Chainage Management**

This layer manages project schedules, quantity records, milestone definitions, and chainage-oriented activity mapping. Planning systems such as Primavera or MS Project can be integrated with digital quantity measurement systems and bill-of-quantities databases.

Each project segment is linked to planned activities, target quantities, completion criteria, and payment milestones.

**Layer 3 – Integration and Oracle Layer**

The oracle layer acts as an intermediary between external project management systems and the blockchain network. It validates schedule data, inspection results, quantity records, and logistics information against predefined rules.

Once all contractual conditions are satisfied, the oracle generates verified milestone events and submits them to the blockchain network for smart contract execution.

**Layer 4 – Smart Contract Layer**

This layer contains the programmable smart contracts responsible for automating contractual workflows.

The framework includes multiple categories of smart contracts:

Progress verification smart contracts for milestone certification and payment calculation.

Supply chain smart contracts for tracking material movement and automating supplier payments.

Interface management smart contracts for documenting interdependent work handovers.

Retention and defects liability smart contracts for managing post-completion obligations.

These smart contracts execute automatically once predefined verification conditions are met.

**Layer 5 – Blockchain and Network Layer**

This layer consists of a permissioned blockchain network operated by project stakeholders. The blockchain stores smart contract logic, milestone events, approvals, and payment records within a tamper-resistant distributed ledger.

Detailed project documents may remain off-chain while their digital hashes are stored on-chain to ensure integrity verification.

**Layer 6 – Application and User Interface Layer**

This layer provides dashboards and digital interfaces for stakeholders to monitor project status, approvals, payment events, supply chain activities, and interface coordination.

The interfaces enable users to access project information according to their roles and permissions while maintaining integration with existing project management systems.

**Layer 7 – Governance, Legal, and Policy Layer**

The governance layer establishes legal, operational, and cybersecurity frameworks for smart contract deployment.

This layer defines procedures for dispute resolution, data correction, stakeholder responsibilities, blockchain governance policies, and integration of smart contract outputs within contractual agreements.

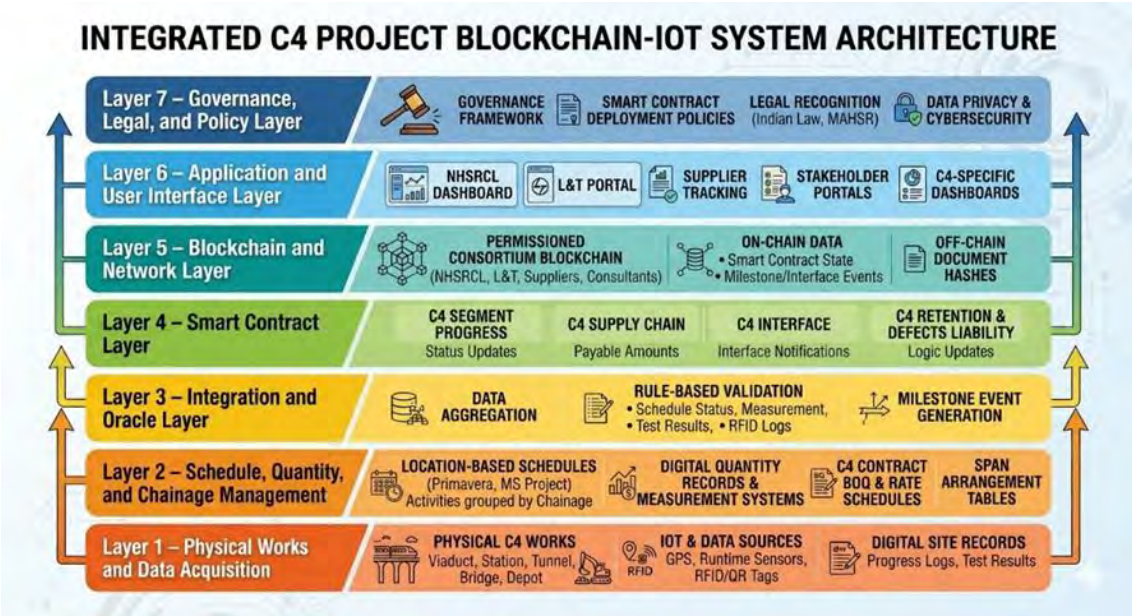



*Figure 2: Diagrammatic representation of the 7-layer framework*

## 6. DISCUSSION

The proposed blockchain-based smart contract framework effectively addresses several operational and contractual challenges associated with large linear EPC construction projects, particularly fragmented information management, manual progress verification, distributed logistics coordination, and interface management across geographically dispersed work fronts. The chainage-based segmentation approach supports location-oriented monitoring and milestone verification, which aligns with findings by Ye et al. (2022) that repetitive and standardised workflows in construction are well suited for smart

contract implementation. Similarly, the use of IoT, RFID, GPS technologies, and oracle-based validation mechanisms support automated and reliable verification of construction progress, extending the work of Hamledari and Fischer (2021), who highlighted the role of digital data capture and reality-based verification in blockchain-enabled payment automation systems.

The framework contributes to existing literature by integrating multiple contractual functions including progress certification, supply chain management, interface coordination, and retention management within a unified smart contract environment. Previous studies have largely focused on isolated applications such as payment automation or BIM-based contract execution (Kamel et al., 2023). In contrast, the present framework broadens the application scope to address the distributed and interdependent nature of linear infrastructure projects. The inclusion of interface smart contracts is particularly relevant for linear projects where delays or disruptions in one work zone frequently affect downstream activities and multiple contractors simultaneously.

Unlike many existing blockchain frameworks that rely heavily on BIM environments and centralised digital models, the proposed system adopts a BIM-independent framework using scheduling systems, digital quantity records, logistics data, and chainage-based workflows. This improves practical applicability in large infrastructure projects where BIM implementation may be incomplete or inconsistent, thereby addressing limitations identified in earlier studies (Gupta & Jha, 2024; Lima et al., 2023). The seven-layer framework provides clearer functional separation between data acquisition, validation, contract execution, blockchain infrastructure, stakeholder interaction, and governance compared to several conceptual blockchain models proposed in existing construction literature.

However, despite its advantages, the framework remains conceptual and faces several implementation challenges similar to those identified in prior blockchain studies. Integration with legacy project management systems, cybersecurity vulnerabilities, legal enforceability of smart contracts, interoperability among stakeholders, and organisational resistance may limit practical adoption (Hunhevicz et al., 2022; Hu et al., 2020). Furthermore, the scalability of blockchain networks and the reliability of oracle-generated data remain important technical concerns in large-scale distributed infrastructure environments. Nevertheless, the framework demonstrates significant potential for advancing Construction 4.0 principles in linear infrastructure projects by improving transparency, automation, traceability, and trust without requiring full BIM dependency.

## 7. CONCLUSIONS

This study proposed a blockchain-enabled smart contract framework for improving contract administration, workflow coordination, and information management in linear construction projects characterised by geographically distributed work fronts, repetitive construction activities, extensive logistics operations, and multi-stakeholder interactions. The framework integrates chainage-based scheduling systems, digital quantity records, RFID/GPS-enabled logistics tracking, oracle-based validation mechanisms, and blockchain-supported smart contracts within a seven-layer framework designed to automate milestone verification, payment processing, supply chain traceability, interface coordination, and retention management. By eliminating fragmented workflows and reducing dependency on manual verification processes, the framework aims to improve

transparency, traceability, accountability, and operational efficiency across distributed project environments.

The study contributes to theoretical knowledge by extending existing blockchain and smart contract research beyond BIM-centric and building-oriented applications toward the specific operational characteristics of linear infrastructure projects. Unlike many previous studies that focus primarily on payment automation, the proposed framework integrates multiple contractual and administrative functions into a unified blockchain-enabled ecosystem tailored for chainage-based project execution. From a practical perspective, the framework provides a scalable and adaptable implementation model for large infrastructure projects such as highways, rail corridors, metro systems, pipelines, and transmission networks where distributed logistics, repetitive workflows, and interface management create major coordination challenges.

However, the study has several methodological limitations. The framework is conceptual in nature and has not been validated through real-world implementation, pilot deployment, or quantitative performance analysis. The study is primarily based on literature synthesis and process-level analysis rather than empirical data collection from active projects or stakeholder interviews. In addition, issues related to blockchain scalability, cybersecurity risks, interoperability with legacy systems, organizational readiness, legal enforceability of smart contracts, and regulatory compliance require further investigation before large-scale implementation can be achieved.

Future research may focus on developing prototype systems and conducting pilot implementations in live linear infrastructure projects to evaluate technical feasibility and operational performance. Further studies may examine integration with digital twins, IoT ecosystems, AI-based analytics, and automated inspection systems for real-time project monitoring and decision-making. Quantitative assessment of impacts on project cost, schedule performance, dispute reduction, payment efficiency, and supply chain visibility would provide stronger validation of the framework's effectiveness. Additionally, future work should investigate governance models, cybersecurity protocols, legal frameworks, and stakeholder adoption strategies necessary for large-scale deployment of blockchain-enabled smart contract systems in the construction industry.

# 8. REFERENCES

Alhanaee, N., & Alhanaee, T. (2021). Smart contract using blockchain in construction and infrastructure sector in the COVID-19 pandemic. In *Proceedings of the 38th International Symposium on Automation and Robotics in Construction* (pp. 1018–1024). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2021/0137

Bottoni, P., Gessa, N., Massa, G., Pareschi, R., Selim, H., & Arcuri, E. (2020). Intelligent smart contracts for innovative supply chain management. *Frontiers in Blockchain*, 3, Article 535787. https://doi.org/10.3389/fbloc.2020.535787

Elghaish, F., Abrishami, S., & Hosseini, M. R. (2020). Integrated project delivery with blockchain: An automated financial system. *Automation in Construction*, 114, Article 103182. https://doi.org/10.1016/j.autcon.2020.103182

Elsharkawi, H., Elbeltagi, E., Eid, M. S., Alattyih, W., & Wefki, H. (2025). Construction payment automation through scan-to-BIM and blockchain-enabled smart contract. *Buildings*, 15(2), Article 213. https://doi.org/10.3390/buildings15020213

Gupta, P., & Jha, K. N. (2024). Integration of blockchain in contract management for prevention of construction disputes: A systematic literature review and conceptual framework. *International Journal of Construction Management*, 24(10), 1054–1065. https://doi.org/10.1080/15623599.2023.2274720

Hamledari, H., & Fischer, M. (2021). Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. *Automation in Construction*, 132, Article 103926. https://doi.org/10.1016/j.autcon.2021.103926

Hu, B., Zhang, Z., Liu, J., Liu, Y., Yin, J., Lu, R., & Lin, X. (2020). A comprehensive survey on smart contract construction and execution: paradigms, tools, and systems. *Patterns*, 2, 1–51. https://doi.org/10.48550/arxiv.2008.13413

Hunhevicz, J. J., Brasey, P., Bonanomi, M. M. M., Hall, D. M., & Fischer, M. (2022). Applications of Blockchain for the governance of Integrated Project Delivery: a Crypto Commons approach. Project Leadership and Society, 5, 1–19. https://doi.org/10.48550/arxiv.2207.07002

Kamel, M. A., Bakhoum, E. S., & Marzouk, M. M. (2023). A framework for smart construction contracts using BIM and blockchain. Scientific Reports, 13(1), 10217. https://doi.org/10.1038/s41598-023-37353-0

Lima, T. a. R. M., Da Mota, I. T. S., & Melo, C. M., Junior. (2023). Blockchain e contratos inteligentes na construção civil 4.0. Revista Multidisciplinar Do Nordeste Mineiro, 11(1). https://doi.org/10.61164/rmnm.v11i1.1598

Luo, H., Das, M., & Wang, J. (2019). Construction payment automation through smart contract-based blockchain framework. In *Proceedings of the 36th International Symposium on Automation and Robotics in Construction* (pp. 280–287). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2019/0168

Song, W., Wu, H., Meng, H., Bian, E., Tang, C., Xi, J., & Zhu, H. (2023). A Blockchain based Fund Management System for Construction Projects -- A Comprehensive Case Study in Xiong'an New Area China. In *8th International Conference on Smart Finance*. https://doi.org/10.48550/arxiv.2308.12834

Ye, X., Zeng, N., & König, M. (2022). Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges. *Frontiers of Engineering Management*, 9(2), 196–213. https://doi.org/10.1007/s42524-022-0188-2

Nazeer, F.S., Kamardeen, I. and Hasan, A., 2026. Digital System for effective end-user engagement in higher education building design. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 552-564. DOI: https://doi.org/10.31705/WCS.2026.41. Available from: https://ciobwcs.com/papers/

# DIGITAL SYSTEM FOR EFFECTIVE END-USER ENGAGEMENT IN HIGHER EDUCATION BUILDING DESIGN

**Fathima Sabrina Nazeer[1], Imriyas Kamardeen[2] and Abid Hasan[3]**

## *ABSTRACT*

*Higher education (HE) buildings often experience performance gaps that undermine occupant comfort, health, and overall satisfaction. These gaps are partly attributed to fragmented end-user engagement during the design process and the lack of effective tools and strategies to support such engagement. To address this issue, this study aims to develop a computerised system that enables professionals to effectively engage end-users in HE building design within real-world practice. The study adopts the Design Science Research methodology to develop a practical and implementable solution. The system is grounded in a knowledge-to-action end-user engagement framework derived from three key knowledge domains: the building design process, user engagement principles, and critical design elements. This framework was systematically developed and refined through multiple empirical research phases. The framework was operationalised using MS Access. The resulting computerised system supports several functions, including user requirement acquisition during the pre-design stage and design evaluation during schematic and detailed design stages. It enables the systematic collection and aggregation of feedback from diverse end-user groups and generates consolidated reports that visualise user preferences and satisfaction levels. By providing a structured mechanism for integrating end-users throughout the design process, the system offers a practical roadmap for professionals. This study bridges theory and practice by delivering a holistic computerised system that translates research knowledge into an industry-ready solution to address persistent performance gaps in HE buildings.*

***Keywords:*** *Computerised System, End-user Engagement, End-User Requirement Acquisition, Higher Education Building Design, Pre-Occupancy Design Evaluation.*

## 1. INTRODUCTION

Higher education (HE) buildings play a critical role in facilitating teaching, learning and research (Abisuga et al., 2020). However, previous research on the performance of HE buildings reveals a significant gap between the intended design and the actual experience of building occupants (Abdullah et al., 2012; Kim et al., 2018). These gaps often manifest in aspects related to health, comfort, functionality, spatial usability and overall

[1] Graduate Researcher, School of Architecture and Built Environment, Deakin University, Australia, f.nazeer@deakin.edu.au
[2] Professor, School of Architecture and Built Environment, Deakin University, Australia, imriyas.kamardeen@deakin.edu.au
[3] Senior Lecturer, School of Architecture and Built Environment, Deakin University, Australia, abid.hasan@deakin.edu.au

satisfaction, which lead to absenteeism, poor academic progression, lower productivity and health issues (Bae et al., 2021; Beckers et al., 2016). A key reason for these discrepancies lies in the limited and fragmented integration of end-user perspectives during the HE building design process (Gooding et al., 2021).

End-user engagement in design is an iterative process that ideally begins at the predesign and continues through schematic and detailed design. During the predesign stage, end-user requirements are identified to inform the development of the project brief. As the design progresses, these requirements should be revisited to evaluate whether the proposed design solutions effectively address the end-user needs. Such iterative engagement allows designers to refine design decisions and ensure the final outcome aligns with user expectations. However, in practice, this integrated continuous engagement rarely occurs. Several challenges hinder effective end-user participation, such as issues of accountability, limited resources, extensive time required to gather and process feedback, and lack of systematic approaches or tools to structure and manage end-user inputs (Gooding et al., 2021; Kjolle & Blakstad, 2014; Latortue et al., 2015; Seki et al., 2022).

To address these challenges and facilitate more effective end-user engagement, a systematic end-user engagement framework was developed (Nazeer et al., 2025a) and validated through previous empirical findings. Building on this foundation, the present study advances the research by translating the acquired knowledge into practical implementation through the development of a computerised system. This system represents one of the initial attempts to provide a practical solution for the effective integration of end-user engagement in HE building design.

The remainder of the paper is structured as follows. First, the end-user engagement framework underpinning the system is introduced. This is followed by the description of the system architecture. The subsequent section outlines the system development process, along with its functionality and benefits. Finally, the paper concludes with the study's contribution and direction for future research.

## 2. END-USER ENGAGEMENT FRAMEWORK

The framework provides a structured approach for integrating end-user inputs throughout the design process in HE building design settings. The key aspect of end-user engagement relies upon effective acquisition of end-user requirements in pre-design and evaluating the design in schematic and detailed design. Thus, the framework encompasses the following three main components:

(1) End-user engagement process map (see Figure 1),

(2) End-user requirement acquisition module (see Table 1),

(3) Pre-occupancy Design Evaluation module (see Table 2).

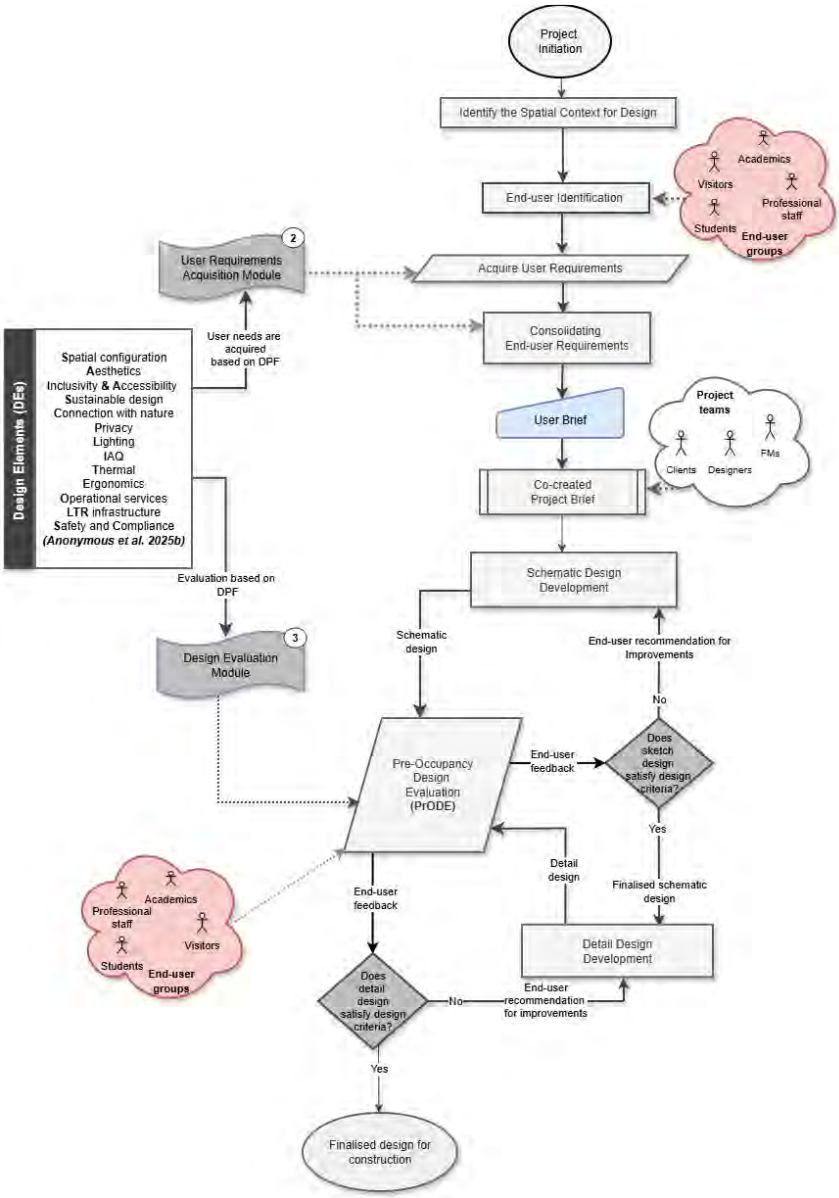



*Figure 1: End-user engagement process map (Amended from Nazeer et al., 2025a)*

This process map presents the steps to be taken for end-user engagement from project initiation across schematic and detailed design phases. Once the project is initiation the process map emphasises identifying respective end-user groups for iterative engagement in the design process. Initially, end-user requirements are gathered using the end-user requirement acquisition module with respect to the identified 13 Design Elements (DEs) (Nazeer et al., 2025b). The user requirements are consolidated and provide a document referred to as the "User brief". This document summarises the overall requirements and highlights the preferences of different end-user groups for designers to base their project brief formation. Subsequently, the initial design will be developed and carried forward to the design evaluation phase. The proposed design is evaluated during both phases from the lens of end-users to assess their level of satisfaction using the design evaluation module. The evaluation results generate a total design satisfaction index (TDSI), which indicates whether the design meets the expected level of satisfaction or requires further

revisions. Sample user requirement acquisition module and design evaluation modules are presented in Tables 1 and 2.

*Table 1: Sample module for end-user requirements acquisition (Amended from: Nazeer et al., 2025a)*

| **Design Element: Aesthetics (AE)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| How important are the following aesthetic features to support your work productivity/learning within the space/building? | Importance rating Low…….High | | | | | | Additional comments |
| (1) Warm colours (red, oranges, yellows) | NA | 1 | … | … | … | 10 | |
| (2) Cool colours (blues, greens, purples) | NA | 1 | … | … | … | 10 | |
| (3) Neutral colours (White, greys, beiges) | NA | 1 | … | … | … | 10 | |
| (4) Nature texture (wood grain, stone textures, …) | NA | 1 | … | … | … | 10 | |
| (5) Smooth surface | NA | 1 | … | … | … | 10 | |
| (6) Rough surface | NA | 1 | … | … | … | 10 | |
| (7) Patterns | NA | 1 | … | … | … | 10 | |
| (8) Identity (local environment/ heritage) | NA | 1 | … | … | … | 10 | |
| (9) Personalisation/ workstation spatial views | NA | 1 | … | … | … | 10 | |
| (10) Historical/ achievement wall | NA | 1 | … | … | … | 10 | |
| (11) Ceiling preferences | NA | 1 | … | … | … | 10 | |
| (12) Ease of maintainability and practicality | NA | 1 | … | … | … | 10 | |
| Please indicate any other important features for the aesthetic appearance you prefer within the space. | | | | | | | |

*Table 2: Sample module for PrODE (Amended from: Nazeer et al., 2025a)*

| **Design Element: Connection with nature (CN)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| How effective are the following natural elements to support your work productivity or learning within the space/building? | Satisfaction rating Low…….High | | | | | | Additional comments |
| (1) Indoor plants and selection of plants (native/foreign) | NA | 1 | … | … | … | 10 | |
| (2) Courtyards or greenspaces, | NA | 1 | … | … | … | 10 | |
| (3) Rooftop gardens, | NA | 1 | … | … | … | 10 | |
| (4) Study gardens, | NA | 1 | … | … | … | 10 | |
| (5) Window views/ quality views/unobstructed views/ view types: flora, fauna or sky, movement, objects | NA | 1 | … | … | … | 10 | |
| (6) Layout arrangement, textures and colour selection | NA | 1 | … | … | … | 10 | |
| (7) Connected with nature | NA | 1 | … | … | … | 10 | |
| (8) Waterscape design | NA | 1 | … | … | … | 10 | |

To operationalise the framework and support its practical implementation, it was translated into a technology-supported application. The next section presents the methodology adopted for this study.

# 3. METHODOLOGY

This research adopts the Design Science Research (DSR) methodology to develop an industry-ready computerised system for the effective engagement of end-users in HE building designs. The DSR approach emphasises the balance between maintaining scientific rigour and ensuring industry relevance, with the development of an artefact as an outcome. Within this methodology, appropriate data collection methods can be selected at different stages of the research process, including the exploration of existing theories and principles, systematic literature reviews (SLR), and empirical data collection techniques to inform the development of the artefact. Accordingly, the development of the proposed computerised system is grounded in a series of rigorous scientific data collection and analysis techniques conducted across four research phases.

## 3.1 SETTING THE SCENE

In phase I, a preliminary literature review was conducted to determine the root causes of performance gaps in HE buildings. The review revealed that one of the key issues is the limited participation of end-users in the design process. To further investigate this issue, three series of SLR were undertaken focussing on: (1) end-user engagement principles, (2) design evaluation and (3) design elements. The findings from these reviews were disseminated in previous publications (Nazeer et al., 2024, 2025a, 2025b). In addition, related knowledge domains, including the project life cycle, functional performance specification (FPS) theories and knowledge-based expert systems, were reviewed to inform the development of a potential solution. These investigations collectively led to the development of a conceptual framework for end-user engagement.

Phase II focused on the empirical validation and refinement of the conceptual framework. In this phase, four focus group discussions and 70 interviews were conducted with professionals and end users. The findings enabled the identification of significant design elements (Nazeer et al., 2025b) and contributed to the validation of the proposed framework. These findings informed the design and development of the system in Phase III for developing the computerised system in facilitating effective end-user engagement and decision support. Finally, phase IV involved the evaluation of the developed system through a focus group discussion with experienced HE building professionals from a single institution. The session aimed to assess the system's functionality, potential benefits and areas of improvements.

# 4. DESIGN AND DEVELOPMENT OF A COMPUTERISED SYSTEM

## 4.1 SYSTEM ARCHITECTURE

Figure 2 portrays the system architecture adopted for this study. This computerised system comprises four components:

(1) Project team and End-user groups – this refers to the system users for data entry and information retrieval.

(2) User requirement acquisition module: This facilitates the engagement of users in acquiring their requirements for the design. The user requirement acquirer will obtain and process the user requirements based on the design elements (DEs) and design features (DFs), and the overall user requirement will be fed into the project

end-user interface (EUI) data. The numerical and subjective data will be consolidated and processed in the user requirement acquirer and organised into a heatmap. This will be translated into a user brief and carried forward to the co-creator project brief. The project brief co-creator will combine both project teams and user brief details, form the co-creator project brief and store it in the project database.

(3) Database: This stores all the output from the user requirement acquirer, design satisfaction rater, and the designs produced based on the co-creator project brief.

(4) Design evaluation module: This module evaluates designs using the design satisfaction rater. End-users provide satisfaction ratings based on the DEs and DFs in schematic and detailed design. These ratings are processed in the system to compute the Total Design Satisfaction Index (TDSI) and consolidate qualitative feedback, which informs decisions on design improvements or acceptance.

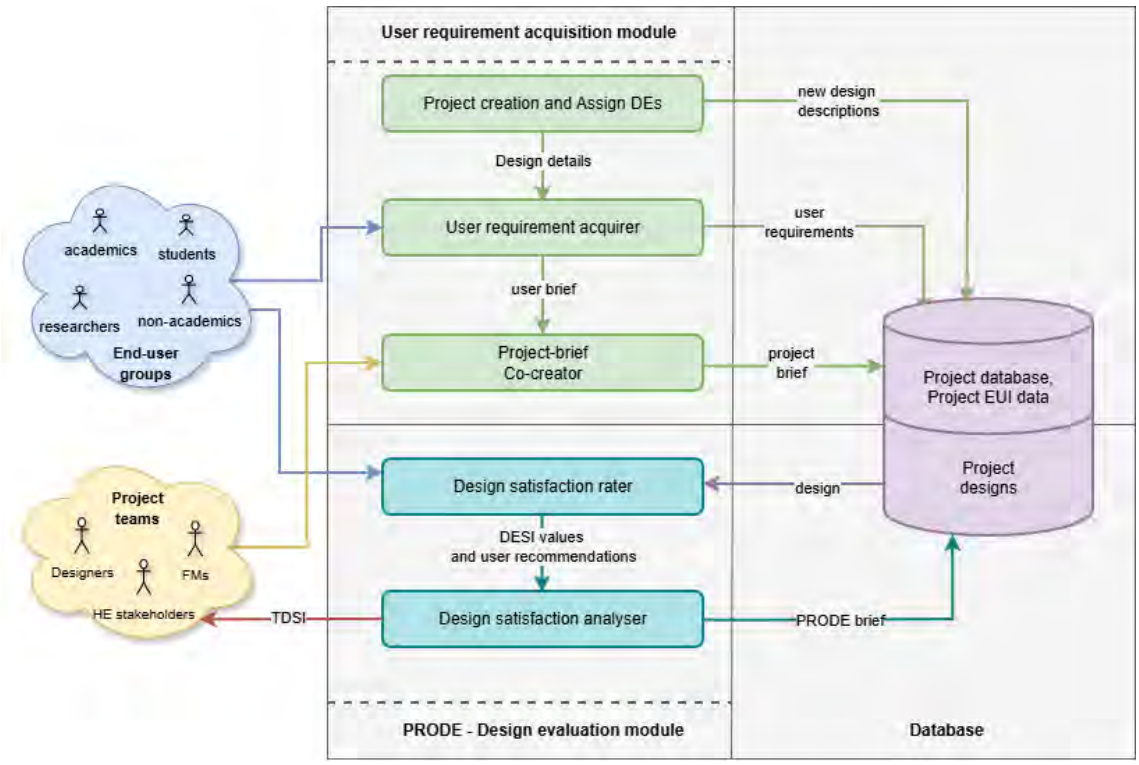



*Figure 2: System architecture*

## 4.2 DEVELOPMENT AND INTEGRATION OF SYSTEM COMPONENTS

The development of the computerised system involved the integration of an intermediate unit processing (IPU) and a system database, enabling both knowledge processing and structured data management. The system database was designed and implemented using MS Access to store and manage project data and user inputs. MS Access was chosen due to its capacity to efficiently manage relational data, support the development of user-friendly interfaces and facilitate integration with external applications. Furthermore, its accessibility and cost-effectiveness make it a suitable platform for developing initial proof of concept using database-driven prototype systems.

The development of the IPU utilised the basic and advanced features of MS Access, including: Tables, Queries, Forms, Macros, Reports, and Modules. As an initial step, an entity-relationship diagram (ERD) was developed to define entities and relationships required for structuring the system database, as presented in Figure 3.

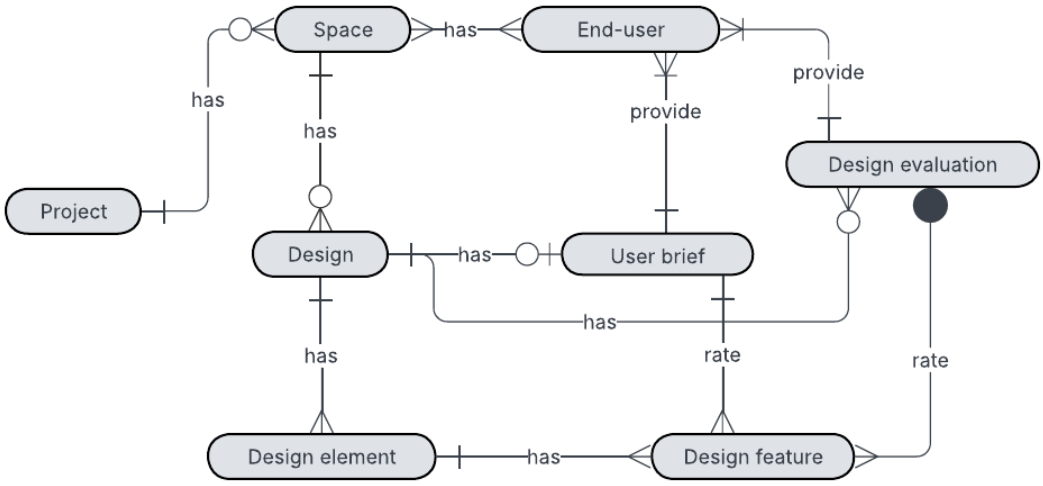



*Figure 3: Entity-relationship diagram*

### 4.2.1 Formation of Tables

Based on the ERD, the following database tables were created to store the relevant system inputs, rules and output.

*Table 3: Table database structure of the computerised system*

| | Table name | Description/Purpose |
|---|---|---|
| 1 | Project | Stores information on each project |
| 2 | Space | Contains spaces within projects |
| 3 | Design | Stores designs associated with individual spaces |
| 4 | Design element | Contains identified DEs |
| 5 | Design feature | Contains identified DFs linked to DEs |
| 6 | Design- design element | Links designs to associated DEs |
| 7 | End-user | Stores end-user details |
| 8 | User brief | Stores user briefs associated with individual designs |
| 9 | User brief - rating | Stores ratings provided by end-users |
| 10 | User brief – comment | Stores comments from end-users on DEs |
| 11 | PRODE | Stores design evaluation sessions for each design |
| 12 | PRODE-schematic rating | Feeds schematic design evaluation ratings and comments from end-users |
| 12 | PRODE- detailed rating | Feeds detailed design evaluation ratings and comments from end-users |

### 4.2.2 Defining Relationships

Subsequently, after creating the tables, the relationships between these tables were defined to ensure data integrity and proper linkage across the system. The defined relationships are presented in Figure 4, illustrating how projects, spaces, designs, end-users, DEs, DFs, user brief and design evaluation (PRODE) data are interconnected.

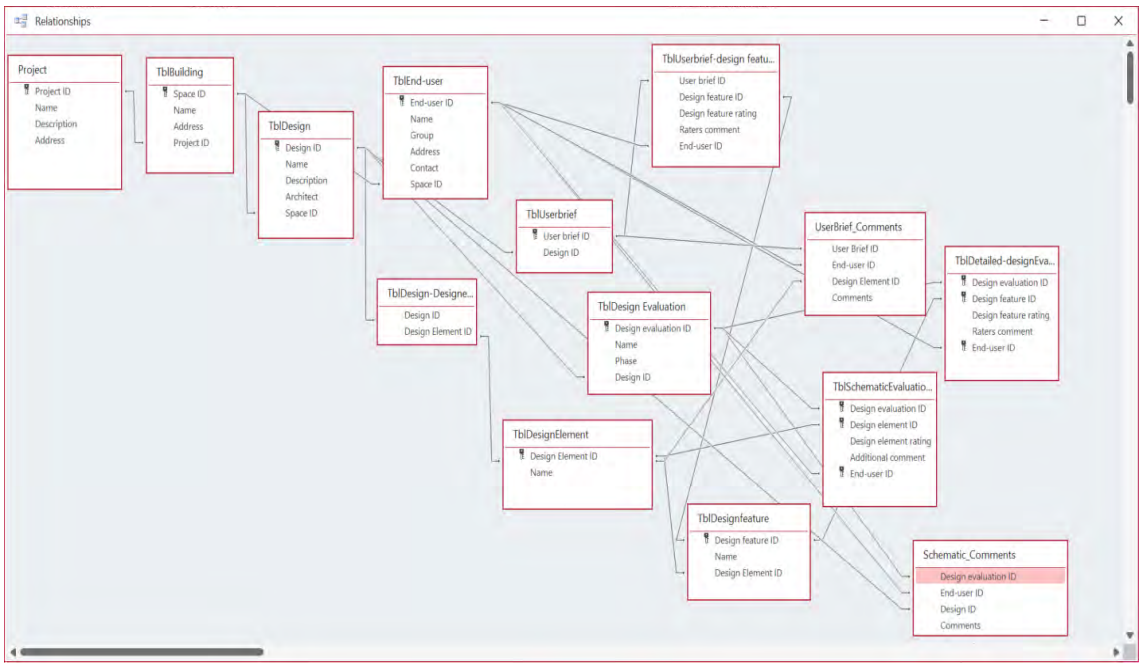



*Figure 4: Relationship between data tables*

### 4.2.3 Queries and Computational Procedures

After defining the relationships, a series of queries was created to process the data within the system database. Queries transform raw data stored in tables into meaningful information, forming the analytical engine of the system. Data retrieval queries, structure management queries, feature and element level calculation queries, summary and comparison, and crosstab and visualisation queries were generated to process the computerised system.

User-friendly interfaces for data entry and management were developed using Form Wizard. Subforms were incorporated where necessary to improve the navigation and usability. For example, the subforms for assigning design elements and creating new projects were embedded within the Create project and assign DEs form, allowing related information to be managed within a single interface. Reports were then generated using the Report Wizard to summarise, analyse, and present the processed data into a structured format. Two main reports were produced: a user brief (summarising user requirements) and PRODE (presenting design evaluation results).

Macros were used to generate simple routine automation tasks like: navigating between forms, deleting records, and triggering predefined commands. For more advanced operations, VBA modules were implemented to control system mechanisms, including managing application behaviour, refreshing queries when data changes, and coordinating data processing steps. Through this integrated workflow, the system converts raw user responses into structured results and supports intelligent decision-making.

# 5. COMPUTERISED SYSTEM FOR END-USER ENGAGEMENT

This system is developed to support effective, integrated end-user engagement practice in HE building design. This comprises many functions, which are incorporated into a user-friendly Graphical User Interface (GUI) that can be navigated through point-and-click icons. All the functions in the computerised system are grouped under three main catalogues: (1) Create project and assign DEs, (2) User brief, and (3) PRODE. Functions in the system were refined and optimised through multiple trial-and-error interactions and brainstorming sessions. These improvements were targeted at effectively integrating the framework developed and finalised during the empirical phase of the study. Through these iterative improvements, the computerised system was structured to provide a clear workflow, allowing project managers/architects to create projects, capture end-user requirements, and evaluate design options within a single integrated platform. The final GUI of the computerised system is presented in Figure 5.

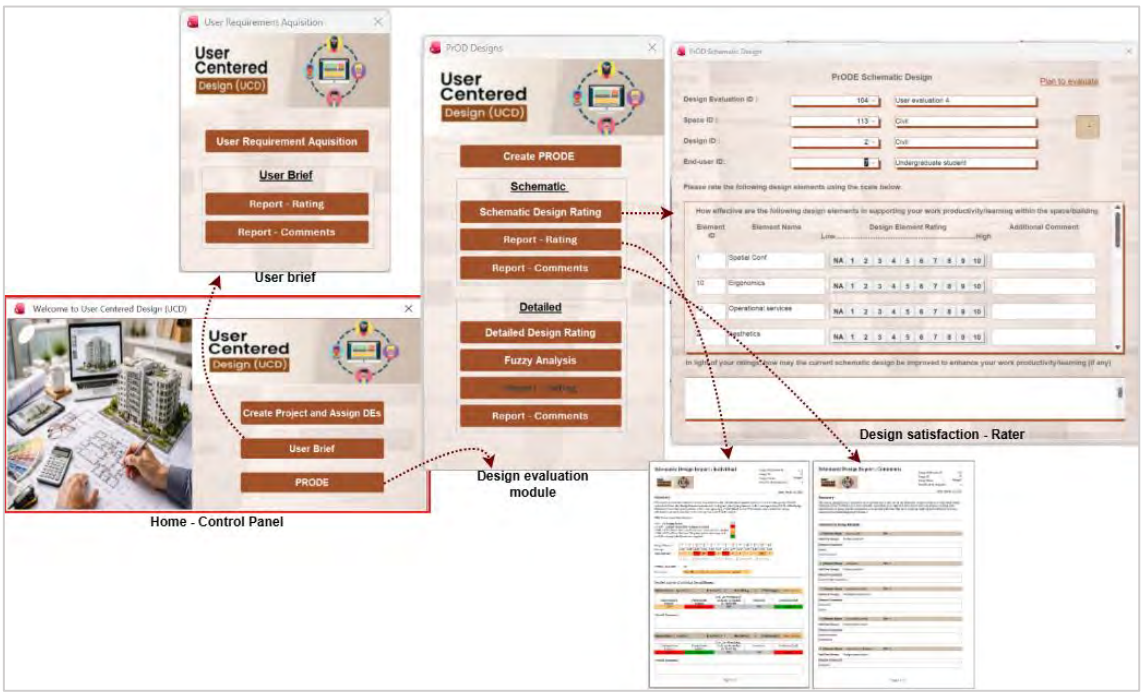



*Figure 5: Sample GUI of the developed computerised system*

## 5.1 WORKFLOW MODEL FOR THE COMPUTERISED SYSTEM

This section presents the workflow model for the developed computerised system. The process begins with a project need set up by the HE stakeholders or HE building professionals. The following sequential steps shall be taken:

i. **Project creation:** The project manager or architect creates a new project within the system by registering project information, space details, design descriptions and architect details. A unique design ID is automatically generated, which is used for gathering end-user requirements and later performing the design evaluations.

ii. **Assignment of DEs:** The architect or project manager assigns the relevant DEs associated with the particular design.

iii. **User requirement acquisition:** End-user requirements are collected through the user requirement acquisition interface by following these sub-steps:

   a. An end-user manual is created and uploaded to the interface to guide users.

   b. End-users register themselves by furnishing basic information such as: name, end-user group, address, contact details and associated space.

   c. Registered end-users provide their preferences and expectations for each DF by rating on a 1 – 10 Likert scale and adding additional comments, if any.

iv. **User brief generation:** The system generates user brief reports that summarise the rating and comments. These reports provide both quantified and qualitative feedback to understand end-user priorities.

v. **Schematic design preparation and evaluation:** Prepare the co-creator project brief, and the schematic design is finalised for evaluation. Follow the sub-steps:

   a. The schematic design and any instructions are uploaded to the PRODE – schematic design RATER interface.

   b. Registered end-users evaluate the design by rating their satisfaction with individual DEs, and providing additional comments for any improvements.

vi. **Schematic design report:** The system generates a schematic design report presenting ratings, comments, and the TDSI, along with recommendations.

vii. **Design improvement decisions:** Based on the evaluation results and suggestions, the design may either be improved or progressed to the detailed design phase.

viii. **Detailed design evaluation:** For detailed design evaluation, the following sub-steps are performed:

   a. The detailed design and relevant instructions are uploaded to the PRODE – detailed design RATER interface.

   b. Registered end-users evaluate their satisfaction with individual DFs and provide additional comments.

ix. **Detailed design report:** The system generates a detailed design report presenting ratings, comments, and the TDSI, along with recommendations. These outputs provide both quantitative and qualitative feedback to support further design refinement if required.

## 6. SYSTEM VALIDATION

An initial evaluation of the developed computerised system was conducted through a focus group discussion involving four experienced HE building professionals. The participant represented diverse professional disciplines, including a senior designer, project manager, engagement specialist and property and portfolio manager. Each participant possessed a minimum of ten years of experience in the HE building settings.

During the session, the developed system was initially presented to the group, demonstrating all the functions and capabilities of the system. This presentation provided participants with an overview of how the system operates and how it can support the end-

user engagement process. Subsequently, an interview guide was shared to the participants to facilitate structured feedback on the system. The discussion focused on three key aspects of the system: functionality, benefits and improvements under 15 questions as presented in Table 4.

*Table 4: Expert's judgement over the developed computerised system*

| | Questions | Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree | Total |
|---|---|---|---|---|---|---|---|
| **Function of the system:** | | | | | | | |
| Q-01 | Provides a more structured and systematic approach | 1 | 3 | 0 | 0 | 0 | 4 |
| Q-02 | Support active participation, direct representation, and gather feedback | 2 | 2 | 0 | 0 | 0 | 4 |
| Q-03 | Support an effective documentation process and reduce repetitions | 3 | 1 | 0 | 0 | 0 | 4 |
| Q-04 | Increase effective communication between end-users and project stakeholders | 3 | 1 | 0 | 0 | 0 | 4 |
| Q-05 | Capture, aggregate, and prioritise end-users' requirements at the pre-design stage | 3 | 1 | 0 | 0 | 0 | 4 |
| Q-06 | Evaluate and capture recommendations from end-users at the schematic design stage | 2 | 2 | 0 | 0 | 0 | 4 |
| Q-07 | Evaluate and capture recommendations from end-users at the detailed design stage | 0 | 4 | 0 | 0 | 0 | 4 |
| Q-08 | Addresses the challenges inherent in the subjective evaluation | 1 | 3 | 0 | 0 | 0 | 4 |
| Q-09 | An effective method for improved engagement of end-users in HE building design | 3 | 1 | 0 | 0 | 0 | 4 |
| **Benefits of the system:** | | | | | | | |
| Q-10 | Enable designing HE buildings that satisfy the needs of diverse user groups | 3 | 1 | 0 | 0 | 0 | 4 |
| Q-11 | Minimise the discrepancies between the performance of the building and the expectations of end-users during the operation stage | 1 | 3 | 0 | 0 | 0 | 4 |
| Q-12 | Help reduce costly modifications to the building during the operation stage | 4 | 0 | 0 | 0 | 0 | 4 |
| Q-13 | Supports inclusivity, accessibility and presence accountability | 2 | 2 | 0 | 0 | 0 | 4 |
| Q-14 | Help minimise the time taken for engaging users in the design | 2 | 2 | 0 | 0 | 0 | 4 |

All participants in the focus group discussion either strongly agreed or agreed with the positive aspects of the developed system. None of the participants expressed neutral or negative views regarding the system. The following comments and insights were collated from the participants' feedback.

- Functionality – The system provides a centralised platform to facilitate end-user engagement and collect feedback throughout the process. It assists in minimising challenges commonly associated with end-user participation, such as removal of

subjectivity, fragmented communication and inefficient feedback management. Furthermore, the system enables documentation of user inputs and design evaluations, reducing redundant work while ensuring the information remains traceable and accessible in later phases. The experts overall strongly agreed that this system offers an efficient mechanism for integrating end-users throughout the design process, spanning from pre-design to schematic to detailed design.

- Benefits – The experts highlighted several foreseeable benefits of implementing the system in the industry. They noted that the system has the capability to accommodate diverse end-user needs while reducing discrepancies between end-user expectations and the final built outcome. Additionally, it can help minimise costly modifications during the operational stage by facilitating early identification and incorporation of user requirements during the design process. The experts further indicated that the system supports inclusivity, accessibility and accountability in the implementation of engagement practices. Overall, it was recognised as a platform that can enhance transparency in the decision-making process.
- Improvements – The expert suggested that the system be integrated into real-world projects to further evaluate its practical applicability and performance. Since this was developed as a proof of concept, the experts suggested further improvements to the user interface and navigation features to enhance usability and accessibility. Furthermore, they recommended pursuing patent rights to protect the novelty and potential commercial value of the system.

Further evaluations may be undertaken with a large number of participants.

## 7. CONCLUSIONS

This study presented the developed computerised system to facilitate effective integration of end-users throughout the design process in HE buildings. The development and application of this system using DSR methodology provides a more robust and legitimate solution with practical applicability to real-world design problems associated with end-user engagement.

The proposed system serves as a roadmap for integrating end-users throughout the HE building design process. It adopts a holistic approach by identifying the significant DEs and DFs to acquire end-user requirements and evaluate the HE building design. The computerised system includes key functions such as project creation, assignment of relevant DE to specific designs, collection of end-user requirements and design assessment feedback, consolidation of end-user input, and automated report generation (presented through quantitative scores, heat colour-coded visualisation and qualitative summaries). The system facilitates systematic collection, processing and analysing of user feedback, thereby supporting more informed decision-making during the design process.

The system can be effectively utilised by designers or professionals who may have limited experience in end-user engagement. By incorporating this, the system facilitates the adoption of best practices for engaging end-users throughout the design process. The use of this computerised system can reduce the costs, time and planning effort required to organise and manage user participation compared with conventional practices. As a

result, the proposed computerised system offers a practical industry-oriented solution to a prolonged challenge in integrating end-users within the design process. This may ultimately enable the reduction/mitigate the performance gap. Although the system was developed and evaluated within HE building setting, the underlying framework, decision-making logic, and evaluation approach can be adapted to other project types with appropriate modifications to the design parameters. Nevertheless, further studies are required to test and refine the computerised system through real-world applications.

## 8. ACKNOWLEDGEMENTS

This study acknowledges the funding received from Deakin University as part of the PhD studies.

## 9. REFERENCES

Abdullah, S., Mohd Ali, H., & Sipan, I. (2012). Benchmarking space usage in higher education institutes: attaining efficient use. *Journal of Techno-Social*, *4*(1), 11–20. https://publisher.uthm.edu.my/ojs/index.php/JTS/article/view/1346

Abisuga, A. O., Wang, C. C., & Sunindijo, R. Y. (2020). A holistic framework with user-centred facilities performance attributes for evaluating higher education buildings. *Facilities*, *38*(1–2), 132–160. https://doi.org/10.1108/F-07-2018-0083

Bae, S., Martin, C. S., & Asojo, A. O. (2021). Higher education students' indoor environmental quality satisfaction benchmark. *Building Research and Information*, *49*(6), 679–694. https://doi.org/10.1080/09613218.2020.1813012

Beckers, R., van der Voordt, T., & Dewulf, G. (2016). Learning space preferences of higher education students. *Building and Environment*, *104*, 243–252. https://doi.org/10.1016/j.buildenv.2016.05.013

Gooding, L., Erdogan, B., & Gürsel Dino, I. (2021). Involving end users in retrofit of higher education buildings. *Journal of Building Engineering*, *44*, 102633. https://doi.org/10.1016/j.jobe.2021.102633

Kim, T. W., Cha, S., & Kim, Y. (2018). Space choice, rejection and satisfaction in university campus. *Indoor and Built Environment*, *27*(2), 233–243. https://doi.org/10.1177/1420326X16665897

Kjolle, K. H. , & Blakstad, S. H. (2014). Architects and end-users: boundary objects in participatory briefing and design. *Nordic Journal of Architectural Research*, (1), 35–64. https://arkitekturforskning.net/na/article/view/477

Latortue, X., Minel, S., Pompidou, S., & Perry, N. (2015). Integration of end-user needs into building design projects: use of boundary objects to overcome participatory design challenges. *20th International conference on engineering design (ICED2015)* (pp. 269-278). HAL Open Science. https://hal.science/hal-01360417

Nazeer, F. S., Kamardeen, I., & Hasan, A. (2024). Research needs for enhancing pre-occupancy evaluation of buildings. *Built Environment Project and Asset Management*, *14*(4), 529–546. https://doi.org/10.1108/BEPAM-11-2023-0190

Nazeer, F. S., Kamardeen, I., & Hasan, A. (2025a). Establishment of an end-user engaged building design framework. *Built Environment Project and Asset Management*, *15*(1), 106–124. https://doi.org/10.1108/BEPAM-01-2024-0010

Nazeer, F. S., Kamardeen, I., & Hasan, A. (2025b). Redefining design features for mitigating performance gaps in higher education buildings. *Smart and Sustainable Built Environment*, *Ahead-of-Print*. https://doi.org/10.1108/SASBE-02-2025-0059

Seki, Y., Olanipekun, A. O., & Sutrisna, M. (2022). End-user stakeholder engagement in refurbishment design in higher education. *Sustainability*, *14*(19), 11949. https://doi.org/10.3390/su141911949

Mahawatta, S.I., Waidyasekara, K.G.A.S. and Ranasinghe, P.H.G.M.A., 2026. Digital transformation in large-scale construction: A real-world implementation. In: Waidyasekara, K.G.A.S., Jayasena, H.S.,Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 565-577. DOI: https://doi.org/10.31705/WCS.2026.42. Available from: https://ciobwcs.com/papers/

# DIGITAL TRANSFORMATION IN LARGE-SCALE CONSTRUCTION: A REAL-WORLD IMPLEMENTATION

**S.I. Mahawatta[1], K.G.A.S. Waidyasekara[2] and P.H.G.M.A. Ranasinghe[3]**

## *ABSTRACT*

*Large-scale construction projects in developing economies are constrained by traditional manual site management practices and fragmented technological deployments that are structurally inadequate for the governance and productivity demands of high-density, multi-floor construction environments. While individual technologies demonstrated domain-specific benefits, their isolated deployment leaves the systemic interdependencies between workforce management, cost control and resource utilisation unresolved. This study addresses that gap through an evaluative single case study of a large-scale construction project in Sri Lanka exceeding 83,500m² with a workforce exceeding 1,000 personnel, in which a fully integrated Radio Frequency Identification (RFID)-based digital site management ecosystem was designed and implemented over a ten-month period. The observations were made based on direct observation, system-generated reports and analytics obtained from project management dashboard. The findings demonstrate that the integrated ecosystem comprehensively reduced proxy attendance, payroll manipulation and resource misallocation while strengthening financial transparency, workforce accountability and operational governance. The direct linkage of labour deployment to cost codes, material withdrawals to specific work zones and machinery utilisation to verified task completion created end-to-end operational visibility. Workforce resistance was successfully resolved through phased implementation and structured change management, while the system's uninterrupted performance during the COVID-19 pandemic validated its value as a continuity infrastructure. The study provides practitioners with a replicable operational blueprint for construction digitalisation, and the implemented system validates and advances the theoretical foundation for integrated digital ecosystem research. Further research should identify multi-site cross-country replication as a critical direction for future research across developing economies.*

***Keywords:*** *Automatic attendance; Cost control; Digitalisation of construction processes; Labour productivity; RFID-tracking.*

## 1. INTRODUCTION

The construction industry remains a significant contributor to economic growth in developing nations, supporting infrastructure development, employment and Gross Domestic Product (GDP) expansion (Alaloul et al., 2020). Yet despite its economic

[1] Director/CEO, Prime Construction (Pvt) Ltd, Sri Lanka, saman.mahawatta1234@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, ranasinghephgma.20@uom.lk

centrality, the sector is persistently criticised for low productivity, poor output quality, cost overruns and inadequate system performance deficiencies that persist in developing economies such as Sri Lanka (Bansal, 2020). Rajakaruna et al. (2008) established that approximately 90% of Sri Lankan public sector construction projects experience cost and time overruns, reflecting not merely technical failure but a systemic inadequacy in how construction sites are monitored and controlled. As project scale and spatial complexity increase, these inadequacies are amplified in large, multi-floor, high-density construction environments. These conditions make direct supervision structurally impossible, subjective reporting becomes problematic and manual administration systems collapse under operational load (Santoso & Gallage, 2020).

Traditional site management in Sri Lanka relies predominantly on paper-based attendance registers, manually signed timecards, informal supervisory reporting and fragmented cost recording practices that are fundamentally incompatible with the governance demands of large-scale construction (Wijerathna et al., 2024a). These systems are systematically vulnerable to proxy attendance, unauthorised site exits, payroll manipulation and unofficial idling, directly eroding productivity, inflating labour costs and undermining financial accountability (Huang et al., 2019). The reliance on human judgment in record-keeping further creates conditions leading to collusion among workers, supervisors and security personnel, compromising ethical governance at its foundation (Wijerathna et al., 2024a). These are not incidental operational failures; they represent structural deficiencies inherent to manual site management that cannot be resolved through incremental process improvement alone.

Attempts to address these deficiencies through conventional biometric technologies have proven similarly inadequate. Fingerprint-based systems exhibit high failure rates under construction site conditions, dust, moisture and physical labour render them unreliable, while broader technologies, including RFID, IoT and BIM, remain fragmented and below international benchmarks in Sri Lanka (Manoharan et al., 2020). Critically, individual technologies deployed in isolation resolve fragments of the site management problems, where payroll errors persist, material wastage continues, and cost overruns remain (Wijerathna et al., 2024b).

Traditional site management has demonstrably failed to meet the governance, and productivity demands of large-scale construction, and the literature has responded by proposing individual technological solutions, such as biometric systems, RFID, IoT and BIM, each demonstrating domain-specific benefits in isolation (Wijerathna et al., 2024b). However, biometric systems fail under harsh construction conditions, and individually deployed technologies address only fragments of a deeply interconnected operational problem. As large-scale construction projects grow in spatial complexity, workforce density and cost exposure, this fragmented technological approach is no longer sufficient.

Existing studies have not empirically demonstrated how the aforementioned issues can be addressed with the capability of a fully integrated digital ecosystem in which workforce tracking, attendance verification, task allocation, payroll processing and resource control operate as a unified, closed-loop system delivering real-time, end-to-end operational visibility across all site management domains simultaneously. Therefore, this study addresses that gap through a real-world case study of a large-scale Sri Lankan construction project, providing empirical evidence that an integrated digital site management ecosystem outperforms both traditional manual systems and isolated

technology deployments, offering a replicable and scalable digital ecosystem for construction digitalisation in developing economies.

## 2. LITERATURE REVIEW

Mega-scale construction projects require massive demands on site management systems that conventional approaches are structurally ill-equipped to meet (Lu et al., 2011). In addition, the absence of real-time operational visibility creates cascading inefficiencies in decision-making, resource allocation and cost control (Santoso & Gallage, 2020). Traditional site management lacks the capacity for proactive operational adjustment or real-time governance, creating vulnerabilities in payroll processing, resource allocation and accountability (Wijerathna et al., 2024a). These vulnerabilities are compounded in large-scale environments by the volume and velocity of operational transactions occurring simultaneously across dispersed work zones (Huang et al., 2019). In developing economy contexts specifically, these deficiencies are further enhanced by informal site management cultures, limited technological infrastructure and institutional resistance to change, creating a management environment in which transparency and accountability are structurally difficult to enforce (Manoharan et al., 2020)

However, the literature has responded by exploring individual technological interventions across specific domains. As an example, construction 4.0 paradigm, which advocates for the digital transformation of construction processes through the integration of cyber-physical systems, real-time data analytics, and interconnected technologies (Kozlovska et al., 2021).In addition, RFID technology has emerged as particularly well-evidenced, with Kereri & Adamtey (2019) confirming its effectiveness across labour management, equipment tracking and materials control. Kineber et al. (2023) further established that RFID delivers measurable improvements in resource traceability, inventory accuracy and productivity when deployed in construction project management. Beyond RFID, IoT-enabled sensing frameworks, biometric verification systems, cloud-based platforms and centralised analytical dashboards have each demonstrated domain-specific operational value, with Kozlovska et al. (2021) identifying these technologies as foundational components of the Construction 4.0 paradigm and Tan & Sidhu (2022) confirming the operational benefits of RFID and IoT integration within resource management contexts.

However, the collective limitation of this literature is its persistent focus on isolated technological deployment. Each intervention addresses a specific operational domain while leaving the interdependencies between workforce management, cost control, resource utilisation and productivity measurement fundamentally unresolved (Kereri & Adamtey., 2019). Technologies deployed in isolation deliver marginal efficiency gains relative to the complexity of the problem they are designed to solve. These inefficiencies can be overcome by a fully integrated digital ecosystem across all site management domains (Wijerathna et al., 2024b).

## 3. METHODOLOGY

This study adopts an evaluative research approach within a single case study design, a methodology widely recognised as appropriate for investigating complex, real-world phenomena within their natural operational context (Yin, 2018). The single case study design is justified on the grounds that the ABC Project represents a critical case, a large-scale, high-density construction environment of sufficient complexity to expose the

systemic limitations of traditional site management and test the viability of an integrated digital ecosystem as a practical alternative. As Yin (2018) notes, a critical case satisfies the criteria for a single case study when it permits logical generalisation and allows propositions derived from the case to be extended to broader theory. The aim was to assess the overall effectiveness and governance outcomes associated with the transition from manual, paper-based site management to a centralised, cloud-based digital platform.

## 3.1 CASE INTRODUCTION

The ABC Project, undertaken by a major contractor in Sri Lanka, constitutes the unit of analysis. The project encompasses a built-up area of over 83,500m² and accommodates a peak workforce exceeding 1,000 personnel across multiple floors, residential units, service corridors and restricted-access areas. In addition, this configuration renders the conventional supervision structurally inadequate and creates significant vulnerability to attendance irregularities, payroll manipulation and resource misallocation, making it an analytically appropriate case for evaluating integrated digital site management under real-world conditions.

## 3.2 DATA COLLECTION AND ANALYSIS METHODS

Data collection was conducted over ten months, capturing the full implementation lifecycle from initial deployment through operational stabilisation. Three complementary data sources were employed to ensure methodological triangulation and strengthen evaluative validity (Creswell, 2014).

The first source comprised systematic direct observation conducted by embedded managerial staff, capturing authentic operational behaviour while minimising social desirability bias. Direct observation by embedded participants is considered a high-validity method for capturing real-world practice in its natural context, particularly where respondent self-reporting may be subject to distortion (Yin, 2018). The data gathered through direct observation was analysed using manual content analysis, a method appropriate for systematically identifying patterns, themes and deviations within qualitative field data (Krippendorff, 2018).

The second source consisted of system-generated reports extracted from the centralised digital platform. These automated records provided objective, timestamped documentation of workforce attendance, task allocations, material movements, equipment utilisation and payroll transactions, offering a verifiable, tamper-resistant data trail independent of human reporting.

The third source was the project management dashboard, which consolidated real-time data on manpower, productivity, costs and resource deployment across all site operations. The dashboard served as the primary instrument for identifying operational deviations and evaluating system responsiveness, enabling cross-referencing of observations and platform-generated records to verify consistency and detect discrepancies.

Together, these three sources provided a comprehensive, cross-validated empirical basis for evaluating the operational viability and governance impact of the integrated digital ecosystem.

Furthermore, the qualitative, single-case study design adopted in this study is acknowledged to carry inherent limitations with respect to researcher subjectivity and potential confirmatory bias. Several strategies were employed to mitigate these risks.

First, methodological triangulation across three independent data sources reduced dependence on any single informant perspective and allowed cross-verification of findings (Yin, 2018). Second, the use of system-generated, automated records, which are objective and not subject to retrospective adjustment, provided an anchor of verifiable evidence against which observational data could be tested. Third, the ten-month data collection period, spanning the full implementation lifecycle, reduced the risk of findings being attributable to novelty effects or short-term behavioural change. Fourth, the research was designed using an evaluative rather than exploratory framing, with assessments structured against pre-defined operational performance criteria rather than interpreted post-hoc. Notwithstanding these measures, the findings remain contextually bounded, and their applicability to other settings should be considered with appropriate interpretive caution.

# 4. CASE STUDY FINDINGS

## 4.1 PROJECT ENVIRONMENT AND OPERATIONAL CHALLENGES

Project ABC operated in a highly demanding environment, with fast timelines, concurrent multi-trade activities, and large vertical and horizontal work areas. Coordinating thousands of subcontractors, labour providers, and specialised trades across multifamily floors, service cores, and restricted-access areas created major challenges in workforce management, particularly for attendance tracking, labour deployment, productivity monitoring, and cost control.

The existing site-management system relied on a centralised time office supported by multiple supervisory layers. Up to six staff were needed daily to record attendance, compile site information, verify labour-supplier submissions, and process payroll. Despite this, labour data remained unreliable: attendance records were often delayed, discretionary, and prone to post-factum adjustments, limiting their usefulness for timely managerial decisions. The project's complex layout with enclosed and partially completed spaces restricted direct supervision, enabling proxy attendance, early releases, and manipulation of records, often coordinated between workers, supervisors, and security staff. Third-party credential misuse and unverified supervisor confirmations further undermined data integrity, affecting labour cost reporting and productivity measurement.

Fingerprint-based biometric systems were trialled but proved unreliable due to dust, moisture, chemicals, and manual work, causing verification failures, congestion, and operational disruption. These shortcomings directly reduced productivity, inflated costs, and threatened transparency and managerial accountability. The traditional system's inability to provide real-time, verifiable, and tamper-proof workforce data highlighted the need for a radically new solution, where an integrated, technology-based control system that reduces manual intervention, prevents manipulation, and provides continuous, accurate visibility of workforce presence and deployment.

## 4.2 IMPLEMENTATION OF AUTOMATED SYSTEMS

The automated tracking and control system at Project ABC was developed as a comprehensive digital ecosystem that integrates labour attendance, productivity, cost control, material use, and machinery deployment into a single real-time platform. An external IT vendor was engaged to design and implement the system architecture,

ensuring it was robust, scalable, and adaptable to the dynamic conditions of a large construction site. Each worker, material, and resource was uniquely registered and linked to predefined work packages and cost codes, providing end-to-end traceability. Personnel were issued RFID cards for site access, with facial recognition ensuring accurate attendance and preventing proxy entries. Supervisors allocated tasks, work zones, and cost codes through tablet-based interfaces, creating a direct, auditable connection between labour deployment, productivity, and project cost. Payroll and timekeeping were fully automated using system-generated digital timecards, eliminating manual input and increasing accuracy and transparency. Materials and machinery were tracked digitally, with withdrawals, operating hours, and idle time recorded and linked to specific work packages and cost codes to enable cost control and efficient utilisation. Welfare and support functions, including cafeteria access, accommodation, leave, and meal requests, were digitised and synchronised with attendance records, further streamlining administrative processes. All modules operated on a centralised, cloud-based platform, ensuring real-time synchronisation, data integrity, and reliable access for authorised stakeholders. A Project Manager dashboard consolidated data on manpower, productivity, costs, materials, and equipment, enabling timely detection of deviations and proactive operational control. The involvement of the IT vendor also allowed continuous updates and system refinements, ensuring the digital ecosystem remained aligned with evolving site requirements. The following subsections discuss the implementation of automated systems across seven key areas in detail.

#### 4.2.1 People Registration and Site Access Control

The first operational layer of the automated track-and-control system at Project ABC was people registration and site access control, establishing a secure and verifiable workforce management system. All employees, personnel, and authorised individuals were officially registered within a centralised digital platform before entering the site. Each person received a comprehensive site-identification profile, detailing employment category, trade classification, labour-supplier affiliation, and access authorisation levels. These profiles were linked to RFID cards issued at registration, creating a long-term, verifiable digital identity for every site user. Physical access to the construction site was restricted to a single controlled entry point, ensuring all ingress and egress were captured digitally. At the gate, individuals validated their identity through a two-step process, RFID card swipe followed by facial recognition. Unauthorised entries were automatically rejected, and all access events were time-stamped and logged, producing a verifiable audit trail. By combining digital registration, RFID-based access control, and facial-recognition attendance into a single workflow, the system provided verified presence information at the point of entry, enabling reliable downstream operations including task assignment, timekeeping, payroll processing, welfare management, and productivity monitoring.

#### 4.2.2 Digital Work Allocation: Supervisor-Based

The second operational layer focused on digital work allocation through supervisor-based interfaces. After site entry and morning assembly, employees reported to their respective supervisors, who allocated tasks using tablet-based digital portals directly linked to the centralised system. These portals provided real-time access to verified personnel profiles, including trade classification, skill set, attendance status, and site location. The supervisor portal featured a visual drag-and-drop interface, allowing workers to be assigned to

specific work packages, floors, zones, or activities, with each assignment linked to relevant cost codes. Task allocations were immediately synchronised across the system, updating attendance records, time-office databases, and the Project Manager dashboard in real time. The system also allowed supervisors to reassign workers dynamically in response to changing site conditions. By digitising work allocation, the system replaced manual allotment sheets and informal verbal instructions, reducing administrative workload and improving accountability.

#### 4.2.3 Real-Time Attendance, Exit Control and Security

The automated system incorporated real-time attendance monitoring and exit management to ensure accurate recording of workforce presence. Employees were required to swipe their RFID cards at designated terminals when leaving work areas or exiting the site. Facial-recognition verification at exit points added an additional layer of identity confirmation. Security personnel were integrated into the digital workflow, relying on system-generated alerts instead of discretionary checks. Abnormal movements, such as repeated exits or leaving designated areas prematurely, triggered automatic alarms. All attendance, exit, and security events were time-stamped and logged, creating a complete and verifiable audit trail.

#### 4.2.4 Timecards, Payroll and Labour Billing Automation

The system enabled full automation of workforce timekeeping, payroll processing, and labour-supplier billing. Digital timecards were automatically generated for each worker based on attendance and exit records, eliminating manual data entry and post-processing. Payroll calculations were directly derived from digital timecards using predefined rules. Salary balances were automatically maintained and made accessible to workers through on-site display systems and RFID-enabled interfaces, allowing workers to independently verify their attendance and earnings, reducing reliance on supervisors and minimising payroll-related disputes. Labour-supplier billing was automated using verified system records, ensuring alignment between attendance data and billed labour and strengthening financial control.

#### 4.2.5 Welfare, Cafeteria and Leave Management

Cafeteria and accommodation access were controlled using the same RFID cards. Scanning at access points enabled real-time recording of usage, allowing accurate tracking of meals and accommodation at an individual level. All transactions were digitally linked to user identities, preventing duplication and unauthorised access. This system replaced manual coupon-based methods, reducing administrative workload, minimising errors, and improving transparency in welfare distribution. Leave and special meal requests were managed through a mobile application, with requests automatically routed through predefined approval workflows and all decisions recorded electronically.

#### 4.2.6 Project Manager Digital Dashboard

A centralised Project Manager (PM) digital dashboard was developed to aggregate and present site-wide operational data through a single visual interface. The dashboard displayed daily manpower distribution by trade, location, and work package, enabling managers to identify labour congestion, imbalances, and coverage gaps. Labour usage was aligned with project cost codes, enabling evaluation of workforce-related expenditure alongside productivity indicators. The dashboard also provided consolidated views of material consumption and equipment performance, including operating hours and idle

time. Exception alerts highlighted critical issues such as workforce shortages, delays, material unavailability, and underutilised equipment, enhancing coordination across supervisory, planning, and commercial teams.

#### 4.2.7 Material and Machinery Tracking Extension

Building on the success of workforce tracking and digital attendance, the automated system was extended to material and machinery management. Every withdrawal from site stores was linked to specific workers, work packages, and cost codes via RFID and digital verification, generating a fully auditable record of material usage. Daily reconciliation of material consumption prevented theft, unauthorised use, or over-issuance. Machinery assignment and operation were centralised through the same digital platform, with operator hours, idle time, and equipment location logged automatically. By consolidating workforce, material, and equipment data in real time, the system enabled proactive decision-making, improved cost management, enhanced resource governance, and facilitated accurate financial forecasting.

### 4.3 CRITICAL CONSTRAINTS AND MITIGATORY STRATEGIES

The automated system was continuously refined to improve productivity measurement and workforce integration in a complex construction environment.

#### 4.3.1 Refinement of Productivity Measurement

Initially, wearable biometric devices, such as wristbands capturing pulse and movement, were tested to monitor productivity in real time. However, these devices misinterpret non-work-related activity, like rest periods or minor movements, as productive work, making the data unreliable. Consequently, the system adopted a task-based productivity model, using digitally assigned tasks, verified attendance, and RFID-tracked work locations. Integration of task allocation, attendance validation, and supervisory confirmation enabled automatic detection of deviations, ensuring productivity data reflected actual labour utilisation rather than inferred activity. This highlighted the limitations of relying solely on biometric data and emphasised the need for combining task-based, location-based, and supervisory verification.

#### 4.3.2 Workforce Adaptation and Change Management

The RFID-based system initially faced resistance, primarily behavioural, due to concerns over increased monitoring, perceived loss of informal practices, and unfamiliarity with digital technology. Previously accepted practices, such as proxy attendance and informal adjustments, were disrupted, creating hesitation among workers. A structured, phased change management strategy addressed these challenges through training, hands-on demonstrations, and orientation programs for workers, supervisors, and administrative staff. Real-time access to attendance and payroll via mobile apps empowered workers to self-verify records, reducing disputes and intermediaries. Extension of the system to store operations, digitised tools and material tracking, further enhancing transparency and accountability. Phased implementation, continuous feedback, and on-site supervisory support ensured gradual adaptation, allowing workers to recognise tangible benefits such as accurate wages, streamlined processes, and improved welfare access.

### 4.4 PERFORMANCE UNDER PANDEMIC CONDITIONS

The COVID-19 pandemic presented an unplanned but analytically significant test environment for the integrated digital ecosystem at the ABC Project, ultimately validating its strategic value beyond routine operational efficiency. Traditional manual site management, which depends on physical presence for attendance verification, task allocation and payroll processing, was rendered unworkable by social distancing mandates and mobility restrictions. The integrated digital platform, however, ensured uninterrupted operational continuity. RFID-based attendance data and facial recognition records were accessible remotely by management and time-office staff, while supervisors retained full operational control through digital interfaces, allocating tasks and overseeing resource utilisation without requiring physical site presence. Payroll processing remained fully automated based on system-verified attendance and task completion data, with subcontractor invoices and salary disbursements authorised electronically, eliminating payment delays and manual reconciliation errors. Centralised dashboards provided management with continuous, real-time visibility into site performance, enabling informed decision-making despite significantly reduced physical oversight capacity. The pandemic experience, therefore, demonstrated that an integrated digital site management ecosystem extends beyond operational efficiency, where it constitutes a governance and continuity under conditions of severe external disruption, demonstrating the necessity of construction digitalisation in large-scale projects across developing economies.

### 4.5 SUMMARY OF FINDINGS

Table 1 presents a consolidated summary of the key operational challenges addressed, digital mechanisms deployed and observed outcomes across the seven functional modules of the integrated site management ecosystem.

*Table 1: Summary of key findings by system module*

| System Module | Key Challenge Addressed | Digital Mechanism Deployed | Observed Operational Outcome |
|---|---|---|---|
| People Registration & Access Control | Proxy attendance; unauthorised site entry; absence of verified audit trail | RFID + facial recognition; single controlled entry point; timestamped access log | Substantially reduced proxy entries; comprehensive audit trail established; verified workforce identity at site entry |
| Digital Work Allocation | Manual allotment sheets; informal verbal instructions; no direct link between labour and cost codes | Tablet-based supervisor portal; drag-and-drop task assignment linked to cost codes and work packages | Improved labour deployment traceability; direct connection between attendance, task, and project expenditure |
| Real-Time Attendance & Exit Control | Delayed and discretionary attendance records; early releases; manipulation by | RFID exit terminals; facial recognition; automatic alerts for abnormal movements | Accurate work-hour recording; reduced dependency on manual checks; strengthened site security |

| System Module | Key Challenge Addressed | Digital Mechanism Deployed | Observed Operational Outcome |
|---|---|---|---|
| | workers and supervisors | | |
| Timecards, Payroll & Labour Billing | Manual payroll processing; discrepancies between billed and actual labour; payroll disputes | Automated digital timecards; predefined payroll rules; supplier billing from verified records | Reduced administrative workload; improved payroll accuracy; fewer disputes; aligned cost reporting |
| Welfare, Cafeteria & Leave Management | Manual coupon systems; unauthorised welfare access; informal leave processes | RFID-controlled cafeteria/accommodation access; mobile app for leave and meal requests | Eliminated unauthorised usage; improved coordination; accurate welfare cost tracking |
| Project Manager Dashboard | Fragmented, delayed operational data; reactive decision-making; limited cost visibility | Centralised cloud-based dashboard aggregating manpower, cost, materials, and equipment data in real time | Enabled data-driven, proactive decision-making; improved resource control and deviation detection |
| Material & Machinery Tracking | Uncontrolled withdrawals; equipment idle time; difficulty linking resource use to cost codes | RFID-based material tracking; machinery allocation and usage logging linked to work packages | Reduced wastage and theft; optimised equipment deployment; accurate financial forecasting |
| System Performance under COVID-19 | Traditional manual management rendered unworkable by mobility restrictions and social distancing | Remote access to RFID attendance data; digital task allocation; automated payroll processing | Uninterrupted operational continuity; validated strategic value as governance and resilience infrastructure |

## 5. DISCUSSION

The findings of this study substantiate and extend existing literature, providing empirical validation that an integrated digital ecosystem approach to construction site management demonstrably outperforms both traditional manual systems and isolated technological deployments in large-scale construction environments. The deficiencies of manual site management, such as proxy attendance, payroll manipulation, resource misallocation and informal supervisory practices, were identified as issues in Sri Lankan construction by Wijerathna et al. (2024a). These were comprehensively eliminated through the closed-loop architecture of the ABC Project platform, confirming that these failures can be resolved when addressed through integrated digital design.

The literature further established that individual technologies, while demonstrating domain-specific benefits, consistently fail to resolve the systemic interdependencies between workforce management, cost control and resource utilisation (Kereri & Adamtey., 2019). The ABC Project findings validate this argument precisely by the integration of RFID access control, facial recognition, supervisor-facing task allocation portals, automated payroll and centralised dashboard analytics into a single, synchronised platform that produced outcomes that no individual technology could have achieved in isolation. The direct linkage of labour deployment to cost codes and work packages,

material withdrawals to specific work zones, and machinery utilisation to verified task completion created an end-to-end operational visibility that fundamentally restructured the informational architecture of site management, as theoretically anticipated by Lu et al. (2011) and Tan and Sidhu (2022).

The workforce resistance encountered during initial implementation aligns with findings recorded by Wijerathna et al. (2024b), who identified resistance to technology adoption as one of the most significant barriers to construction digitalisation in developing economies. However, the findings demonstrate that structured change management through phased deployment, training and transparent self-verification of attendance and payroll successfully converted resistance into acceptance, confirming that adoption barriers are more transitional than structural. Finally, the system's uninterrupted performance during the COVID-19 pandemic showcases and validates findings that are absent from the existing literature, that integrated digital ecosystems constitute a governance and continuity infrastructure extending beyond routine operational efficiency. This establishes a compelling empirical foundation for construction digitalisation across developing economies.

While the ABC Project was implemented within a specific Sri Lankan context, there are reasonable grounds to consider its implications for similar settings. Large-scale construction projects in other developing economies share comparable structural challenges including high workforce density, limited supervisory reach, vulnerability to informal practices, and weak real-time data infrastructure. The core enabling factors of the ABC Project, including RFID access control, cloud-based data integration, supervisor-facing digital interfaces, and automated payroll are technically deployable across a range of project scales and national contexts. The general operational principles of digital workforce verification, task-linked cost tracking and centralised dashboard governance are not exclusive to Sri Lanka, and analogous outcomes might reasonably be expected in other developing-economy mega-projects where similar manual management deficiencies are present. However, variations in institutional readiness, IT infrastructure maturity, labour relations, regulatory environments and organisational capacity could meaningfully influence implementation outcomes.

The findings carry significant implications across multiple dimensions. For practitioners, the study provides a blueprint for integrated digital site management in large-scale construction projects across developing economies. For academia, it establishes a real-life implemented digital system that validates and advances the theoretical understanding of integrated digital ecosystems in construction management. For society, this system promotes ethical labour practices, fair wage distribution and transparent resource governance in an industry that directly affects large working populations. In addition, future research should pursue multi-site replication studies to develop and validate a standardised integrated digital site management framework across diverse developing-economy construction contexts.

## 6. CONCLUSIONS AND RECOMMENDATIONS

Large-scale construction projects in developing economies such as Sri Lanka have long been constrained by traditional manual site management practices. Attempts to address these deficiencies through isolated technological deployments have proven insufficient. This study addresses that gap by integrating a digital site management ecosystem.

Through a ten-month evaluative case study of the ABC Project, a large-scale, high-density construction environment in Sri Lanka, the study provides real-world evidence that such integration is not only technically achievable but operationally transformative.

The findings demonstrate that the integrated digital ecosystem comprehensively eliminated the structural deficiencies of traditional manual site management, such as proxy attendance, payroll manipulation, resource misallocation and informal supervisory practices while simultaneously strengthening governance, financial transparency and workforce accountability. The task-based productivity model, developed following the rejection of wearable biometric devices, established a more valid and reliable approach to productivity measurement in construction environments. The system performance during the COVID-19 pandemic further validated its strategic value as a continuity infrastructure extending beyond routine operational efficiency.

This study is limited to a single case in the Sri Lankan context. Additionally, only qualitative data was collected, as the research was planned after actual implementation; the study therefore relies on observation-based evidence from real-world experience rather than quantitative pre-post measurement. These limitations constrain the generalisability of findings and should be addressed in future research. Future studies should pursue multi-site, cross-country replication to develop and validate a standardised framework for integrated digital site management across diverse developing-economy construction contexts. Based on the findings, this study recommends that future large-scale projects adopt end-to-end integrated digital platforms connecting workforce, task, resource and cost in real time, supported by phased implementation, structured change management, task-based productivity measurement and remote operational capability.

## 7. REFERENCES

Alaloul, W. S., Liew, M. S., Zawawi, N. A. W., Mohammed, B. S., Adamu, M., & Musharat, M. A. (2020). Structural equation modelling of construction project performance based on coordination factors. *Cogent Engineering*, *7*(1). https://doi.org/10.1080/23311916.2020.1726069

Bansal, V. K. (2020). Use of GIS to consider spatial aspects in the construction planning process. *International Journal of Construction Management*, *20*(3), 1–16. https://doi.org/10.1080/15623599.2018.1484845

Creswell, J. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). Sage Publications Ltd.

Huang, R., Tsai, T.Y., & Wang, H.H. (2019). Developing an RFID-based tracking system to improve the control of construction surplus soil disposal in Taiwan. *Journal of the Chinese Institute of Engineers*, *42*(2), 175–188. https://doi.org/10.1080/02533839.2018.1553629

Kereri, J. O., & Adamtey, S. (2019). RFID use in residential/ commercial construction industry. *Journal of Engineering, Design and Technology*, *17*(3), 591–612. https://doi.org/10.1108/jedt-07-2018-0118

Kineber, A. F., Oke, A. E., Elseknidy, M., Hamed, M. M., & Kayode, F. S. (2023). Barriers to the Implementation of Radio Frequency Identification (RFID) for Sustainable building in a developing economy. *Sustainability*, *15*(1), 825. https://doi.org/10.3390/su15010825

Kozlovska, M., Klosova, D., & Strukova, Z. (2021). Impact of industry 4.0 platform on the formation of construction 4.0 concept: A literature review. *Sustainability*, *13*(5), 2683. https://doi.org/10.3390/su13052683

Krippendorff, K. (2018). *Content analysis: An introduction to its methodology* (4th ed.). SAGE Publications.

Lu, W., Huang, G. Q., & Li, H. (2011). Scenarios for applying RFID technology in construction project management. *Automation in Construction*, *20*(2), 101–106. https://doi.org/10.1016/j.autcon.2010.09.007

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2020). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. *International Journal of Construction Management*, *23*(1), 1–35. https://doi.org/10.1080/15623599.2020.1854042

Rajakaruna, R., Bandara, K., & Silva, N. De. (2008). Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors. In: Haigh, D. Amarathunga (eds.), *Proceedings from international conference on building education and research (BEAR)* 11-15 February 2008, School of the Built Environment, University of Salford, UK. 158-169.

Santoso, D. S., & Gallage, P. G. M. P. (2020). Critical factors affecting the performance of large construction projects in developing countries. *Journal of Engineering, Design and Technology*, *18*(3), 531–556. https://doi.org/10.1108/jedt-05-2019-0130

Tan, W. C., & Sidhu, M. S. (2022). Review of RFID and IoT integration in supply chain management. *Operations Research Perspectives*, *9*(9), 100229. https://doi.org/10.1016/j.orp.2022.100229

Wijerathna, M. R. D. P., Waidyasekara, K. G. A. S., & Atapattu, A. M. D. S. (2024a). Strategies to enhance radio frequency identification (RFID) technology applications in the construction industry. *Construction Innovation*. *26*(4), 984–1005. https://doi.org/10.1108/ci-06-2024-0174

Wijerathna, M. R. D. P., Waidyasekara, K. G. A. S., & Atapattu, A. M. D. S. (2024b). Unveiling the benefits of radio frequency identification (RFID) technology for enhancing technological applications in Sri Lankan construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds) *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. 1088–1100. https://doi.org/10.31705/wcs.2024.86

Yin, R.K. (2018), *Case Study Research and Design Methods*, 6th ed., Sage.

Mai, V. and Nguyen, T.Q., 2026. Digitalising urban drainage systems: Barriers and implications for Vietnam. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 578-591. DOI: https://doi.org/10.31705/WCS.2026.43. Available from: https://ciobwcs.com/papers/

# DIGITALISING URBAN DRAINAGE SYSTEMS: BARRIERS AND IMPLICATIONS FOR VIETNAM

**V. Mai[1] and T.Q. Nguyen[2]**

## *ABSTRACT*

*Urban flooding is an increasing challenge for cities due to rapid urbanisation, climate change, and the growing complexity of urban infrastructure systems. Digital technologies such as Internet of Things monitoring networks, Artificial Intelligence (AI), digital twins, and geographic information systems have been proposed to enhance the monitoring and management of Urban Drainage Systems (UDS). However, large-scale implementation of digitalised drainage infrastructure remains constrained by multiple socio-technical barriers. This study conducts a structured literature review to identify key barriers to the digitalisation of urban drainage systems and to examine their implications for digital infrastructure governance in Vietnam. Using the Scopus database, a multi-stage screening process identified 71 peer-reviewed publications addressing digital technologies in drainage infrastructure. The studies were analysed using thematic synthesis to identify recurring implementation challenges and develop a structured framework of barriers to UDS digitalisation. The analysis reveals four major barrier categories. Data-related barriers include incomplete infrastructure records, legacy datasets, fragmented data management, and unreliable sensor data. Technological barriers involve integration with legacy infrastructure, high computational requirements, limited model scalability, and low interpretability of AI systems. Institutional barriers relate to shortages of interdisciplinary expertise, fragmented governance structures, and risk-averse organisational cultures, while financial barriers include high capital investment, ongoing operational costs, and uncertain economic returns. The findings highlight several implications for Vietnam, including strengthening infrastructure data governance, adopting phased technology deployment strategies, improving coordination among urban infrastructure agencies, and developing sustainable financing mechanisms for digital infrastructure investment.*

***Keywords:*** *Digital Infrastructure Barriers; Digitalisation; Smart Water Management; Urban Drainage Systems; Urban Flood Resilience.*

## 1. INTRODUCTION

Urban flooding has become an increasingly critical challenge for cities worldwide due to rapid urbanisation, climate change, and the growing complexity of urban infrastructure systems. Intensifying rainfall events and expanding impervious surfaces have placed substantial pressure on conventional UDS, many of which were designed under historical climatic assumptions. As a result, cities are experiencing more frequent pluvial flooding

[1] Msc, Faculty of Information Technology, Hanoi Architectural University, Vietnam, maivu@hau.edu.vn
[2] Associate Professor, PhD, Faculty of Construction Economics and Management, Hanoi University of Civil Engineering, Vietnam, quannt@huce.edu.vn

and infrastructure overload, highlighting the need for more adaptive drainage management strategies (Pirone et al., 2026; Rasool et al., 2025).

Traditionally, drainage management has relied on hydraulic modelling, periodic inspections, and reactive maintenance. While these approaches remain essential for infrastructure operation, their effectiveness is increasingly constrained by limited monitoring coverage, delayed data availability, and fragmented infrastructure information systems (Okwori et al., 2024). These limitations reduce the ability of urban authorities to anticipate flooding risks and coordinate infrastructure planning across complex urban systems.

Recent advances in digital technologies offer new opportunities to enhance the monitoring and management of drainage infrastructure. The integration of these technologies supports a transition from reactive maintenance toward more proactive and data-driven drainage management (Rousso & Gong, 2026). In this study, digitalisation refers to the progressive integration of digital technologies, data infrastructures, and analytical capabilities into the planning, operation, and management of urban drainage systems. This process may range from basic digital asset management and monitoring to more advanced applications such as predictive analytics and digital twins (Rousso & Gong, 2026). Accordingly, barriers are defined as technical, organisational, institutional, or financial constraints that hinder the adoption, integration, or scaling of digital technologies within urban drainage management.

Despite recent technological developments, the implementation of digitalised drainage systems remains uneven across cities due to barriers related to fragmented datasets, technological integration, institutional coordination, and financial capacity (Cabral et al., 2019; Okwori et al., 2024; Rousso et al., 2024). These challenges are particularly relevant in rapidly urbanising countries such as Vietnam. Although drainage infrastructure in cities such as Hanoi and Ho Chi Minh City has been upgraded in recent decades, many networks still rely on incomplete infrastructure records, limited monitoring systems, and fragmented data management practices (Doan et al., 2023; Nguyen et al., 2022). Recent studies have begun to explore the application of digital technologies for drainage modelling and infrastructure management in Vietnam (Mai et al., 2025).

However, existing research largely focuses on the technical performance of individual technologies rather than the broader socio-technical barriers affecting large-scale digital transformation of UDS. Consequently, there remains limited synthesis of the organisational, technological, and financial constraints shaping the digitalisation of drainage infrastructure (Pirone et al., 2026; Rousso & Gong, 2026). To address this gap, this study provides a structured literature review of the barriers to the digitalisation of urban drainage systems and examines their implications for urban infrastructure management in Vietnam.

Specifically, the study addresses the following research questions: (i) What are the main barriers to the digitalisation of UDS identified in the existing literature? (ii) What implications do these barriers have for the development of digital drainage management strategies in Vietnam? By synthesising current research on digital technologies and infrastructure governance, this study makes three contributions. First, it provides one of the first integrated reviews focused specifically on the digitalisation of urban drainage systems rather than individual technologies or broader smart water initiatives. Second, it develops a synthesis framework that consolidates fragmented evidence into four

interconnected categories of barriers affecting digital transformation. Third, it translates international evidence into context-specific implications for Vietnam, thereby linking global digitalisation challenges with the needs of rapidly urbanising cities.

# 2. RESEARCH METHODOLOGY

This study adopts a structured literature review to identify and synthesise research on the digitalisation of UDS and the associated technological and organisational challenges. Literature reviews are widely used to consolidate fragmented knowledge in rapidly evolving interdisciplinary domains such as smart infrastructure and digital water management (Pirone et al., 2026; Rousso & Gong, 2026). The review process comprised three stages: literature identification, screening of relevant publications, and thematic synthesis.

## 2.1 LITERATURE SEARCH AND DATA COLLECTION

The primary data source was the Scopus database, one of the largest indexing platforms for peer-reviewed research in engineering and environmental infrastructure. A structured keyword query was used to identify studies addressing both urban drainage systems and digital technologies. The search expression included terms related to drainage infrastructure and digitalisation technologies such as BIM, digital twins, remote sensing, and reality capture.

(urban OR city OR cities OR metropolitan OR municipal) AND (("drainage system*" OR "drainage network*" OR "stormwater system*" OR "stormwater drainage" OR "sewer system" OR "sewer network*" OR "wastewater network*" OR "drainage infrastructure") AND (BIM OR "Building Information Modelling" OR "Building Information Modeling" OR digital* OR "digital twin" OR "digital twins" OR "reality capture" OR "point cloud" OR "laser scanning" OR LiDAR OR photogrammetry OR UAV OR "remote sensing"))

The initial search returned 741 publications. After restricting the dataset to English-language research papers and removing unrelated subject areas, the dataset was reduced to 372 studies. Title and abstract screening were then conducted to identify studies specifically addressing digital technologies in UDS. After verifying full-text availability, the final dataset consisted of 71 peer-reviewed publications from different international contexts, which formed the basis for the thematic synthesis of barriers.

## 2.2 IDENTIFICATION OF STUDIES RELATED TO VIETNAM

To provide contextual insights for policy implications, a supplementary search was conducted to identify studies addressing urban drainage systems in Vietnam using the following query:

(urban OR city OR cities OR metropolitan OR municipal) AND (("drainage system*" OR "drainage network*" OR "stormwater system*" OR "stormwater drainage" OR "sewer system" OR "sewer network*" OR "wastewater network*" OR "drainage infrastructure") AND Vietnam)

The search initially identified 73 publications. After excluding conference reviews and screening titles and abstracts, the dataset was restricted to studies published from 2020 onwards. Following full-text screening, 22 publications were retained (including one study overlapping with the international dataset). These studies were used solely to

provide contextual insights for the discussion of implications in Vietnam and were not included in the primary thematic synthesis, which was based on the 71 international publications identified in Section 2.1.

### 2.3 LITERATURE SYNTHESIS AND ANALYTICAL APPROACH

The selected publications were analysed using thematic synthesis, a method commonly applied in structured literature reviews to identify recurring patterns across heterogeneous studies (Pirone et al., 2026; Rousso & Gong, 2026). An inductive coding approach was adopted to allow barrier categories to emerge from the literature rather than being predefined. Similar coding procedures have been widely adopted in thematic synthesis studies to improve transparency and consistency in qualitative evidence synthesis (Thomas & Harden, 2008).

The coding process involved three stages. First, statements describing implementation challenges were extracted from each publication and assigned descriptive codes. For example, findings related to missing historical flood records, incomplete monitoring datasets, and outdated infrastructure documentation were initially coded as data availability limitations. These codes were subsequently grouped into the broader theme of data management challenges and ultimately classified under the category of data-related barriers. Similarly, findings describing fragmented agency responsibilities and coordination difficulties were initially coded as governance fragmentation. These codes were subsequently grouped into broader institutional coordination challenges and ultimately classified under institutional and human capacity barriers. Second, similar codes were iteratively compared and grouped into higher-order themes through constant comparison across the reviewed studies. Third, the resulting themes were repeatedly reviewed and refined to ensure conceptual consistency and minimise overlaps between categories. To enhance methodological rigour, the coding process involved multiple rounds of review and re-coding, and categories were retained only when they consistently represented similar implementation challenges across multiple publications. This iterative process continued until no additional categories emerged from the literature.

The final synthesis identified four major categories of barriers: data-related barriers, technological and modelling barriers, institutional and human capacity barriers, and financial barriers. These categories form the analytical framework used to examine the challenges of digitalising urban drainage systems.

## 3. DIGITALISATION TECHNOLOGIES IN UDS

Recent advances in digital technologies are transforming the monitoring and management of UDS. Conventional drainage management has traditionally relied on hydraulic modelling and periodic inspections; however, these approaches often struggle to address the increasing complexity of urban hydrological processes driven by urbanisation and climate change. Consequently, digital technologies have emerged as key enablers for improving monitoring accuracy, predictive capabilities, and operational efficiency in drainage management (Pirone et al., 2026; Rousso & Gong, 2026). The literature indicates that the digitalisation of UDS typically involves the integration of several complementary technologies that support real-time monitoring, data-driven analysis, and infrastructure simulation. Four major technological domains are commonly highlighted i.e. (i) IoT-based monitoring systems, (ii) artificial intelligence for flood prediction, (iii) digital twin platforms, and (iv) GIS-based infrastructure mapping.

### 3.1 IoT-Based Monitoring Systems

IoT-based monitoring systems enable continuous observation of drainage network conditions through sensors deployed in pipes, manholes, and pumping stations. These sensors monitor variables such as water level, flow velocity, and rainfall intensity, transmitting real-time data to monitoring platforms. Such systems improve situational awareness and enable utilities to detect anomalies and respond more rapidly to flooding risks (Pedersen et al., 2022; Wei et al., 2026). Although widely adopted, IoT monitoring systems face operational challenges, including sensor degradation, signal interference, and maintenance requirements in harsh sewer environments (Cabral et al., 2019). Nevertheless, real-time monitoring remains a foundational component of digitalised drainage systems.

### 3.2 AI and Data-Driven Flood Prediction

Artificial intelligence and machine learning techniques are increasingly applied to improve flood prediction and hydrological modelling in urban drainage systems. By analysing datasets generated from monitoring systems and rainfall observations, machine learning models can identify patterns and support short-term flood prediction and anomaly detection in drainage networks (Agonafir et al., 2022). Recent studies have explored deep learning architectures, including convolutional and recurrent neural networks, for analysing large spatiotemporal datasets associated with urban flooding (Gao et al., 2024). While these models show promising predictive performance, their reliability depends strongly on data availability and monitoring coverage.

### 3.3 Digital Twin Platforms

Digital twin technology has gained increasing attention as a platform for integrating monitoring data, simulation models, and decision-support tools. A digital twin represents a dynamic virtual model of infrastructure that continuously updates its state using real-time monitoring data (Kim & Bartos, 2024). In drainage management, digital twins allow operators to simulate hydraulic behaviour, evaluate infrastructure performance, and support predictive maintenance and operational decision-making (Fan et al., 2025). However, implementing such systems requires substantial investment in digital infrastructure and organisational capacity.

### 3.4 GIS and Digital Infrastructure Mapping

GIS provide the spatial framework for managing drainage infrastructure data. GIS-based platforms enable utilities to map drainage networks, manage asset inventories, and analyse flood vulnerability using spatial datasets such as topography and land use (Martin et al., 2020). Recent research also highlights the integration of GIS with BIM and digital twin platforms to create more comprehensive digital representations of urban infrastructure systems (Smith et al., 2023; Yang et al., 2021).

Table 1 summarises the main digital technologies identified in the literature together with their key functions and applications in urban drainage management.

*Table 1: Major digital technologies applied in urban drainage systems*

| Technology | Main functions | Typical applications in drainage systems | Key references |
|---|---|---|---|
| IoT sensors and monitoring networks | Real-time data acquisition and infrastructure monitoring | Monitoring water levels, flow rates, rainfall intensity, and sewer network performance | (Pedersen et al., 2022); (Wei et al., 2026) |
| Artificial intelligence models | Data-driven prediction and anomaly detection | Flood prediction, pattern recognition, and anomaly detection in drainage networks | (Agonafir et al., 2022); (Gao et al., 2024) |
| Digital twin platforms | Dynamic simulation and system optimisation | Simulation of drainage network behaviour, predictive maintenance, and operational decision support | (Kim & Bartos, 2024); (Fan et al., 2025) |
| GIS infrastructure databases | Spatial infrastructure mapping and asset management | Mapping drainage networks, flood vulnerability analysis, and infrastructure asset management | (Martin et al., 2020); (Smith et al., 2023) |

Table 1 illustrates that the digitalisation of UDS relies on the integration of monitoring, analytical, simulation, and spatial information technologies. These technologies provide the technical foundation for more proactive and data-driven drainage management. The following section examines the key barriers that constrain their large-scale implementation.

# 4. BARRIERS TO THE DIGITALISATION OF UDS

Despite growing interest in digital technologies for urban drainage management, the implementation of digitalised UDS remains constrained by several systemic barriers. Based on the synthesis of the 71 peer-reviewed publications analysed in this study, the literature indicates that these challenges can be broadly grouped into four categories: data-related barriers, technological and modelling barriers, institutional and human capacity barriers, and financial and economic barriers. These barriers are closely interconnected and collectively influence the pace and effectiveness of digital transformation. Although certain barriers are more strongly associated with specific technologies (e.g., sensor reliability for IoT systems or interoperability challenges for digital twins), the reviewed literature indicates that many barriers, particularly those related to data governance, institutional capacity, and financing, recur across multiple digital technologies. For this reason, the barriers were classified according to their underlying characteristics rather than individual technology types.

## 4.1 DATA-RELATED BARRIERS

Data-related barriers represent one of the most frequently reported challenges in the literature. Digital technologies such as AI-based flood prediction, digital twins, and predictive maintenance systems depend on reliable datasets describing infrastructure assets and hydrological conditions. However, many studies highlight that drainage infrastructure data are often incomplete, fragmented, or outdated. In many cities, historical flood records and infrastructure documentation remain limited, which restricts the development and calibration of predictive models (Ahmad et al., 2025; Anik et al.,

2025). Legacy data formats remain a major constraint. Infrastructure information is frequently stored in paper archives or static CAD drawings, which limits integration with digital monitoring platforms and modelling systems (Sivakumar et al., 2025). Another widely reported issue is data fragmentation across organisational units. Infrastructure datasets are often maintained by separate agencies using incompatible database structures and asset identification systems, which complicates data integration and interoperability between digital platforms (Li et al., 2022; Okwori et al., 2024). In addition, sensor-based monitoring systems may generate noisy or incomplete datasets due to harsh underground operating environments. These data quality issues can reduce the reliability of digital models and decision-support systems (Kim et al., 2025; Wei et al., 2026). These findings highlight the importance of improving data availability, standardisation, and governance.

## 4.2 TECHNOLOGICAL AND MODELLING BARRIERS

The literature identifies several technological and modelling challenges associated with implementing digital solutions in drainage infrastructure systems. One major challenge concerns the integration of new digital technologies with legacy drainage infrastructure. Urban sewer networks often consist of heterogeneous components developed over long periods, which complicates the integration of modern monitoring systems and digital platforms (Okwori et al., 2024). Hardware reliability represents a significant constraint. Sensors deployed in underground sewer environments are exposed to moisture, corrosion, sediment accumulation, and limited maintenance accessibility, which can reduce system reliability and increase maintenance requirements (Rousso & Gong, 2026). Another challenge relates to the computational requirements of advanced modelling systems. High-resolution hydrodynamic simulations and digital twin platforms often require substantial computational resources that may exceed the technical capacity of many municipal utilities (Fan et al., 2025; Yang et al., 2021). The literature highlights limitations associated with AI-based modelling approaches. While machine learning algorithms can improve predictive performance, many models function as “black box” systems, which reduces interpretability and may limit trust among infrastructure operators (Sharifi et al., 2024). In addition, many digital modelling frameworks remain highly site-specific and require extensive recalibration when applied to different urban contexts, limiting their scalability (Wei et al., 2026).

## 4.3 INSTITUTIONAL AND HUMAN CAPACITY BARRIERS

Digitalisation of UDS requires significant organisational adaptation within infrastructure management institutions. One commonly cited barrier is the shortage of interdisciplinary expertise required to develop and operate digital infrastructure systems. Implementing technologies such as digital twins or AI-based monitoring requires combined knowledge in hydrology, data science, and information technology, which remains limited in many water utilities (Bertrand-Krajewski et al., 2025; Martin et al., 2020). Organisational culture can influence technology adoption. Several studies report that water utilities often exhibit risk-averse management cultures, where decision-makers prioritise established operational practices over innovative digital approaches (Rousso et al., 2024). Institutional fragmentation further complicates digital transformation. Responsibilities for drainage infrastructure are frequently distributed across multiple government agencies, which can limit coordination in data management, infrastructure planning, and digitalisation strategies (Mai et al., 2025). In addition, the absence of clear governance

frameworks for digital infrastructure management such as guidelines for data sharing and asset identification, can hinder the development of coherent digitalisation strategies.

### 4.4 FINANCIAL AND ECONOMIC BARRIERS

Financial constraints represent another major obstacle to the digitalisation of UDS. Implementing digital infrastructure requires substantial investment in monitoring systems, communication networks, and modelling platforms. One commonly cited challenge concerns the high initial capital expenditure associated with deploying sensor networks and digital infrastructure platforms (Cabral et al., 2019). Digital systems generate ongoing operational expenditures related to system maintenance, data management, and hardware replacement (Kim et al., 2025). Another challenge involves the difficulty of quantifying the economic benefits of digitalisation initiatives. Although digital technologies can improve monitoring and flood management capabilities, their financial returns are often difficult to measure in conventional cost–benefit frameworks (Rousso et al., 2024).

Finally, many digital infrastructure initiatives rely on short-term research funding or pilot programmes, which may limit the long-term sustainability of implemented technologies. Table 2 summarises the main barriers identified in the literature together with representative examples discussed in previous studies.

*Table 2: Key barriers to the digitalisation of urban drainage systems identified in the literature*

| Category & specific barrier | Description of barrier | Representative references |
|---|---|---|
| ***Data-related barriers*** | | |
| Lack of reliable infrastructure data | Many drainage networks lack accurate digital records, as-built drawings, or long-term monitoring data required for hydraulic model calibration and digital twin development | (Ahmad et al., 2025); (Anik et al., 2025) |
| Legacy and non-digital datasets | Infrastructure information often remains stored in paper archives or static CAD drawings, limiting integration with modern digital platforms | (Sivakumar et al., 2025) |
| Fragmented data management | Infrastructure data are frequently distributed across multiple agencies and databases using incompatible data structures and asset identification systems | (Li et al., 2022); (Okwori et al., 2024) |
| Lack of data standardisation | Absence of standardised metadata frameworks and asset identification systems reduces interoperability between digital platforms such as GIS, hydraulic models, and digital twins | (Li et al., 2022); (Okwori et al., 2024) |
| Sensor data reliability issues | IoT sensors deployed in sewer environments often produce noisy, incomplete, or inconsistent datasets due to harsh environmental conditions | (Kim et al., 2025); (Wei et al., 2026) |
| ***Technological and modelling barriers*** | | |
| Integration with legacy infrastructure | Existing drainage systems consist of heterogeneous infrastructure built over long periods, making integration with modern digital technologies technically complex | (Okwori et al., 2024) |

| Category & specific barrier | Description of barrier | Representative references |
|---|---|---|
| Hardware reliability and maintenance | Sensors and monitoring equipment in sewer environments are exposed to corrosion, debris, and high humidity, increasing maintenance requirements | (Rousso & Gong, 2026) |
| High computational requirements | Advanced hydrodynamic models and digital twin simulations require high-performance computing resources that may exceed the technical capacity of many utilities | (Yang et al., 2021); (Fan et al., 2025) |
| Limited interpretability of AI models | Many machine learning models operate as "black-box" systems, which reduces trust among infrastructure operators and decision-makers | (Sharifi et al., 2024) |
| Limited scalability of digital models | Digital modelling frameworks often require extensive recalibration when applied to different urban environments | (Wei et al., 2026) |
| ***Institutional and human capacity barriers*** | | |
| Lack of interdisciplinary expertise | Digital drainage systems require combined expertise in hydrology, data science, and software engineering, which is often scarce in municipal utilities | (Martin et al., 2020); (Bertrand-Krajewski et al., 2025) |
| Conservative organisational culture | Water utilities often exhibit risk-averse management cultures that discourage the adoption of innovative digital technologies | (Rousso et al., 2024) |
| Fragmented institutional governance | Drainage management responsibilities are often distributed across multiple government agencies, limiting coordinated digitalisation efforts | (Mai et al., 2025) |
| Absence of digital governance frameworks | Many cities lack clear policies or guidelines for data sharing, digital asset management, and digital infrastructure governance | (Asghari et al., 2023) |
| ***Financial and economic barriers*** | | |
| High initial capital investment (CAPEX) | Deployment of monitoring infrastructure, sensor networks, and digital platforms requires substantial upfront investments | (Cabral et al., 2019) |
| Long-term operational costs (OPEX) | Maintenance of sensors, communication networks, and data platforms generates ongoing operational costs | (Kim et al., 2025) |
| Uncertain economic benefits | Difficulty in quantifying economic returns of digital drainage systems can discourage investment decisions | (Rousso et al., 2024) |
| Dependence on short-term project funding | Many digital infrastructure initiatives rely on research grants or pilot projects that lack long-term financial sustainability | (Cabral et al., 2019) |

Table 2 demonstrates that barriers to UDS digitalisation extend beyond technology and encompass data, institutional, and financial dimensions. These findings provide the basis

for the implications discussed in the following section. Although the identified barriers may influence different stages and levels of digitalisation to varying degrees, the reviewed literature consistently highlights them as recurrent constraints affecting the broader digital transformation of urban drainage systems.

The reviewed studies further suggest that these barriers are highly interdependent rather than isolated. Data-related limitations, such as fragmented infrastructure records and poor data quality, directly constrain the effectiveness of AI models, digital twins, and other advanced technologies. At the same time, institutional fragmentation and limited interdisciplinary expertise often hinder data sharing, technology integration, and long-term digital governance. Financial constraints further influence the ability of utilities to invest in monitoring infrastructure, maintain digital platforms, and develop organisational capabilities. Consequently, barriers to UDS digitalisation should be viewed as a socio-technical system of interacting constraints rather than as independent challenges.

# 5. IMPLICATIONS FOR VIETNAM

The synthesis identifies four key implications for the digital transformation of urban drainage systems in Vietnam i.e. (i) data governance, (ii) technology adoption pathways, (iii) institutional coordination, and (iv) financing strategies.

## 5.1 STRENGTHENING DATA GOVERNANCE FOR DIGITAL DRAINAGE INFRASTRUCTURE

Reliable and interoperable data represent a fundamental requirement for digital drainage systems. However, drainage management in Vietnam still relies heavily on fragmented datasets and non-standardised documentation, often stored in paper records or static CAD drawings. International studies emphasise that standardised infrastructure datasets and monitoring data are essential for hydraulic modelling, predictive flood management, and digital platform integration (Pedersen et al., 2022; Smith et al., 2023). Similar challenges related to fragmented databases and inconsistent asset records have been widely reported in municipal water utilities (Okwori et al., 2024). Evidence from Vietnamese studies confirms that limited monitoring data and incomplete infrastructure records often constrain drainage modelling efforts in cities such as Hanoi and Ho Chi Minh City (Doan et al., 2023; Nguyen et al., 2025). In addition, rainfall and hydrological datasets remain insufficient in many cities, reducing the reliability of flood prediction models (Minh et al., 2022). An important implication for Vietnam is therefore the development of national or municipal data governance frameworks that support standardised asset identification, shared geospatial databases, and interoperable data platforms. International experience shows that GIS-based infrastructure databases can significantly enhance drainage planning and monitoring capabilities (Martin et al., 2020).

## 5.2 PATHWAYS FOR TECHNOLOGY ADOPTION IN VIETNAMESE CITIES

Digital technologies such as IoT monitoring systems, AI-based flood prediction, and digital twin platforms offer significant opportunities for improving drainage management (Fan et al., 2025; Sharifi et al., 2024). However, their implementation in Vietnam must account for the physical and operational constraints of existing infrastructure systems. Many drainage networks in Vietnamese cities consist of legacy infrastructure that was not designed for current rainfall intensities and urban densities. As a result, large-scale deployment of advanced digital technologies may face significant technical and

operational constraints. International studies highlight that successful digitalisation often occurs through incremental technological integration rather than large-scale system replacement (Rousso et al., 2024). Initial steps may include sensor-based monitoring and GIS asset databases, followed by the gradual integration of predictive modelling and digital twin technologies. Existing modelling studies in Vietnamese cities already demonstrate the potential of digital tools to improve flood management and drainage system planning (Doan et al., 2023; Nguyen et al., 2022). These findings suggest that a phased technology adoption strategy would be the most feasible pathway for digital drainage transformation.

### 5.3 INSTITUTIONAL COORDINATION AND GOVERNANCE REFORM

Digital drainage management requires institutional coordination across multiple agencies responsible for urban infrastructure. International studies highlight that fragmented governance structures often hinder digital infrastructure integration (Asghari et al., 2023). In Vietnam, responsibilities for drainage management are distributed across municipal departments, utilities, and environmental agencies, which can limit coordination in infrastructure planning and data management. Studies on urban flood management in Vietnamese cities emphasise the importance of cross-sector collaboration between planning authorities, water utilities, and environmental agencies (Downes et al., 2024; Nguyen et al., 2025). Developing integrated governance frameworks and cross-agency data-sharing mechanisms will therefore be essential for supporting the implementation of digital drainage systems.

### 5.4 FINANCING STRATEGIES FOR DIGITAL DRAINAGE TRANSFORMATION

Financial constraints represent another major challenge for digital drainage transformation. Deploying monitoring infrastructure, modelling platforms, and digital data systems requires significant investment, while operational expenditures for system maintenance and upgrades can further increase long-term costs. International studies show that digital water management systems often involve substantial capital investment, particularly for cities with limited financial resources (Cabral et al., 2019). In Vietnam, infrastructure investment gaps and rapid urbanisation continue to intensify urban flooding risks (Nguyen et al., 2025). As a result, incremental financing strategies may provide a more feasible pathway for digitalisation. Pilot projects in high-risk flood zones, combined with public–private partnerships or international development funding, could help demonstrate the benefits of digital drainage technologies before scaling them across larger urban areas (Nguyen & Huynh, 2024).

## 6. CONCLUSIONS

This study examined the digitalisation of UDS through a structured synthesis of international literature together with contextual insights from Vietnamese studies. The review highlights the increasing role of digital technologies including IoT monitoring networks, artificial intelligence, digital twins, and GIS-based infrastructure databases in enabling more proactive and data-driven drainage management. The analysis identifies four major categories of barriers to UDS digitalisation i.e. (i) data-related constraints, (ii) technological and modelling challenges, (iii) institutional and human capacity limitations, and (iv) financial barriers. These challenges are closely interconnected, as fragmented data infrastructures, limited institutional coordination, and high investment requirements

collectively constrain the large-scale implementation of digital drainage solutions. For rapidly urbanising countries such as Vietnam, the findings highlight several key implications. Improving data governance and establishing interoperable infrastructure databases are essential foundations for digitalisation. Technological adoption should follow a gradual pathway, beginning with sensor-based monitoring and GIS-based asset management before progressing toward advanced tools such as predictive analytics and digital twins. In addition, effective implementation requires stronger institutional coordination and sustainable financing mechanisms for digital infrastructure development.

Beyond synthesising existing knowledge, the study contributes by consolidating fragmented evidence into a coherent barrier framework and by contextualising international lessons for Vietnam. The findings highlight that successful digitalisation of UDS depends not only on technological innovation but also on improvements in data governance, institutional coordination, and long-term investment strategies. Future research should further explore economic evaluation frameworks for digital drainage investments and empirical case studies of digital monitoring and digital twin implementation in rapidly urbanising cities. Such research will be critical for supporting evidence-based digital transformation of urban water infrastructure in rapidly urbanising regions.

# 7. REFERENCES

Agonafir, C., Lakhankar, T., Khanbilvardi, R., Krakauer, N., Radell, D., & Devineni, N. (2022). A machine learning approach to evaluate the spatial variability of New York City's 311 street flooding complaints. *Computers, Environment and Urban Systems*, *97*, 101854. https://doi.org/10.1016/j.compenvurbsys.2022.101854

Ahmad, M. N., Skilodimou, H. D., Islam, F., Javed, A., & Bathrellos, G. D. (2025). Drainage network generation for urban pluvial flooding (UPF) using generative adversarial networks (GANs) and GIS data. *Sustainability*, *17*(10), 4380. https://doi.org/10.3390/su17104380

Anik, M. S. B. M., An, C., & Li, S. S. (2025). Evolution from the physical process-based approaches to machine learning approaches to predicting urban floods: A literature review. *Environmental Systems Research*, *14*(1), 15. https://doi.org/10.1186/s40068-025-00409-3

Asghari, F., Piadeh, F., Egyir, D., Yousefi, H., Rizzuto, J. P., Campos, L. C., & Behzadian, K. (2023). Resilience assessment in urban water infrastructure: A critical review of approaches, strategies and applications. *Sustainability*, *15*(14), 11151. https://doi.org/10.3390/su151411151

Bertrand-Krajewski, J.-L., Lepot, M., & Invernon, N. (2025). UDMT–Urban drainage metrology toolbox: A software tool facilitating the adoption of better metrology practices. *Water Practice & Technology*, *20*(8), 1784-1796. https://doi.org/10.2166/wpt.2025.102

Cabral, M., Loureiro, D., Almeida, M. d. C., & Covas, D. (2019). Estimation of costs for monitoring urban water and wastewater networks. *Journal of Water Supply: Research and Technology—AQUA*, *68*(2), 87-97. https://doi.org/10.2166/aqua.2019.043

Doan, P. T. K., Le, X. C., & Némery, J. (2023). Evaluating the impacts of an improved sewer system on city flood inundations using MIKE Urban Model. *Vietnam Journal of Earth Sciences*, *45*(4), 438-455.

Downes, N. K., Viet, P. Q., Huynh, T. N., Dang, T. H., & Storch, H. (2024). The urban growth challenges of implementing nature-based solutions for stormwater management in Ho Chi Minh City, Vietnam. In *Rethinking stormwater management through sustainable urban design* (pp. 75-88). Springer. https://doi.org/10.1007/978-981-97-4924-9_4

Fan, C., Hou, J., Li, X., Song, G., Yang, Y., Liang, X., Zhou, Q., Imran, M., Chen, G. & Wang, Z. (2025). Efficient urban flood control and drainage management framework based on digital twin technology and optimization scheduling algorithm. *Water Research*, *282*, 123711. https://doi.org/10.1016/j.watres.2025.123711

Gao, W., Liao, Y., Chen, Y., Lai, C., He, S., & Wang, Z. (2024). Enhancing transparency in data-driven urban pluvial flood prediction using an explainable CNN model. *Journal of Hydrology*, *645*, 132228. https://doi.org/10.1016/j.jhydrol.2024.132228

Kim, M.-G., & Bartos, M. (2024). A digital twin model for contaminant fate and transport in urban and natural drainage networks with online state estimation. *Environmental Modelling & Software*, *171*, 105868. https://doi.org/10.1016/j.envsoft.2023.105868

Kim, Y., Oh, J., & Bartos, M. (2025). Stormwater digital twin with online quality control detects urban flood hazards under uncertainty. *Sustainable Cities and Society*, *118*, 105982. https://doi.org/10.1016/j.scs.2024.105982

Li, X., Luo, J., Li, Y., Wang, W., Hong, W., Liu, M., Li, X. & Lv, Z. (2022). Application of effective water-energy management based on digital twins technology in sustainable cities construction. *Sustainable Cities and Society*, *87*, 104241. https://doi.org/10.1016/j.scs.2022.104241

Mai, V., Ngo, V. Y., & Pham, Q. T. (2025). Managing urban drainage systems with Digital Twins: Global insights and applications in Vietnam. *International Journal of Sustainable Construction Engineering and Technology*, *16*(2), 246-279. https://doi.org/10.30880/ijscet.2025.16.02.016

Martin, C., Kamara, O., Berzosa, I., & Badiola, J. L. (2020). Smart GIS platform that facilitates the digitalization of the integrated urban drainage system. *Environmental Modelling & Software*, *123*, 104568. https://doi.org/10.1016/j.envsoft.2019.104568

Minh, H. V. T., Lavane, K., Lanh, L. T., Thinh, L. V., Cong, N. P., Ty, T. V., Downes, N. K. & Kumar, P. (2022). Developing intensity-duration-frequency (IDF) curves based on rainfall cumulative distribution frequency (CDF) for Can Tho City, Vietnam. *Earth*, *3*(3), 866-880. https://doi.org/10.3390/earth3030050

Nguyen, H. T. T., Nguyen, B. T. H., & Le, G. S. (2025). Assessing the risk of inundation in Thu Duc City using an integrated 1D-2D hydrodynamic model with a combination of boundary conditions defined by probability analyses. *Journal of Water Management Modeling*, *33*. https://doi.org/10.14796/JWMM.S558

Nguyen, T. H., & Huynh, N. T. (2024). Cost-benefit analysis for sustainable urban drainage systems (SuDS) project in Mekong Delta: A case study of the pilot project in Long Xuyen City. In *International Conference on Asian Urbanization Forging a Livable and Sustainable Urban Future*. https://doi.org/10.1007/978-981-96-9924-7_17

Nguyen, V. M., Tran, K. C., & Nguyen, T. T. (2022). Modelling the influences of river water level on the flooding situation of urban areas: A case study in Hanoi, Vietnam. Advances in Research on Water Resources and Environmental Systems (GTER 2022). https://doi.org/10.1007/978-3-031-17808-5_9

Okwori, E., Viklander, M., & Hedström, A. (2024). Data integration in asset management of municipal pipe networks in Sweden: Challenges, gaps, and potential drivers. *Utilities Policy*, *86*, 101689. https://doi.org/10.1016/j.jup.2023.101689

Pedersen, A. N., Pedersen, J. W., Borup, M., Brink-Kjær, A., Christiansen, L. E., & Mikkelsen, P. S. (2022). Using multi-event hydrologic and hydraulic signatures from water level sensors to diagnose locations of uncertainty in integrated urban drainage models used in living digital twins. *Water Science and Technology*, *85*(6), 1981-1998. https://doi.org/10.2166/wst.2022.059

Pirone, D., Padulano, R., & Del Giudice, G. (2026). Approaching urban flood modelling according to available data: A state-of-the-art review and future challenges. *Journal of Flood Risk Management*, *19*(1), e70184. https://doi.org/10.1111/jfr3.70184

Rasool, U., Yin, X., Xu, Z., Rasool, M. A., Hussain, M., Siddique, J., & Hai, N. T. (2025). Quantifying pluvial flood simulation in ungauged urban area: A case study of 2022 unprecedented pluvial flood in Karachi, Pakistan. *Journal of Hydrology*, *655*, 132905. https://doi.org/10.1016/j.jhydrol.2025.132905

Rousso, B. Z., Do, N. C., Gao, L., Monks, I., Wu, W., Stewart, R. A., Lambert, M. F. & Gong, J. (2024). Transitioning practices of water utilities from reactive to proactive: Leveraging Australian best practices in digital technologies and data analytics. *Journal of Hydrology*, *641*, 131808. https://doi.org/10.1016/j.jhydrol.2024.131808

Rousso, B. Z., & Gong, J. (2026). Smart sewers in practice: a systematic review of instrumentation, applications and pathways to adoption for sustainable urban systems. *Journal of Environmental Management*, *401*, 128922. https://doi.org/10.1016/j.jenvman.2026.128922

Sharifi, A., Beris, A. T., Javidi, A. S., Nouri, M., Lonbar, A. G., & Ahmadi, M. (2024). Application of artificial intelligence in digital twin models for stormwater infrastructure systems in smart cities. *Advanced Engineering Informatics*, *61*, 102485. https://doi.org/10.1016/j.aei.2024.102485

Sivakumar, A., Melina Jv, T., & Suresh, E. S. M. (2025). BIM-GIS integration for efficient management of urban underground stormwater networks. *Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction*, *178*(3), 186-199. https://doi.org/10.1680/jsmic.23.00092

Smith, V. B., McGauley, M. W., Newman, M., Garzio-Hadzick, A., Kurzweil, A., Wadzuk, B. M., & Traver, R. (2023). A relational data model for advancing stormwater infrastructure management. *Journal of Sustainable Water in the Built Environment*, *9*(1), 04022023. https://doi.org/10.1061/JSWBAY.SWENG-478

Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC medical research methodology*, *8*(1), 45. https://doi.org/10.1186/1471-2288-8-45

Wei, Q., Chen, Y., Qi, H., Jia, Z., Xie, Y., Zhang, H., Xu, Z. & Yin, H. (2026). Advances in extraneous water detection of urban sewer networks: From conventional methods to data-driven approaches. *Critical Reviews in Environmental Science and Technology*, *56*(1), 1-21. https://doi.org/10.1080/10643389.2025.2576726

Yang, Y., Ng, S. T., Dao, J., Zhou, S., Xu, F. J., Xu, X., & Zhou, Z. (2021). BIM-GIS-DCEs enabled vulnerability assessment of interdependent infrastructures–A case of stormwater drainage-building-road transport Nexus in urban flooding. *Automation in Construction*, *125*, 103626. https://doi.org/10.1016/j.autcon.2021.103626

Ikuabe, M., Aigbavboa, C., Ogungbe, M., Aregbesola, T. and Ogunade, T., 2026. Distance is no barrier: Drivers of the deployment of remote construction management for project delivery in South Africa. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 592-600. DOI: https://doi.org/10.31705/WCS.2026.44. Available from: https://ciobwcs.com/papers/

# DISTANCE IS NO BARRIER: DRIVERS OF THE DEPLOYMENT OF REMOTE CONSTRUCTION MANAGEMENT FOR PROJECT DELIVERY IN SOUTH AFRICA

**Matthew Ikuabe[1], Clinton Aigbavboa[2], Mayowa Ogungbe[3], Tunde Aregbesola[4] and Toluwanimi Ogunade[5]**

## *ABSTRACT*

*Addressing obstacles to effective project execution is an essential priority for stakeholders within the construction sector. Utilizing delivery methods such as remote construction management presents considerable advantages that aligns with the aforementioned goal. This research aims to evaluate the deployment of remote construction management in South Africa's construction industry. A quantitative research design was utilized to elicit data from construction professionals located in the Gauteng province of South Africa, selected through purposive sampling. A total of eighty-four responses were received and deemed appropriate for analysis. The collected data underwent suitable analytical techniques using exploratory factor analysis (EFA). The results of the study revealed three primary constructs that serve as the drivers of the use of remote construction management. These are improved project performance and operational efficiency, enhanced health & safety and workforce wellbeing, and optimised organisational operations. Based on these findings, the study made recommendations that can help drive the espousal of remote construction management in the South African construction industry.*

***Keywords:*** *Construction; Digital Technologies; Drivers; Remote Construction; South Africa.*

## 1. INTRODUCTION

The construction sector plays a crucial role in the economic advancement of both developed and developing nations (Ikuabe et al., 2022; Otasowie et al., 2023). This is evident through the establishment of vital infrastructure that supports economic growth, job creation, and community well-being (Adekunle et al., 2024). Additionally, it enables

[1] Senior Lecturer, School of Construction Economics and Management, University of the Witwatersrand, South Africa, matthew.ikuabe@wits.ac.za
[2] Professor, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, caigbavboa@uj.ac.za
[3] Postdoctoral Researcher, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, ogungbemayowa@yahoo.com
[4] Postdoctoral Researcher, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, aregbesolatunde13@gmail.com
[5] Doctoral Researcher, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, ogunadetoluwanimi@gmail.com

the development of physical assets that other sectors of the economy rely on. These physical assets encompass residential properties, manufacturing facilities, office spaces, urban infrastructure, educational institutions, transportation networks, water supply systems, retail businesses, and more. According to Olanrewaju and Ibrahim (2020), the construction industry in South Africa is highly significant due to its impact on the country's Gross Domestic Product (GDP). On a global scale, this industry constitutes 13% of the world's GDP (McKinsey, 2017).

The execution of construction projects involves a multitude of both organized and unforeseen activities aimed at achieving the desired success of the project (Hetemi et al., 2020). Typically, these activities encompass various job roles that contribute to reaching project objectives. These objectives often focus on aspects such as timely completion, cost efficiency, quality standards, sustainability, and health and safety (Aghimien et al., 2021; Ikuabe et al., 2024). The fragmented structure of construction project execution has created difficulties in optimizing project delivery. This situation is further intensified by the use of traditional project management methods. As noted by Ikuabe et al., (2023), construction companies face challenges in integrating the necessary resources, technology, and skills required for project execution due to the ever-changing nature of the industry's business environment. As a result, the delivery of projects has been facing challenges such as insufficient performance, delays in execution, reduced productivity, budget overruns, and diminished quality (Aghimien et al., 2024). Therefore, it is essential to explore alternative methods for improving project delivery in the construction sector. One possible method is remote construction management.

Remote construction management, as noted by Weippert et al. (2022), leverages technology to oversee construction projects from a distance without the necessity of being physically present at the job site. Additionally, Wolfram (2023) emphasizes that remote construction management involves the administration and supervision of construction projects from a location away from the site, utilizing digital communication and collaboration tools. This cutting-edge strategy allows project managers and stakeholders to effectively monitor construction projects from remote sites, thereby reducing the requirement for on-site presence (Rabida, 2020). This method of managing construction projects leverages various technologies to effectively coordinate and supervise projects from multiple locations. These technologies encompass drone technology, cloud-based applications, building information modeling (BIM), virtual reality (VR), augmented reality (AR), and other related technologies (Elabd et al., 2020; Gontier et al., 2021). Utilizing these innovative technologies in construction project management can assist in addressing some of the issues linked to traditional project management approaches. Despite the growing discourse on digital transformation within the construction sector, there is a lack of research focused on the drivers of the deployment of remote construction management in the context of South Africa. Although studies highlight the challenges, yet there is no identification of the factors that influence successful project delivery outcomes. In light of this, the objective of the study is to assess the drivers of implementing remote construction management for successful project execution in South Africa.

## 2. REVIEW OF RELATED LITERATURE

Weippert et al. (2022) characterized remote construction management as the use of technology to oversee construction projects from afar, eliminating the need for a physical

presence at the construction site. Conversely, Wolfram (2023) explained remote construction management as the supervision and administration of construction projects from a distant location through digital technology, communication, and collaborative tools. This innovative method allows project managers and stakeholders to effectively monitor construction endeavors from remote sites, reducing the necessity for on-site attendance (Rabida, 2020). Nevertheless, remote construction management depends on a variety of technologies to successfully coordinate and manage construction projects across different distances. These technologies encompass drone technology, cloud-based applications, building information modeling (BIM) software, information communication technology (ICT), as well as virtual reality (VR) and augmented reality (AR) systems (Ahmed et al., 2017).

A key driver of the use of remote construction management is the rising need of the digital transformation of processes in construction project delivery. The integration of innovative technologies enables real-time monitoring and management of construction activities remotely. These technologies permit project stakeholders to manage construction data continuously, hence helping to improve decision-making and project coordination (Zhu et al., 2022). The visualisation and digital representation of real-time data of projects enables project teams to make informed decisions while enabling efficient management of complex construction projects. Furthermore, the need for improved monitoring and performance in construction projects drives the use of remote construction management (Islam, 2020). Traditional construction monitoring often relies heavily on frequent site visits, which can be time-consuming, costly, and sometimes ineffective in detecting emerging problems early. The technologies associated with the deployment of remote management of construction projects provides continuous oversight of project activities aided by sensors, digital dashboards, and other automated data capture systems. Alaloul et al., (2022) noted that the use of remote monitoring systems for construction projects demonstrates resource optimisation when compared to conventional site supervision methods. The need for cost efficiency serves as a need for the deployment of remote construction management. Construction projects are often attributed to cost overruns which is antithetical to the pursuit of effective project performance. Remote management technologies facilitate improved coordination among stakeholders, enabling faster problem identification and more effective resource allocation. Through continuous monitoring and predictive analysis of construction processes, organisations can reduce operational inefficiencies and minimise unnecessary site visits, which ultimately lowers project management costs (Kehinde, 2025).

Moreover, the increasing sophistication and complexity of construction projects further drives the need for the deployment of remote construction management (Dagou et al., 2025). The project team formation of construction projects predominantly features numerous stakeholders, which sometimes are geographically dispersed. Remote construction tools allows project team members to access project information simultaneously regardless of location. These systems enhance collaboration and communication among project team members, which leads to improvement of the project during its lifecycle. Also, the safety considerations serves as a major instigator for the use of remote construction management. Construction sites are inherently hazardous environments, and frequent physical inspections can expose project managers and supervisors to safety risks. Remote monitoring technologies enables project team members to follow up with progress and milestones being made on site without being

physically present, hence eliminating the exposure to hazardous environments while maintaining effective oversight of site activities (Harris et al., 2020). According to Sharma (2024), automated monitoring systems can help trigger safety risks alert and operational anomalies. One of the drivers of remote construction management is the increasing demand for data-driven decision-making and real time information in project delivery. The deployment of digital systems for construction project delivery enables continuous capture and integration of onsite data, which can be used for forecasting and scheduling when analysed. The availability of real-time project data allows project managers to make informed decisions quickly and respond proactively to emerging issues (Rahaman et al., 2024).

# 3. METHODOLOGY

A quantitative research method was utilized in this study to assess the drivers of the deployment of remote construction management in the South African construction industry. The quantitative method follows a deductive approach, where phenomena are observed in an attempt to maintain an objective stance (Kumar, 2011). A questionnaire survey was employed in eliciting responses from the study's respondents. The research instrument comprised of two sections. The former focused on the demographic details of the respondents, while the latter focused on the drivers of remote construction management in the South African construction industry. The study employed a purposive sampling due to the nature of the study, which sought for construction professionals with knowledge of the use of digital technologies. A total of eighty-four responses were received and deemed appropriate for analysis. The target respondents were architects, quantity surveyors, construction managers, construction project managers, and engineers. The analysis method used for the data was exploratory factor analysis (EFA), which helps to reveal the relationships among a set of variables. The extraction method employed was principal component analysis (PCA), as demonstrated by Ikuabe et al. (2022). Pallant (2007) notes that PCA is performed to assess the uni-dimensionality of the factors, thereby determining their suitability for analysis. Additionally, the reliability and validity of the questionnaire were evaluated using Cronbach's alpha test, which resulted in a value of 0.883, confirming the research instrument's reliability and validity (Tavakol and Dennick, 2011).

# 4. FINDINGS

## 4.1 DEMOGRAPHIC INFORMATION OF RESPONDENTS

The results from the analysis of the respondent demographics for the study indicate that 46% of the respondents are connected to contracting firms. In contrast, 34% are linked to consulting agencies, while 20% are employed by governmental organizations. Additionally, regarding the respondents' years of work experience, 70% have been working for 6-10 years, 20% have 11-15 years of experience, and 8% have worked for 1-5 years. Moreover, concerning the highest level of academic achievement among the respondents, 54% hold an honour's degree, 18% possess a bachelor's degree, and 12% have a master's degree.

## 4.2 EXPLORATORY FACTOR ANALYSIS

The findings from the exploratory factor analysis (EFA) revealed the grouping of variables into clusters with similar underlying dimensions. This process allowed for a reduction in the number of variables, presenting them within a clearly defined and more comprehensible framework. To accomplish this, an evaluation of the dataset's suitability was performed using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy alongside Bartlett's test of sphericity. These tests were employed to determine whether the dataset utilized in this study was suitable for factor analysis. According to Pallant (2007), a dataset must show significant results in Bartlett's test of sphericity ($p < 0.05$) to be considered appropriate for analysis. As demonstrated in Table 1, the outcome of Bartlett's sphericity test is significant, with a p-value of 0.000. Additionally, the KMO should exceed a value of 0.6 to be deemed suitable for factor analysis, in accordance with previous research (Aghimien et al., 2021; Ikuabe et al., 2020). The analysis revealed a KMO value of 0.853. These findings provide guarantee regarding the appropriateness of the dataset for the EFA.

*Table 1: KMO and Bartlett's test*

| | | |
|---|---|---|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy. | | 0.853 |
| Bartlett's Test of Sphericity | Approx. Chi-Square | 1278.115 |
| | Df | 86 |
| | Sig. | 0.000 |

A principal component analysis with varimax rotation was conducted to evaluate the underlying structure of thirteen (13) items. The assumption of independent sampling was satisfied. The conditions of normality, linear associations between pairs of variables, and moderate correlation levels among the variables were examined. This analysis identified three (3) factors with eigenvalues greater than 1, specifically: Factor one - improved project performance and operational efficiency, which explained 56.37% of the variance and having a factor loading ranging from 0.654 – 0.912. Factor two - enhanced health & safety and workforce wellbeing, which explained 10.11% of the variance explained and having a factor loading ranging from 0.533 – 0.721. Factor three - optimised organisational operations, which explained 6.72% of the variance explained and having a factor loading of ranging from 0.509 – 0.736.

*Table 2: Rotated component matrix*

| **Drivers** | **Component** | | | **Extracted Communalities** | **% of Variance** |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | | |
| ***Improved Project Performance and Operational Efficiency*** | | | | | |
| Improved project monitoring and control | 0.912 | | | 0.692 | |
| Enhanced decision-making through real-time information | 0.826 | | | 0.507 | |
| Productivity and efficiency improvement | 0.805 | | | 0.883 | 56.37 |
| Management of geographically dispersed projects | 0.778 | | | 0.616 | |
| Integration of digital and physical monitoring systems | 0.654 | | | 0.538 | |

| Drivers | Component | | | Extracted Communalities | % of Variance |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | | |
| ***Enhanced Health & Safety and Workforce Wellbeing*** | | | | | |
| Improved health and safety management | | 0.721 | | 0.777 | 10.11 |
| Reduced exposure to high-risk construction environments | | 0.629 | | 0.581 | |
| Enhanced remote collaboration among project teams | | 0.594 | | 0.825 | |
| Workforce flexibility and mobility | | 0.533 | | 0.794 | |
| ***Optimised Organisational Operations*** | | | | | |
| Cost reduction in project management operations | | | 0.736 | 0.645 | 6.72 |
| Improved digital integration across project stakeholders | | | 0.618 | 0.827 | |
| Increased organisational competitiveness | | | 0.565 | 0.522 | |
| Improved resilience to disruptions | | | 0.509 | 0.731 | |

## 5. DISCUSSION

The findings of the study reveal that the deployment of remote construction management is primarily driven by the need to achieve improved project performance and operational efficiency, enhanced health and safety and workforce wellbeing, and optimised organisational operations. The importance of improved project performance and operational efficiency implies that construction organisations identify the value of remote management of construction projects using innovative technologies, which helps in reinforcing the project control and decision making. This is supported by (Zhu et al., 2022) which noted that digital monitoring systems significantly enhance project controls and drives more responsive management of construction processes. The provision of real-time data assists project stakeholders to make better informed decisions and respond proactively to emerging project risks. Furthermore, the findings highlight enhanced health and safety and workforce wellbeing as a significant driver of remote construction management. The use of remote construction management reduces the need for physical onsite oversight activities therefore reducing the exposure to harmful construction environment (Kehinde, 2025). By enabling supervisors and consultants to monitor site activities remotely, organisations can improve safety oversight while protecting personnel from potential risks. Also, a key finding from the study is identification of the role of optimised organisational operations in motivating the adoption of remote construction management. Past studies noted that the use of digital technologies for construction project delivery instigates improved coordination for construction projects, even if they are geographically dispersed (Islam, 2020). These findings suggest that the adoption of remote construction management is motivated not only by technological advancements but also by the broader pursuit of improved project delivery, safer working environments, and more efficient organisational processes.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The study assessed the instigating factors for the deployment of remote construction management for project delivery in South Africa. Using a quantitative methodology, data was collected from the study's target population. The analysis from the retrieved data shows three derived constructs serving as the drivers of remote construction management. These are improved project performance and operational efficiency, enhanced health & safety and workforce wellbeing, and optimised organisational operations. The findings portrays the potential for construction management to drive the transformation of the supervision and management processes engaged in during project execution. Findings from the study can assist contractors, consultants, and policymakers in developing digital strategies, enhancing project implementation efficiency, improving coordination across dispersed project locations, and building resilience and competitiveness. Based on these findings, the study recommends that construction organisations invest in digital technologies which aids remote monitoring of construction projects and ultimately drives effective project management. Also, construction organisations should strive to develop the requisite competence required among personnel to drive the espousal of remote construction management. Furthermore, policymakers and industry stakeholders should promote the integration of remote construction management practices through supportive regulatory frameworks and industry guidelines, thereby encouraging broader adoption across the construction sector. It is worthy to note that the study was conducted in Gauteng province in South Africa. Future studies can be conducted in other provinces of the country to give a broader perspective from the geographical context. Also, a mono methodological method was employed in the current study, other studies can deploy a multi or mixed methods.

## 7. REFERENCES

Adekunle, P., Aigbavboa, C., Akinradewo, O., Ikuabe, M. & Otasowie, K. (2024). Towards the uptake of digital technologies for construction information management: A partial least square structural equation modelling approach. *Buildings*, *14*(3), 827 https://doi.org/10.3390/buildings14030827

Aghimien, D.O., Aigbavboa, C.O., Meno, T., & Ikuabe, M. (2021). Unravelling the risks of construction digitalisation in developing countries. *Construction Innovation*, *21*(3), 456-475 https://doi.org/10.1108/CI-02-2020-0026

Ahmed, S., Hossain, M.M., & Hoque, M.I. (2017). A brief discussion on augmented reality and virtual reality in construction industry. *Journal of System and Management Sciences*, *7*(3), 1-33. https://www.researchgate.net/publication/330655081_A_Brief_Discussion_on_Augmented_Reality_and_Virtual_Reality_in_Construction_Industry

Alaloul, W. S., Alzubi, K. M., Malkawi, A. B., Al Salaheen, M., & Musarat, M. A. (2022). Productivity monitoring in building construction projects: A systematic review. *Engineering, Construction and Architectural Management*, *29*(7), 2760-2785 https://doi.org/10.1108/ECAM-03-2021-0211

Dagou, H. H., Gurgun, A. P., Koc, K., & Budayan, C. (2025). The future of construction: Integrating innovative technologies for smarter project management. *Sustainability*, *17*(10), 4537 https://doi.org/10.3390/su17104537

Elabd, N.M., Mansour, Y.M., & Khodier, L.M. (2020). Social distancing in construction: Investigating the role of technologies in supporting remote management. *Journal of Engineering and Applied Science*, *67*(8), 2073-2091. https://www.academia.edu/45543126/SOCIAL_DISTANCING_IN_CONSTRUCTION_INVESTIGATING_THE_ROLE_OF_TECHNOLOGIES_IN_SUPPORTING_REMOTE_MANAGEMENT

Gontier, J.C., Wong, P.S., Teo, P. (2021). Towards the implementation of immersive technology in construction-a SWOT Analysis. *Journal of Information Technology in Construction*, 26, 366-380 https://dx.doi.org/10.36680/j.itcon.2021.020

Harris, F., McCaffer, R., Baldwin, A., & Edum-Fotwe, F. (2020). *Modern construction management*. John Wiley & Sons.

Hetemi, E., Ordieres-Meré, J., & Nuur, C. (2020). An institutional approach to digitalization in sustainability-oriented infrastructure projects: The limits of the building information mode. *Sustainability*, *12*(9), 3893 https://doi.org/10.3390/su12093893

Ikuabe, M., Aigbavboa, C., Oke, A., Adekunle, S., & Khambule, S. (2023). Key leadership skills for effective project delivery: Placing the lens on construction 4.0. In: Clinton Aigbavboa, Emmanuel Oke and Wellington Thwala (eds) *Sustainable Construction in the Era of the Fourth Industrial Revolution. AHFE (2023) International Conference*. *AHFE Open Access*, (107), AHFE International, USA, http://doi.org/10.54941/ahfe1003098

Ikuabe, M., Aigbavboa, C., Thwala, W., Chiyangwa, D., & Oke, A. (2024) Critical factors influencing the failure of joint ventures in the South African construction industry: A confirmatory factor analysis approach. *Engineering, Construction and Architectural Management*, *31*(4), 1678-1695 https://doi.org/10.1108/ECAM-04-2022-0298

Ikuabe, M., Akinshipe, O., Aigbavboa, C., Ebekozien, A., Oke, A., & Mofokeng, R. (2022). Foreign direct investments in the South African construction industry: Promulgating the inherent benefits. In: Salman Nazir (Eds). *Human Factors in Management and Leadership*. *AHFE (2022) International Conference*. *AHFE Open Access*, (vol 55). AHFE International, USA http://doi.org/10.54941/ahfe1002238

Ikuabe, M., Oke, A. and Aigbavboa, C. (2020). Impact of contractors' opportunism on construction project transaction costs: Construction professionals' perception. *Journal of Financial Management of Property and Construction*, *25*(1), 125-141. https://doi.org/10.1108/JFMPC-04-2019-0040

Ikuabe, M.O., Aigbavboa, C.O., Anumba, C., Oke, A.E. & Aghimien, L. (2022). Confirmatory factor analysis of performance measurement indicators determining the uptake of CPS for facilities management. *Buildings*, *12*(4) 466 https://doi.org/10.3390/buildings12040466

Islam, M. M. (2020). Impact of digital construction management platforms on project performance post-covid-19. *American Journal of Interdisciplinary Studies*, *1*(04), 1-25 https://doi.org/10.63125/nqp0zh08

Kehinde, S. (2025). Remote project management: Tools and techniques for effective delivery in a virtual environment. *Journal of Artificial Intelligence and Technological Development*, *1*(1), 10-22 https://doi.org/10.59324/jaitd.2025.1(1).02

Kumar. R. (2011). *Research Methodology*. London. SAGE publications.

McKinsey Global Institute. (2017). A route to higher productivity. Reinventing construction, [online] mckinsey & company. Available at: https://www.mckinsey.com/~/media/McKinsey/Industries/Capital%20Projects%20and%20Infrastructure/Our%20Insights/Reinventing%20construction%20through%20a%20productivity%20revolution/MGI-Reinventing-construction-A-route-to-higher-productivity-Full-report.ashx [Accessed 18 August 2025].

Olanrewaju, O., & Ibrahim, S. Construction industry performance and the growth of South African economy: Any causal relationship. *Test Engineering and Management*, *83*(9), 22509-22521. https://www.researchgate.net/publication/342449569_Construction_Industry_Performance_and_the_Growth_of_South_African_Economy_Any_Causal_Relationship

Otasowie, K., Ikuabe, M., Aigbavboa, C., & Oke, A. (2023). Factors militating against the use of digital technology by sub-contractors in South Africa. In: K. Arai, (Eds) *Proceedings of the Future Technologies Conference (FTC), Lecture Notes in Network and Systems*, (560, pp.749-757). Springer, Cham, 749-757 http://dx.doi.org/10.1007/978-3-031-18458-1_50

Pallant, J. (2007). *SPSS survival manual: A step-by-step guide to data analysis using SPSS version 15*. Nova Jorque: McGraw hill.

Rabida, K. (2020, July 20). *How project managers can handle Remote construction teams*, Spica International. Retreived 16 July, from 2025 from https://www.spica.com/blog/remote-construction-teams-management

Rahaman, M. A., Rozony, F. Z., Mazumder, M. S. A., Haque, M. N., & Rauf, M. A. (2024). Big data-driven decision making in project management: A comparative analysis. *Academic Journal on Science, Technology, Engineering & Mathematics Education*, *4*(03), 44-62 https://doi.org/10.69593/ajsteme.v4i03.88

Sharma, R. (2024). Enhancing industrial automation and safety through real-time monitoring and control systems. *International Journal on Smart & Sustainable Intelligent Computing*, *1*(2), 1-20 https://doi.org/10.63503/j.ijssic.2024.30

Tavakol, M., Dennick, R. (2011). Making sense of Cronbach's Alpha. *International Journal of Medical Education*, 2, 53-55 https://doi.org/10.5116/ijme.4dfb.8dfd

Weippert, A., & Kajewski, S.L. & Tilley, P.A. (2002). Internet-based information and communication systems on remote construction projects: A case study analysis. *Construction Innovation*, *2*(2), 103-116 https://doi.org/10.1108/14714170210814702

Wolfram, B. (2023). *Remote construction management: How teams collaborate in 2023*. Retreived August 10 2025 from https://blog.magicplan.app/virtual-construction-management-a-short-guide-to-successful-collaboration

Zhu, H., Hwang, B. G., Ngo, J., & Tan, J. P. S. (2022). Applications of smart technologies in construction project management. *Journal of Construction Engineering and Management*, *148*(4), 04022010 https://doi.org/10.1061/(ASCE)CO.1943-7862.0002260

Kumari, H.D.A.S., Abeynayake, D.N. and Piranavan, S., 2026. Early contractor involvement in a developing country context: Public - private sector differences and emerging variants. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 601-614. DOI: https://doi.org/10.31705/WCS.2026.45. Available from: https://ciobwcs.com/papers/

# EARLY CONTRACTOR INVOLVEMENT IN A DEVELOPING COUNTRY CONTEXT: PUBLIC - PRIVATE SECTOR DIFFERENCES AND EMERGING VARIANTS

**H.D.A.S. Kumari[1], D.N. Abeynayake[2] and S. Piranavan[3]**

## *ABSTRACT*

*Early Contractor Involvement (ECI) has been widely promoted for improving project performance and constructability. However, its application in developing country contexts remains underexplored. This study evaluates the awareness and practical adoption of ECI in Sri Lanka, a developing country, across public and private sectors, and identifies the appropriate level of contractor involvement in these sectors. A mixed-methods approach was adopted, combining a questionnaire survey and semi-structured interviews with industry professionals in the procurement of the public and private sectors. Quantitative data were analysed using the Relative Importance Index (RII) and the Mann–Whitney U test, while qualitative insights supported interpretation. The findings reveal that although there is a general awareness of ECI, the private sector demonstrates greater familiarity with its features, mainly in integrating contractor expertise, optimising resources, and enabling constructability inputs to designs. In contrast, the public sector shows limited adoption due to regulatory barriers, including strict adherence to procurement guidelines that prioritise transparency and lowest-cost selection over collaboration. Consequently, approaches such as Public–Private Partnerships and Target Cost Contracting have more potential for ECI in public projects, whereas BIM-based Integrated Project Delivery, Alliance and Design and Build Novated contracting are preferred in the private sector.*

***Keywords:*** *Construction Industry; Early Contractor Involvement (ECI); Private and Public Sector; Sri Lanka.*

## 1. INTRODUCTION

Procurement in construction is the process of identifying, selecting, and engaging suitable stakeholders and organisations to deliver projects (Adamtey, 2022) that significantly influence sustainability, productivity and overall success (Hettiaarachchige et al., 2022). The construction industry commonly adopts four main procurement methods: traditional, integrated, management-oriented, and collaborative (Jayasinghe et al., 2025). Although conventional methods have been widely used in industry since the 20th century, scholars

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, kumarihdas.21@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanina@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sivasothypiranavan27@gmail.com

have identified several issues arising from their adversarial nature and inefficiencies, including poor communication, cost overruns, project delays, and poor stakeholder collaboration (Jayasinghe et al., 2025). As a result, there has been a shift towards more collaborative procurement approaches with Early Contractor Involvement (ECI) emerging as a key method increasingly adopted, particularly in developed countries. (Narum et al., 2022).

The ECI approach facilitates the incorporation of the contractor's expertise during the pre-construction phase, enhancing project outcomes (Ishtiaque et al., 2024). Different countries have adopted ECI through a range of variants tailored to their local contexts and the nature of the construction industry (Tamura, 2022), with ECI implementation reported in around 30 countries (Laryea & Watermeyer, 2016). Osuizugbo et al. (2024) argued that most ECI-related studies have been conducted in developed countries. However, studies focusing on industry awareness and practical adoption of ECI in developing countries remain scarce. Osuizugbo et al. (2024) further highlighted the need for future research on ECI within developing countries.

In Sri Lanka, as a developing country, traditional separated procurement is generally prevalent in the industry, and secondly, the integrated procurement system is utilised (Silva & Kulatunga, 2023). However, current procurement practices in developing countries face several challenges, including increased errors, disputes, poor client satisfaction, and inefficiencies (Ogbu & Ehigiator-Irughe, 2020). Similar issues are evident in the Sri Lankan construction industry (Edirisinghe et al., 2020), highlighting the need for alternative procurement methods to address evolving challenges (Hettiaarachchige et al., 2022). As per Ishtiaque et al. (2024), the ECI approach promotes greater cost and time certainty by facilitating early clarification of scope, fewer variations, and greater transparency. Despite growing interest in a new procurement approach, research on the adoption of ECI within the Sri Lankan construction industry remains limited. Therefore, the research mounting to research question of *"what is the level of awareness and practical adoption of ECI in the Sri Lankan construction industry within public and private sectors?"* The study aims to evaluate awareness and practical adoption of ECI in Sri Lanka, as a developing country, considering the capacity in both the public and private sectors. The research objectives are;

1. To assess the current level of awareness of ECI within Sri Lanka's construction industry.
2. To evaluate the practical adoptability of the ECI approach in both public and private sector construction projects.
3. To determine the appropriate level of contractor involvement in the industry.
4. To explore emerging variants of ECI within the Sri Lankan context.

## 2. LITERATURE REVIEW

This section reviews the literature on the concept of ECI, its evolution, the level of contractor involvement, its features and variants, and its global implementation.

### 2.1 CONCEPT OF EARLY CONTRACTOR INVOLVEMENT (ECI)

The concept of ECI was first introduced in 1998 by the Institution of Civil Engineers in England, as an alternative to conventional procurement methods (Turner & Riding,

2015). In the early 2000s, the UK's Roads and Highways Agency adopted this collaborative method (Laryea & Watermeyer, 2016; Turner & Riding, 2015).

ECI is an advanced collaborative procurement strategy that promotes the contractor's active involvement in the design and development stages before entering a contract (Narum et al., 2022), thereby creating a supportive environment for innovative solutions and complex problem-solving (Ishtiaque et al., 2024). Early collaboration improves constructability and buildability by combining design expertise with contractors' practical knowledge on construction methods, materials, and local practices (Rahmani, 2021). However, ECI features may vary by project context (Ishtiaque et al., 2024).

## 2.2 LEVEL OF CONTRACTOR INVOLVEMENT

ECI is characterised by varying levels of Contractor involvement in the design development, ranging from limited involvement focused on constructability and cost advice to full integration with the client and design team at the earliest concept stage (Wondimu et al., 2020). Scheepbouwer and Humphries (2011) identified ECI approaches in which contractors provide advisory input during design, while Laryea and Watermeyer (2016) demonstrate moderate-to-high engagement, with contractors actively reviewing detailed design and contributing to value engineering.

## 2.3 FEATURES OF EARLY CONTRACTOR INVOLVEMENT (ECI)

The ECI approach is defined by a set of principles that distinguish it from conventional procurement methods and enable it to deliver successful construction and infrastructure projects (Farrell & Sunindijo, 2022). Table 1 provides ECI features and detailed descriptions, enabling a clearer understanding of the ECI collaborative approach.

*Table 1: Features of the ECI approach*

| Features of ECI | Description |
|---|---|
| Early engagement of contractor [6],[7] | Contractors are involved in the pre-construction stage |
| Collaborative working [1],[6] | Trust-based collaboration among all parties involved in the project. |
| Joint risk management [6],[7] | The joint responsibility in the identification of risks, allocation, and management |
| Integration of Contractor expertise [3],[6],[7] | Strategic use of contractor experience in buildability, construction techniques, and Value Engineering |
| Integration with technology [4],[6] | Integrates through BIM to facilitate collaborative 3D modelling |
| Integration with technology [4],[6] | Integrates through BIM to facilitate collaborative 3D modelling |
| Mutual commitment [2],[6] | Align stakeholders using shared risks and shared rewards through collaborative contracting frameworks |
| Long-term relationship [7],[10] | Emphasises long-term relationships over conventional approaches |
| Requirement of optimising the use of resources [5],[6] | All participants maximise their resource effectiveness to achieve shared project goals and collective success |

| Features of ECI | Description |
|---|---|
| Contractor responsible for financing the project [6] | Responsibility for financing the project, in addition to their early involvement |
| Package Orders [3],[6] | Provide design and cost expertise for subsequent projects |
| Focus on innovation [8],[11] | To foster collaborative problem-solving and the development of creative technical solutions |
| Value-Based Selection [6],[7],[11] | Selection of contractors on non-price factors, like experience, innovative ideas, and cooperative mindset, rather than the lowest bid |

[1] Rahman and Alhassan (2012); [2] Walker and Loyd-Walker (2012); [3] Laryea and Watermeyer (2016); [4] Ferme et al. (2018); [5] Eriksson et al. (2019); [6] Wondimu et al. (2020); [7] Farrell and Sunindijo (2022); [8] Finnie et al. (2023); [9] Ishtiaque et al. (2024); [10] Osuizugbo et al. (2024); [11] Filho (2025)

## 2.4 VARIANTS OF EARLY CONTRACTOR INVOLVEMENT (ECI)

ECI involves engaging contractors early in a construction project through various approaches, with different project delivery arrangements applied across countries (Wondimu et al., 2020). Public sector clients adopt ECI approaches based on their specific requirements and circumstances (Wondimu et al., 2018), while private sector projects implement diverse ECI variants tailored to their needs and contexts to enhance collaboration and innovation in project delivery (Filho, 2025). **Error! Reference source not found.** summarises ECI approaches identified in the literature with their features.

## 2.5 GLOBAL IMPLEMENTATION OF EARLY CONTRACTOR INVOLVEMENT

ECI has been adopted globally to enhance design efficiency and achieve economic benefits (Laryea & Watermeyer, 2016) in various forms (Wondimu et al., 2020). However, in some developing countries, ECI has been implemented through various variants such as partnering in Iran and Ghana, framework agreements in South Africa, Design-Build (DB), Construction Management at Risk (CMR), alliance, and the Swiss Challenge method in India, and low-cost housing project approaches in Nigeria (Jayasinghe et al., 2024; Laryea & Watermeyer, 2016; Sagvekar & Wayal, 2019; Wondimu et al., 2020).

## 2.6 OVERVIEW OF THE CURRENT PROCUREMENT PRACTICES IN THE CONSTRUCTION INDUSTRY OF SRI LANKA

In Sri Lanka, traditional and integrated procurement dominate, with growing interest in alternative approaches such as Public-Private Partnerships (PPPs), which require substantial investment to fund public infrastructure projects (Silva & Kulatunga, 2023; Fernando & Nanayakkara, 2020) and face challenges such as improper proposal analysis and a lack of prior experience in execution (Kavinda & Gallage, 2024). Partnering and Alliancing are currently practised in a low profile within the Sri Lankan construction industry, with a growing tendency among local clients to collaborate with foreign contractors (Hettige et al., 2025). In Sri Lanka, these procurement practices are applied without formally recognising them as ECI variants.

This study, therefore, aims to assess current awareness of ECI and its practical adoption in the Sri Lankan construction industry, considering both the public and private sectors. It also seeks to determine the most appropriate level of contractor involvement during the pre-contract stage for successful ECI adoption.

## 3. RESEARCH METHODOLOGY

The study utilised a mixed approach, adopting a sequential explanatory design, in which a quantitative survey was conducted first, followed by qualitative expert interviews to obtain a comprehensive understanding of the ECI approach. A quantitative survey was used to collect numerical data on ECI awareness, the adoptability of its key features, and alignment with ECI variants, as well as contractor involvement in Sri Lanka's public and private sectors. Using purposive sampling, 140 questionnaires were distributed to procurement professionals based on accessibility and availability of contacts, including 75 in the private sector and 65 in the public sector, yielding 50 responses from each sector. The absence of a comprehensive list of all professionals necessitated the use of purposive sampling, with criteria for involvement in construction procurement and accessibility. Cronbach's alpha was used to assess the reliability and internal consistency of the Likert scale data, following recommended thresholds of 0.90 for high reliability, 0.80 for moderate reliability, and 0.70 for low reliability (Maree & Pietersen, 2007). The Mann–Whitney U test was then applied to examine differences between the public and private sectors in ECI awareness and preferred levels of contractor involvement (McKnight & Najab, 2010). Finally, descriptive statistics and the Relative Importance Index (RII) were used to evaluate the practical adoptability and significance of ECI features (Kassem et al., 2020).

In the qualitative phase, semi-structured interviews were conducted to obtain contextual insights, in addition to findings from the questionnaire survey. This is used to further explain and interpret the quantitative findings by examining stakeholder experiences, perceptions, and contextual factors that influence ECI adoption. The integration of both methods enables enhancing the validity and reliability of the study (Creswell & Clark, 2018). Five interviews were conducted with experts purposively selected for their experience, profession and procurement experience in both the private and public sectors (Table 2). Thereafter, manual content analysis was used to analyse qualitative data.

*Table 2: Experts' profile*

| Code | Designation | Experience | Experience in procurement |
|---|---|---|---|
| R1 | Ch. Quantity Surveyor | More than 20 years | More than 10 years |
| R2 | Ch. Quantity Surveyor | More than 20 years | More than 20 years |
| R3 | Ch. Quantity Surveyor/Client Representative | More than 20 years | More than 20 years |
| R4 | Ch. Quantity Surveyor/Project Manager | More than 20 years | More than 15 years |
| R5 | Ch. Quantity Surveyor | More than 20 years | More than 15 years |

# 4. FINDINGS

This section presents the analysis of quantitative data obtained from the questionnaire survey, followed by qualitative analysis to further explain and interpret the quantitative findings.

## 4.1 DETAILS OF SURVEY RESPONSES

A total of 100 completed responses out of 140 were targeted and received, with 50 responses from each sector. The respondent profile indicates that in the private sector, most participants were Contractors (58%), while Consultant/Client representatives were of 42%. In contrast, the public sector was mostly represented by Consultant/Client parties (70%). Quantity Surveyors formed the majority in both sectors (Private - 67% and Public - 68%), followed by Engineers (Private - 25% and Public - 22%), with other roles (Architects and procurement specialists) making up a smaller proportion.

## 4.2 AWARENESS LEVEL OF EARLY CONTRACTOR INVOLVEMENT (ECI)

The awareness level of ECI within the industry, in both the public and private sectors, was assessed through a survey to determine professionals' familiarity with the ECI concept as a collaborative procurement approach. The results indicate that the majority of respondents in both sectors reported having a basic understanding of ECI**,** 60**%** of private sector respondents and 58% of public sector respondents, as shown in **Error! Reference source not found.**. To examine whether there is a significant difference in familiarity levels between the two sectors, a Mann–Whitney U test was conducted. The results indicate a statistically significant difference between public- and private-sector respondents (U = 871.50, Z = -2.953, p = 0.003**)**. The findings further illustrate that the private sector (Mean = 3.22) is more familiar with the ECI concept than the public sector

(Mean = 2.68)**.**

*Figure 1: ECI Familiarity*

## 4.3 PRACTICAL ADOPTABILITY OF THE ECI APPROACH WITHIN THE SRI LANKAN CONTEXT THROUGH THE IMPLEMENTATION OF ECI VARIANTS

The questionnaire assessed respondents' perceptions of the practical adoptability of selected ECI features in the Sri Lankan construction industry in the public and private sectors. Cronbach's alpha was within the range of 0.8 to 0.9 in both sectors, indicating a high level of consistency and reliability. The RII method was used to rank ECI features and align them with identified ECI variants, while their levels of applicability were classified based on RII ranges proposed by Buertey et al. (2024), as presented in Table 3.

*Table 3: RII classification*

| RII Values | Level | Colour Indication |
|---|---|---|
| $0.90 \leq RII \leq 1$ | Strongly Adoptable | |
| $0.75 \leq RII \leq 0.89$ | Very Adoptable | |
| $0.60 \leq RII \leq 0.74$ | Adoptable | |
| $0.45 \leq RII \leq 0.59$ | Moderately Adoptable | |
| $0.30 \leq RII \leq 0.44$ | Not adoptable | |
| $0.15 \leq RII \leq 0.29$ | Very not Adoptable | |
| $0 \leq RII \leq 0.14$ | Strongly not Adoptable | |

Table 3 shows the RII of features aligned with ECI variants, indicating the level of adoptability for both sectors.

As per Table 4, in the Sri Lankan private sector, ECI features show high applicability. The “Integration of Contractor Expertise” is the most feasible feature (RII=0.892), “Requirement of optimising the use of resources for overall success by all participants” followed by (RII=0.840), and “Joint risk management” (0.828). Other features, such as “Early involvement of the Contractor”, “Long-term commitment”, and “Package orders”, are classified as “Very Adoptable”. This indicates that ECI Variants listed in the literature are adoptable in the private sector, confirming the need for collaborative, knowledge-driven decision-making and openness to a trust-based relationship.

In the public sector, “Integration of Contractor Expertise” (RII=0.74), “Mutual commitment” (RII=0.72), and collective decision-making (RII=0.66) fall into the "Adoptable" category. Features like “Requirement of optimising the use of resources for overall success by all participants” and “Integration with technology” also show moderate adoptability. However, “Early involvement of the Contractor” (RII= 0.432) and “Package orders” (RII= 0.352) are significantly hindered within the public sector, which are indicated as “Not adoptable”. This indicates that the adoption of ECI Variants listed in the literature is limited because the early involvement of the Contractor, a primary feature, is not acceptable in the public sector. Therefore, while certain collaborative ECI features, such as integrating contractor expertise and mutual commitment, are moderately feasible, the core element of ECI, the early involvement of the contractor, is significantly constrained in the public sector. Expert interviews elaborated on the most applicable ECI Variants in both the public and private sectors, as discussed in the following sections.

## 4.4 MOST APPLICABLE ECI VARIANTS FOR THE PUBLIC SECTOR

Experts highlight that the implementation of ECI variants in the Sri Lankan public sector is relatively limited, and the primary hindrance is regulatory and governance restrictions. The government procurement procedures emphasise principles of transparency, accountability, and strict adherence to established procurement guidelines.

R1 explained, “*the public sector does not easily believe contractors, because they always have to consider transparency and the use of public money”.* R1 further explained that most public projects strictly adhered to the National Procurement Commission (NPC) guidelines and standard bidding documents, which limit ECI. Similarly, R3 indicated that the public sector prioritises competitive bidding and lowest-price selection.

Apart from these issues, experts identified the Public-Private Partnership arrangement as one of the most feasible methods for incorporating ECI into the public sector. Respondents (R1, R3 and R4) added that Build-Operate-Transfer (BOT) and Build-Own-Operate-Transfer (BOOT) models are appropriate for long-term infrastructure developments where ECI principles can be embedded to some extent to enhance project outcomes.

R2 explained, "*the reason why PPP is possible is that the government can carry out projects without using big sums of public money and enjoy the benefits of the infrastructure in the long run*". R5 highlighted that BOT and BOOT schemes enable the government to deliver projects without upfront public funding as PPP delivery models rather than pure ECI approaches. According to R2, *"PPP is a better model to integrate ECI because the Sri Lankan public sector already uses this model to finance, build, and operate projects"*

In addition, R4 and R5 identified Target Cost Contracting (TCC) as a suitable ECI variant for the public sector, describing it as a structured cost-sharing mechanism. R4 added, *"Target cost contracting can be beneficial because the public sector often faces budget control issues."* R6 further explained, "*TCC facilitate ECI while maintaining financial discipline through pre-agreed target costs and pain-gain sharing"*.

## 4.5 MOST APPLICABLE ECI VARIANTS FOR THE PRIVATE SECTOR

Compared to the public sector, the private sector showed greater flexibility in adopting ECI approaches, especially for high-level, technically complex projects.

R1 explained, *"In the Sri Lankan private sector, ECI is sometimes used in complex projects such as power plant developments, where approaches like Alliancing and Target Cost Contracting allow contractors to provide technical input during early project stages*." Furthermore, Experts explained that BIM-based procurement approaches, such as Integrated Project Delivery (IPD) and partnering, facilitate ECI better. R2 and R5 noted that a BIM-based procurement approach facilitates ECI by enabling contractors to participate in the project through a shared digital model during the early stages, improving communication, reducing project risks, and enhancing coordination among project participants.

R1 and R3 highlighted that the implementation of ECI in the private sector is limited by clients' need to maintain a high level of architectural and aesthetic control to prioritise design quality. In this context, R3 introduced the Design and Build Novated contract, which promotes ECI while maintaining original design intent, stating, "*Design and Build novated contract supports ECI where the design consultants can be transferred to the contractor, allowing them to integrate constructability and cost optimisation inputs to designs".* R5 also agreed with the newly proposed variant, proposing the mechanism to implement, *"in a Design and Build novated contract, the client can initially appoint the consultant, particularly a design consultant, who is later novated to the contractor after selection, enabling active contractor participation during design development."*

In addition, Best Value Procurement (BVP) was highlighted as a suitable approach for the private sector, as explained by R4, *"private sector clients expect the best value for their investment, therefore procurement approaches such as BVP are more suitable as ECI where they combine cost efficiency with early technical inputs."*

*Table 4: ECI Variants align with features*

| | **Literature Findings** | | | | | | | | | | **Survey Findings** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Target Cost Contacting | | | | | |
| Common Features | IPD | Partnering | Alliance | PPP | Framework agreement | Best value procurement | Single TCC | Competitive single | Multiple/ dual TCC | 2 -ECI | RII-Public | RII-Private |
| Early involvement of the Contractor | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.432** | **0.816** |
| Collaborative working | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.54** | **0.764** |
| Joint risk management | ☒ | ☒ | ☒ | ☒ | ☒ | ☐ | ☒ | ☒ | ☒ | ☒ | **0.516** | **0.828** |
| Integration with technology | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.648** | **0.728** |
| Mutual commitment | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.72** | **0.776** |
| Long-term commitment between the client & contractor | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.58** | **0.816** |
| Requirement of optimising the use of resources for overall success by all participants | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.648** | **0.84** |
| Collective decision making | ☒ | ☒ | ☒ | ☒ | ☐ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.66** | **0.808** |
| Contractor responsible for financing the project | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | **0.68** | **0.732** |
| Package Orders | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | **0.352** | **0.804** |
| Focus on innovation | ☒ | ☒ | ☒ | ☐ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.68** | **0.768** |
| Integration of Contractor Expertise | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | ☒ | **0.74** | **0.892** |
| References | [8] [10] [15] [17] | [4] [10] | [2] [4] [10] | [4] [10] [14] | [6] [7] [10] | [9] [10] | [1]; [5]; [10] | | | [11] [12] [13] [16] | | |

[1] Lahdenperä (2010); [2] Lahdenperä (2012); [3] Rahman & Alhassan (2012); [4] Walker & Lloyd-Walker (2012); [5] Lahdenperä (2015); [6] Walker & Lloyd-Walker (2015); [7] Laryea & Watermeyer (2016); [8] Pishdad-Bozorgi & Srivastava (2018); [9] Wondimu et al. (2018); [10] Wondimu et al. (2020); [11] Rahmani (2021); [12] Finnie et al., (2023); [13] Ng et al. (2023); [14] Mishra & Shah (2023); [15] Weinmann et al. (2024); [16] Filho (2025); [17] Nwajei et al. (2025)

### 4.6 LEVEL OF INVOLVEMENT

According to a survey, private-sector projects are in favour, with a mean of 4.04, that the most appropriate level of contractor involvement is during the pre-contract stage. However, in the public sector, it is lower (with the Mean = 3.12). An Independent-Samples Mann–Whitney U test was conducted to compare the two sectors, and the results ($U = 502$, $Z = -5.435$, $p < 0.001$) show a statistically significant difference, indicating that perceptions regarding the appropriate level of contractor involvement vary significantly between the two sectors. Interviews found that the level of contractor involvement in the Sri Lankan context was limited to providing constructability and cost optimisation inputs at the design stage, rather than being involved in decision-making.

## 5. DISCUSSION

While ECI literature has largely focused on developed countries, this research addresses that gap by examining the practical adoptability of the ECI approach in the Sri Lankan context, using ECI variants within Sri Lanka's public and private sectors, considering the current structure and capacity of the industry. The findings indicate that while the Sri Lankan construction industry is generally aware of the ECI concept, the level of familiarity is higher in the private sector than in the public sector.

The applicability of ECI features and variants in the public sector is influenced by the existing procurement framework. Although the public sector has recognised the importance of integrating contractor expertise in the design stage, ECI implementation remains largely governed by national procurement guidelines, as identified by Silva and Kulatunga (2023), emphasising competitive tendering and transparency requirements. Furthermore, as per findings, the package order cannot be implemented within the public sector, which is one of the key features of the framework agreement. Therefore, some ECI variants cannot be implemented within the current public procurement framework. However, Public-Private Partnership (PPP) models such as Build-Operate-Transfer (BOT) and Build-Own-Operate-Transfer (BOOT) appear to be a feasible option that could enable contractors to participate in the early stages. Literature also identified the growing interest in PPP in the Sri Lankan construction industry (Fernando & Nanayakkara, 2020). Furthermore, Target Cost Contracting (TCC) is identified as another potential ECI variant because it supports improved cost management, collaborative risk-sharing, and greater cost certainty in public sector construction projects (Lahdenperä, 2015).

The private sector indicates a comparatively higher willingness to adopt ECI features such as early contractor participation, joint risk management, and resource optimisation due to its greater flexibility in selecting procurement approaches (Silva & Kulatunga, 2023) similar to the findings of this study. Literature has identified that Alliance Target Cost contracting, BIM-based procurement, and Partnering are used in the private sectors of many developed countries, facilitating early contractor involvement more effectively. Findings revealed Sri Lanka's potential to apply the same approach in the private sector, addressing the main constraint of the need for high architectural and aesthetic standards. This study suggests D&B-Novated as an emergent ECI variant, although it is not widely recognised in existing literature.

This study finds that higher levels of contractor involvement in the pre-contract stage are more suitable for the private sector in Sri Lanka, while the public sector prefers moderate

involvement. Literature identified that the contractor involvement may vary from limited roles in constructability and cost advice to highly active involvement in design reviews, value engineering, and collective decision making (Laryea & Watermeyer, 2016; Scheepbouwer & Humphries, 2011). However, this study found that, in Sri Lanka, it is typically limited to design reviews based on constructability and value engineering.

# 6. CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates that the Sri Lankan construction industry has basic awareness of the ECI procurement approach, while the private sector shows greater potential for adopting its features than the public sector. Public sector adoption is primarily hindered by strict adherence to strict regulatory frameworks that prioritise transparency and lowest-price selection over early collaboration. However, ECI through Public-Private Partnership (PPP) and Target Cost Contracting (TCC) have some potential for adoption in public projects, whereas the private sector prefers BIM-based Integrated Project Delivery (IPD), Alliance contracting, and partnering. A key novel contribution of this study is the identification of the Design and Build-Novated approach as an emergent ECI approach that helps balance technical constructability with architectural expectations to adopt in the private sector. Moreover, Contractors' level of involvement in the early stages of private projects is preferred to be high-level active participation, while the public sector may prefer moderate active participation. Both sectors in Sri Lanka currently have limited involvement in design reviews through constructability inputs, cost optimisation and value engineering.

The study recommends providing industry awareness on ECI while revising procurement frameworks to support early collaboration with contractors without compromising transparency. The newly proposed Design and Build-Novated approach should be further explored for implementation in private-sector projects. This study extended ECI research to a developing-country context, with a clear comparison between the public and private sectors regarding awareness, applicable variants, and preferred levels of contractor involvement.

The study is limited by the use of purposive sampling and a relatively small sample size, which may affect statistical robustness. However, these were mitigated by including respondents from both the public and private sectors with diverse perspectives. The findings may be applicable to similar developing country contexts, although the Sri Lanka-specific context may introduce contextual bias. Future research is required to investigate the Design and Build-Novated contract as a potential ECI variant and to explore strategies to integrate collaborative provisions into public procurement guidelines to enable ECIs.

# 7. REFERENCES

Adamtey, S. A. (2022). An empirical study to assist owners in selecting the right procurement method for design-build projects. *International Journal of Construction Education and Research*, 18(1), 67–84. https://doi.org/10.1080/15578771.2020.1786482

Buertey, J. T. I., Atsrim, F. K., Boateng, K., Brace, R., & Lord, A. (2024). An evaluation of the causes, impact and perceptions about abandoned public-funded projects in Ghana. In *Current approaches in engineering research and technology* (Vol. 6, pp. 94–126). BP International. https://doi.org/10.9734/bpi/caert/v6/1273

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications. https://catalog.maranatha.edu/index.php?p=show_detail&id=51811

Edirisinghe, V., Marsh, D., Borthwick, F., & Cotgrave, A. (2020). An investigation into the significant causes of disputes in the Sri Lankan construction industry. In *Proceedings of the 56th Annual International Conference of the Associated Schools of Construction* (pp. 347–355). https://doi.org/10.29007/vbwk

Eriksson, P. E., Volker, L., Kadefors, A., Lingegård, S., Larsson, J., & Rosander, L. (2019). Collaborative procurement strategies for infrastructure projects: A multiple-case study. *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, *172*(5), 197–205. https://doi.org/10.1680/jmapl.19.00016

Farrell, A., & Sunindijo, R. Y. (2022). Overcoming challenges of early contractor involvement in local government projects. *International Journal of Construction Management*, *22*(10), 1902–1909. https://doi.org/10.1080/15623599.2020.1744216

Ferme, L., Zuo, J., & Rameezdeen, R. (2018). Improving collaboration among stakeholders in green building projects: Role of early contractor involvement. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *10*(4), 04518020. https://doi.org/10.1061/(asce)la.1943-4170.0000278

Fernando, S. N., & Nanayakkara, K. G. M. (2020). Identification of challenges to attract public-private partnerships for power generation infrastructures: A review. *Kelaniya Journal of Management*, *9*(2), 75–89. https://doi.org/10.4038/kjm.v9i2.7644

Filho, T. P. (2025). The role of early contractor involvement in facilitating exploration and exploitation of innovations in megaprojects. *Project Management Journal*, *56*(5), 1-18. https://doi.org/10.1177/87569728251322152

Finnie, D., Ali, N. a. N. A., & Park, K. (2023). Transparent and sustainable procurement through two-stage early contractor involvement (2S-ECI) – Industry perceptions. *AIP Conference Proceedings*, *2947*, 050021. https://doi.org/10.1063/5.0176341

Hettiaarachchige, N., Rathnasinghe, A., Ranadewa, K., & Thurairajah, N. (2022). Lean integrated project delivery for construction procurement: The case of Sri Lanka. *Buildings*, *12*(5), 524. https://doi.org/10.3390/buildings12050524

Hettige, P., Fernando, P., Bandara, K., & Jayasuriya, D. (2025, May). Implementation of collaborative procurement method to Sri Lankan construction industry. *14th International Research Conference, General Sir John Kotelawala Defence University*. https://www.researchgate.net/publication/389039469

Ishtiaque, T. A., Wondimu, P. A., & Klakegg, O. J. (2024). Likelihood of early contractor involvement (ECI) benefits in infrastructure versus building projects: the client's perception. *International Journal of Construction Management*, *25*(10), 1227–1238. https://doi.org/10.1080/15623599.2024.2408179

Jayasinghe, I. D., Domingo, N., & Le, A. (2025). The evolving landscape of procurement methods in the construction industry: A literature review. *CIB Conferences*, *1*. https://doi.org/10.7771/3067-4883.2031

Jayasinghe, I. D., Domingo, N., Le, A., & Potangaroa, R. (2024). A bibliometric analysis of early contractor involvement (ECI) research in the construction industry. In *Lecture Notes in Civil Engineering* (Vol. 480, pp. 445–458). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-56544-1_28

Kassem, A. M., Azry Khoiry, M., & Hamzah, N. (2020). Using relative importance index method for developing a risk map in oil and gas construction projects. *Jurnal Kejuruteraan*, *32*(3), 441–453. https://doi.org/10.17576/jkukm-2020-32(3)-09

Kavinda, S. A. C., & Gallage, S. D. (2024). Challenges for project selection and execution of public-private partnership projects in Sri Lanka. *World Construction Symposium*, 353–364. https://doi.org/10.31705/WCS.2024.28

Lahdenperä, P. (2010). Conceptualizing a two-stage target-cost arrangement for competitive cooperation. *Construction Management and Economics*, *28*(7), 783–796. https://doi.org/10.1080/01446193.2010.487534

Lahdenperä, P. (2012). Making sense of the multi-party contractual arrangements of project partnering project alliancing and integrated project delivery. *Construction Management and Economics*, *30*(1), 57–79. https://doi.org/10.1080/01446193.2011.648947

Lahdenperä, P. (2015). The beauty of incentivised capability-and-fee competition-based target-cost contracting. *Procedia Economics and Finance*, *21*, 609–616. https://doi.org/10.1016/s2212-5671(15)00219-1

Laryea, S., & Watermeyer, R. (2016). Early contractor involvement in framework contracts. *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law*, *169*(1), 4–16. https://doi.org/10.1680/jmapl.15.00012

Maree, K., & Pietersen, J. (2007). Surveys and the use of questionnaires. In K. Maree (Ed.), First steps in research (pp. 155–170). Van Schaik Publisher. https://books.google.lk/books?id=GNIlAQAAIAAJ

McKnight, P., & Najab, J. (2010). Mann-Whitney U test. In I. B. Weiner & W. E. Craighead (Eds.), *The Corsini encyclopedia of psychology* (4th ed., pp. 1–1). John Wiley & Sons. https://doi.org/10.1002/9780470479216.corpsy0524

Mishra, G., & Shah, R. (2023). Prioritising sustainability factors for public-private partnership (PPP)-based mature telecentres using the 'Akshaya' project as a case. *Australasian Journal of Information Systems*, *27*. https://doi.org/10.3127/ajis.v27i0.3135

Narum, K. B., Engebø, A., Lædre, O., & Torp, O. (2022). Collaborative project delivery with early contractor involvement and target cost. *30th Annual Conference of the International Group for Lean Construction, IGLC 2022*, 984–995. https://doi.org/10.24928/2022/0208

Ng, M. S., Graser, K., & Hall, D. M. (2023). Digital fabrication, BIM and early contractor involvement in design in construction projects: A comparative case study. *Architectural Engineering and Design Management*, *19*(1), 39–55. https://doi.org/10.1080/17452007.2021.1956417

Nwajei, U. O. K., Bølviken, T., & Hellström, M. M. (2025). Integrated project delivery in Norway – The client's perspective on challenges. *Annual Conference of the International Group for Lean Construction, IGLC*, *33*, 1243–1254. https://doi.org/10.24928/2025/0154

Osuizugbo, I. C., Fauz, M. A., Omer, M. M., Njogo, B. O., & Orekan, A. A. (2024). Research trends on early contractor involvement in construction projects: A bibliometric analysis. *Construction Economics and Building*, *24*(4/5), 160–178. https://doi.org/10.5130/AJCEB.v24i4/5.9113

Ogbu, C. P., & Ehigiator-Irughe, R. (2020). Cost overrun in civil works: A case-study of engineering, procurement and construction (EPC) gas depot construction projects in Nigeria. *European Journal of Environment and Earth Sciences*, *1*(4), Article 54. https://doi.org/10.24018/ejgeo.2020.1.4.54

Pishdad-Bozorgi, P., & Srivastava, D. (2018). Assessment of integrated project delivery (IPD) risk and reward sharing strategies from the standpoint of collaboration: A game theory approach. *Construction Research Congress*, 196–206. https://doi.org/10.1061/9780784481271.020

Rahman, M. M., & Alhassan, A. (2012). A contractor's perception on early contractor involvement. *Built Environment Project and Asset Management*, *2*(2), 217–233. https://doi.org/10.1108/20441241211280855

Rahmani, F. (2021). Challenges and opportunities in adopting early contractor involvement (ECI): client's perception. *Architectural Engineering and Design Management*, *17*(1–2), 67–76. https://doi.org/10.1080/17452007.2020.1811079

Sagvekar, S., & Wayal, A. S. (2019). Early contractor involvement (ECI): Indian scenario of construction project delivery. *International Journal of Scientific and Technology Research*, *8*(8), 807–811. https://www.ijstr.org/paper-references.php?ref=IJSTR-0819-21101

Scheepbouwer, E., & Humphries, A. B. (2011). Transition in adopting project delivery method with early contractor involvement. *Transportation Research Record Journal of the Transportation Research Board*, *2228*(1), 44–50. https://doi.org/10.3141/2228-06

Silva, H. A. L. V., & Kulatunga, U. (2023). Key procurement selection factors for Sri Lankan private-sector commercial building projects. *Lecture Notes in Civil Engineering*, *266*, 737–752. https://doi.org/10.1007/978-981-19-2886-4_51

Tamura, A. (2022). A study on the characteristics of "early contractor involvement method" in public project in Japan. *The 9th International Conference on Construction Engineering and Project Management*, 42–49. https://ugoki.kensetsunews.com/

Turner, N., & Riding, M. (2015). Early contractor involvement in Australia: Learnings from Transfield Services projects. *Small Enterprise Research*, *22*(2–3), 173–184. https://doi.org/10.1080/13215906.2015.1061724

Walker, D. H. T., & Lloyd-Walker, B. (2012). Understanding early contractor involvement (ECI) procurement forms. *Procs 28th Annual ARCOM Conference*, 877–887. https://www.arcom.ac.uk/-docs/proceedings/ar2012-0877-0887_Walker_Lloyd-Walker.pdf

Walker, D. H. T., & Lloyd-Walker, B. M. (2015). *Collaborative project procurement arrangements*. Project Management Institute. https://www.pmi.org/-/media/pmi/documents/public/pdf/kas/201505_walker_collaborative_project_procurement_arrangements.pdf

Weinmann, M., Baier, C., Schilling Miguel, A., & Haghsheno, S. (2024). Structuring approach and current status of integrated project delivery (IPD) in Germany. *Annual Conference of the International Group for Lean Construction, IGLC*, *32*, 143–154. https://doi.org/10.24928/2024/0171

Wondimu, P. A., Klakegg, O. J., & Lædre, O. (2020). Early contractor involvement (ECI): ways to do it in public projects. *Journal of Public Procurement*, *20*(1), 62–87. https://doi.org/10.1108/JOPP-03-2019-0015

Wondimu, P. A., Klakegg, O. J., Lædre, O., & Ballard, G. (2018). A comparison of competitive dialogue and best value procurement. *Annual Conference of the International Group for Lean Construction*, 13–22. https://doi.org/10.24928/2018/0248

Siriwardana, R. P., Gunarathana, N. and Vivek, S., 2026. Effectiveness of tax administration with respect to the construction industry in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 615-627. DOI: https://doi.org/10.31705/WCS.2026.46. Available from: https://ciobwcs.com/papers/

# EFFECTIVENESS OF TAX ADMINISTRATION WITH RESPECT TO THE CONSTRUCTION INDUSTRY IN SRI LANKA

**R.P. Siriwardana[1], N. Gunarathana[2] and S. Vivek[3]**

## *ABSTRACT*

*The tax system is recognised as a major source of revenue for a country. The money will be utilised to meet the government expenditure as well as to develop the infrastructure of the entire country. Separate government agencies have also been set up for tax administration, and this research is about tax administration related to the construction industry. Given the current economic situation in Sri Lanka, all industries have declined, and tax rates have increased. It has also affected the construction industry. The study is focused on the existing status of tax administration in the construction industry in Sri Lanka. The study has utilised a mixed method of research to explore the subject under review. To gather the study data, an extensive literature review, expert interviews from quantity surveyors, financial managers, accountants, managers, and engineers who are currently engaged in related work in the construction industry, and a questionnaire survey have been used. Information has been included in this research with the responses of thirty (30) industry professionals and the opinions of six (6) industry experts. The information is about Sri Lanka's tax system, tax types, construction industry, concessions due from the government to the construction industry and tax administration related to the construction industry. From that information, it has become clear that there is no efficient tax administration in Sri Lanka regarding the construction industry.*

***Keywords:*** *Construction Industry; Sri Lankan Tax System; Tax Administration.*

## 1. INTRODUCTION

The construction sector forms a fundamental aspect of national development that maintains a symbiosis with the economic trend of a country (Dassanayake & Rathnayake, 2023). It makes significant contributions to the Gross Domestic Product (GDP) through direct and indirect means; in Sri Lanka, the industry usually contributes between 70 - 80 per cent to the national GDP (Chandrasekera et al., 2021). Even though some professional discussion exists whether high tax ratios and growth are positively correlated, it is widely agreed that taxation provides governments with the kind of revenue that cannot be ignored since it helps to invest in infrastructure and higher education, having a positive effect on the productive capacity of the economy (McNabb, 2018). Therefore, the tax system

[1] Graduate, Department of Quantity Surveying, Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka, rashmipiyumika2019@gmail.com
[2] Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka, nishanthi.g@sliit.lk
[3]Academic Instructor, Department of Quantity Surveying, Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka, vivek.s@sliit.lk

influences the long-term economic growth, and a flexible framework allows a controlled developmental course. Due to the cross-sectoral nature of the construction industry, it is prone to various types of taxes, such as Value Added Tax (VAT), Withholding Tax (WHT), Corporate Income Tax (CIT), National Building Tax (NBT), Ports and Airports Development Levy (PAL), and Customs Duties (Chandrasekara et al., 2021). This complex tax system affects many aspects of the industry, especially construction materials, labour, cost generally, and investment. There are typically direct and indirect taxes: the former are levied on income and corporate profits, and the latter are indirectly imposed in the form of the price of the product (Chandrasekara et al., 2021; Ashworth & Perera, 2010). Direct taxes have a significant share of gross revenue in developed economies, but not in developing economies; on the contrary, indirect taxes often become the dominant source of government income in developing countries like Sri Lanka (Amirthalingam, 2013). It is a source of indirect taxation, which frequently increases the cost of construction and makes financial management of such a project more difficult (Vickneswaran, 2014).

Sri Lanka, being a developing country, must fund basic infrastructure and government amenities. The government also tends to increase the ratio of taxes or introduce levies on the industry to raise funds, a concept that is considered a more sustainable source of income as compared to national debt (Amirthalingam, 2013). However, as much as the taxation system has both positive and negative impacts, it must be accompanied by a strong administrative system to make the industry stable. Although previous studies on the general taxation in Sri Lanka still exist, a major gap is prevalent about the tax administration within the construction sector. This study will address the gap by examining the performance of taxation in the Sri Lankan construction sector.

The research aims at achieving three main goals, namely, to investigate what kind of taxes are levied and what their consequences are on the industry; to explore the significance of an appropriate tax administration system; and to evaluate the sufficiency of the existing administrative practices in Sri Lanka. To achieve these objectives, a mixed-method research design was used in three phases. Stage 1 included a comprehensive literature search and initial expert interviews to record the type of tax and economic effects. Stage 2 used a questionnaire survey to understand the way in which industry professionals deal with the effects of taxes in their projects. Stage 3 entailed interviews with government officials, namely the Inland Revenue Department (IRD), the Ministry of Finance (MoF), and the Construction Industry Development Authority (CIDA), to assess the administrative environment. This study is also research on the Sri Lankan construction sector with a focus on how new administrative channels can be proposed to overcome the current setbacks.

# 2. LITERATURE REVIEW

## 2.1 GLOBAL CONTEXT OF TAXATION

The ultimate role of a tax system is to raise funds to be used in present-day spending and in other government institutions. The existing principle of taxation assumes that taxes should be calculated in line with the solvency of the taxpayer (Waidyasekera, 2016). Taxation is an obligatory fee of the state, and as Gangodawilage (2015) noticed, they do not provide any direct benefit to the population, though indirectly, they benefit the rest of the population. Taxpayers do not receive certain payoffs; they gain some indirect

advantages in the form of free healthcare, education, national defence, and infrastructure (Vickneswaran, 2014). Taxation laws are becoming a major issue of concern to policymakers worldwide, especially in the reporting of business revenue. In the example, the tax regime in the United Kingdom has been perceived to be complex and fluctuating (James & Edwards, 2008), compared to Latin America, where income tax has been the key determinant of decline in revenue (Bird et al., 2004). On the other hand, other countries like Ukraine have been able to raise the tax ratio even though the middle-income of the population is lower (Amirthalingam, 2013). Finally, taxation is a means of economic management that is aimed at reducing inflationary and deflationary pressures (Kelegama, 2017).

## 2.2 SRI LANKAN LANDSCAPE AND REVENUE COMPOSITION OF TAXATION

The tax system in Sri Lanka is defined by a variety of limitations, tax holidays, and a broad range of taxes (Kelegama, 2017). The largest part of the government's revenues is tax, which covers about 85 per cent of the total revenues (Vickneswaran, 2014). The Inland Revenue Department (IRD) is the key institution which has administration of taxes and is supervised by the Commissioner General of Inland Revenue (CGIR). During the years 1980 through 2011, the tax rates in the country have generally been lower than 16.5 per cent, which is a common trend among the lower middle-income economies (Amirthalingam, 2013). It is a bifurcated system of Direct Tax (DT) and Indirect Tax (IT) (Chandrasekera et al., 2021). In less developed countries like Sri Lanka, indirect taxes contribute to the government revenue more than direct taxes, but the theoretical models indicate a gradual change of direct taxation with the rise of economic development (Amirthalingam, 2013). Table 1 illustrates the sharp recovery of the construction sector in 2024, which rebounded from a 20.8% contraction to 19.4% growth. Simultaneously, tax administration efficiency is evidenced by a 36.2% increase in total tax revenue, largely driven by the expansion of indirect taxes like VAT following policy revisions

*Table 1: Construction sector growth and government tax revenue performance (2023–2024)*

| Indicator | 2023 (Revised) | 2024 (Provisional) |
|---|---|---|
| Construction Sector Real Growth Rate (%) | (20.8) | 19.4 |
| Construction Share of GDP (%) | 6.2 | 7.0 |
| Total Government Tax Revenue (Rs. billion) | 2,720.6 | 3,704.6 |

*Note. Adapted from* Annual Economic Review 2024 *(pp. 10, 49), by Central Bank of Sri Lanka (2025).*

Table 2 presents the composition of tax revenue in Sri Lanka from 2021 to 2024. It highlights the main tax sources and their contributions to total government revenue in Rs. million.

*Table 2: Tax revenue by major categories in Sri Lanka (2021–2024)*

| Item | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|
| **Tax Revenue (Rs. Mn)** | | | | |
| Taxes on Foreign Trade | 349,836 | 273,926 | 335,266 | 400,149 |
| Taxes on Domestic Goods and Services | 627,786 | 873,706 | 1,428,694 | 2,205,341 |
| VAT | 308,213 | 463,072 | 694,460 | 1,309,680 |
| Turnover Tax/NBT | 687 | 586 | 362 | 206 |
| License Fees | 10,847 | 64,845 | 252,310 | 287,737 |
| Taxes on Net Income and Profits | 302,115 | 534,021 | 911,355 | 1,026,199 |
| Stamp Duty | 38,788 | 59,361 | 62,286 | 49,141 |
| Other | 30,560 | 85,313 | 74,488 | 97,056 |

*Note. Adapted from Annual Report 2024, by the Ministry of Finance, Planning and Economic Development and the Ministry of Public Administration, Provincial Councils and Local Government (2025).*

## 2.3 DIRECT AND INDIRECT TAXATION DYNAMICS

Direct taxes are imposed on income, and transferability to another entity is not possible. The major types of direct taxation in Sri Lanka are personal income tax, corporate income tax, and PAYE (Gangodawilage, 2015). Direct taxes are progressive; however, on the other hand, they can deter investment, savings, and consumption. Indirect taxes, on the contrary, are levied on goods and services that allow for the tax burden on other parties (Vickneswaran, 2014). This mechanism is especially applicable in developing countries since it can be administered more easily (Chandrasekera et al., 2021; Amirthalingam, 2010). Some of the important ones are Value Added Tax (VAT), National Building Tax (NBT), customs duties, and Economic Service Charges (ESC). The kind of taxes applied indirectly is often regressive, and the type of tax applied directly is progressive in nature; these two types of taxes play a significant role in distributing national income (Thilanka & Ranjith, 2021). Table 3 demonstrates the composition of tax revenue in Sri Lanka from 2016 to 2024, highlighting the distribution between direct and indirect taxes. The table also shows the percentage contribution of direct and indirect taxes to total tax revenue over the period, measured in Rs. million.

*Table 3: Distribution of direct and indirect tax revenues in Sri Lanka (2016-2024)*

| Year | Tax Revenue Rs. million | | | Direct tax / Total Tax (%) | Indirect tax / Total Tax (%) |
|---|---|---|---|---|---|
| | Direct Tax | Indirect Tax | Total | | |
| 2016 | 258,857 | 1,204,832 | 1,463,689 | 17.7 | 82.3 |
| 2017 | 274,562 | 1,395,617 | 1,670,178 | 16.4 | 83.6 |
| 2018 | 310,449 | 1,401,868 | 1,712,318 | 18.1 | 81.9 |
| 2019 | 427,700 | 1,307,225 | 1,734,925 | 24.7 | 75.3 |
| 2020 | 268,249 | 948,293 | 1,216,542 | 22.1 | 77.9 |
| 2021 | 302,115 | 995,904 | 1,298,019 | 23.3 | 76.7 |

| Year | Tax Revenue Rs. million | | | Direct tax / Total Tax (%) | Indirect tax / Total Tax (%) |
|---|---|---|---|---|---|
| | Direct Tax | Indirect Tax | Total | | |
| 2022 | 534,021 | 1,217,111 | 1,751,132 | 30.5 | 69.5 |
| 2023 | 911,355 | 1,809,208 | 2,720,563 | 33.5 | 66.5 |
| 2024 (Provisional) | 1,026,199 | 2,678,378 | 3,704,577 | 27.7 | 72.3 |

*Note. Adapted from publications of the Ministry of Finance, Planning and Economic Development and the Central Bank of Sri Lanka (2025).*

## 2.4 THE CONSTRUCTION INDUSTRY IN SRI LANKA: OVERVIEW

The construction business is an essential branch of the economy that is indispensable to the development of the country, and it is highly diverse and competitive (Panagodage & De Silva, 2022; Chandrasekara et al., 2021). In Sri Lanka, the industry has a contribution of about 6 per cent of the Gross Domestic Product (GDP) and an inclusive workforce spread across the value chain (Dassanayake & Rathnayake, 2023; De Silva et al., 2023). However, the industry has been adversely affected by poor policies of the government and the economic recession that took place in 2019-2022, leading to loss of jobs and low wages (De Silva et al., 2008; De Silva et al., 2023). According to the Department of Census and Statistics, the growth in the construction sector has narrowed, and it is decreasing by 12.40% in 2021 to - 8.90% in the first half of 2022.

## 2.5 EFFECT OF TAXATION ON CONSTRUCTION OPERATIONS

The tax regime directly and indirectly influences the construction industry, which makes it one of the most constrained and intricate sectors in terms of resources (Chandrasekera et al., 2021). As a result of the raised tax rates, the cost of construction invariably increases, and contractors and manufacturers will be hesitant to spend on labour, machinery, and materials. The main industry-related taxes are VAT, which impacts inputs, including cement, steel, and bitumen, but that has currently been increased to 15 per cent (Dassanayake & Rathnayake, 2023). Other major taxes include the Ports and Airport Development Levy (PAL), which applies to all imports and the Nation Building Tax (NBT) (Chandrasekera et al., 2021; Vickneswaran, 2014). Despite the fact that the Construction Industry Guarantee Fund Levy (CIGFL) was in force, it is no longer applicable to contracts signed after 1st January 2011. Finally, there should be an efficient tax collection system to reduce the negative situation, such as labour shortage, scaling back of the projects due to increased industry costs (Ranasinghe & Kulathunga, 2016; Chandrasekera et al., 2021). Table 4 indicators reveal a transition toward deflationary costs for construction materials, with the Cost of Construction Index dropping by 4.6% in 2024. Furthermore, business sentiment reached a near-record high as the Purchasing Managers' Index (PMI) for Construction hit 75.0 in early 2026, indicating a significant acceleration in project activity and administrative compliance capacity.

*Table 4: Construction industry operational and financial indicators (2024–2026)*

| Indicator | 2023 Value | 2024 / 2026 Status |
|---|---|---|
| Cost of Construction Index (Annual Avg. % Change) | (1.1) | (4.6) |
| PMI: Construction Total Activity (Index Value) | 51.4 (Dec '23) | 75.0 (Jan '26) |

*Note. Adapted from* Sri Lanka Socio-Economic Data 2025 *(p. 70), by Central Bank of Sri Lanka (2025);* Monthly Economic Indicators: January 2026 *(p. 4), by Central Bank of Sri Lanka (2026); and* Annual Economic Review 2024 *(p. 24), by Central Bank of Sri Lanka (2025).*

# 3. RESEARCH METHODOLOGY

Research methodology is a systematic and scientific approach to solving research problems, requiring a tailored design for each specific issue (Patel & Patel, 2019). It outlines the methods of inquiry adopted to discover and assess the empirical evidence and offers a conceptual framework for the implementation of the study. The main aim of the research was to find the effectiveness of tax administration in the construction industry in Sri Lanka. To operationalise the aim of the study, three objectives that were interconnected were expressed, namely, (1) to categorise the different types of taxes, clarify how they operate and evaluate their effects; (2) to identify the importance of an effective tax management system at the global and domestic level and (3) to establish whether there exist and suffice tax management practices in the construction industry in Sri Lanka.

The mixed-method approach was employed to obtain a comprehensive understanding and combine the qualitative and quantitative methods based on the objectives and scope of the research. In its turn, this led to the use of qualitative data collection tools to gather accurate and subtle data and quantitative analyses to provide a reflective interpretation of the research parameters using numerical data obtained during the data-collection activities (Taherdoost, 2022). Through a combination of three methods, including a literature review, expert interviews, and a questionnaire survey, data were collected. The first objective was considered only through literature review, and the second one was considered in both literature review and expert interviews. The third goal was based mainly on the interviews with experts and the information gathered from questionnaires. Face-to-face meetings or electronic correspondence via Google Forms were selected as the method of expert interviews with the target professionals having substantive knowledge of the industry, such as senior quantity surveyors, financial managers, and accountants working at the Construction Industry Development Authority (CIDA) and representatives of the contracting and consulting firms and academia. Seeing that tax administration is a key issue, it was deemed necessary to address experienced professionals in the field to obtain relevant information. While tax administration is fundamentally a financial function, its operational impact directly alters project cost structures and contract management in construction. Therefore, the deliberate inclusion of quantity surveyors and engineers alongside financial professionals is vital. Quantity surveyors are directly responsible for cost estimation, budget forecasting, and the incorporation of tax fluctuations into contract pricing, while engineers manage procurement schedules and material variations affected by indirect levies. Targeting these

technical professionals ensures that the research captures the practical, project-level execution of tax policies beyond mere corporate accounting compliance.

The survey was distributed to the participants in the Sri Lankan construction sector, who were professionals, and the questionnaire survey was conducted using Google Forms and email and contained about 20 questions, including open-ended and closed-ended questions. In terms of data analysis, thematic analysis, which is a major approach to interpret qualitative data, was used to analyse interview data. The data from the surveys were analysed based on descriptive statistical methods. The mixed-method approach thus provided a formidable and methodical approach to researching the research problem and obtaining the required objectives.

# 4. DATA ANALYSIS AND FINDINGS

## 4.1 DEMOGRAPHIC CHARACTERISTICS OF THE RESPONDENTS

The qualitative part of this research included semi-structured interviews with six (6) carefully chosen industry experts with a view to developing a baseline understanding of the tax administration environment in Sri Lanka. The participants included senior professionals like owners of construction companies, company directors, financial managers, engineers, and senior quantity surveyors, with half of them having over thirty years of professional experience. In a complementary manner, a quantitative questionnaire survey was distributed to a larger professional group comprised of quantity surveyors, managers and accountants working in the construction industry. Thirty (30) valid answers were received within two weeks. These respondents were distributed professionally, with the majority being quantity surveyors (n = 22), accountants (n = 3), financial managers (n = 3), and managers (n = 2), thus offering a multi-disciplinary profile in tax administration. The high representation of quantity surveyors (n = 22) and technical managers within the sample breakdown is heavily justified by the nature of construction financial management. In Sri Lanka's construction industry, quantity surveyors act as the frontline financial controllers of projects; they are the stakeholders who directly calculate tax inputs (such as VAT and SSCL) during bidding, evaluate tax-induced material price variations, and draft interim payment certificates. While accountants handle macro-level corporate tax filing, quantity surveyors and engineers experience the immediate, day-to-day operational frictions of tax administration on project cash flows, making their heavy involvement critical for assessing the practical effectiveness of the system. Table 5 and Figure 1 summarise the professional backgrounds and experience levels of the research participants.

*Table 5: Expert interview participants*

| Participant | Position | Experience in a number of years |
|---|---|---|
| P1 | Construction company owner & Director | More than 30 |
| P2 | Finance Director | 10-15 |
| P3 | Consultant company owner & Quantity Surveyor | More than 30 |
| P4 | Engineer | 15-20 |
| P5 | Engineer | 15-20 |

| | | |
|---|---|---|
| P6 | Senior Quantity Surveyor | 10-15 |

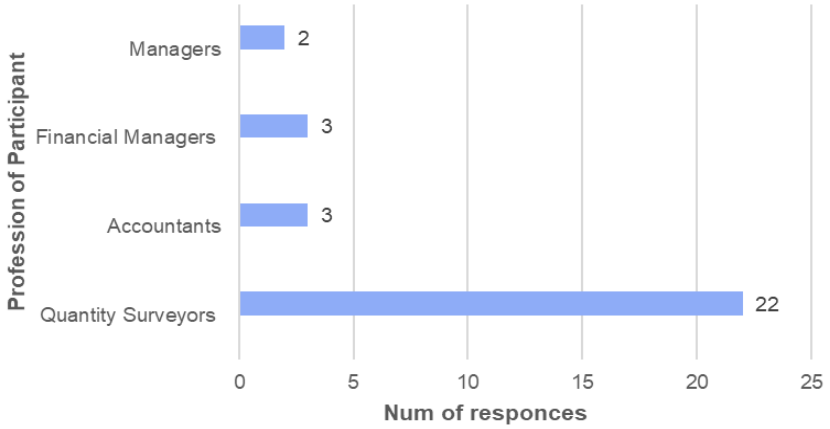



*Figure 1: Questionnaire survey participants*

## 4.2 TAX MANAGEMENT AND SYSTEMS IN SRI LANKA

Thematic analysis of the interviews with the experts revealed that, despite tax revenue being the key source of government revenue used in the national infrastructure, free education, and medical care, there is a current system which is viewed as inefficient. Expert P1 mentioned that the Sri Lankan tax system is not simplified, and it has a drawback of a mess of tax types, which do not favour industry stakeholders. In addition, the lack of a stable structure and the cycling of the tax rates were also discovered as major disadvantages. The agreement of the participants was that there are peculiarities of anomalies in the current administration, specifically the introduction of new levies, including the Social Security Contribution Levy (SSCL), without a qualitative evaluation of the future effect on the construction industry.

## 4.3 APPLICABLE TAXES FOR THE CONSTRUCTION INDUSTRY

The research established some of the relevant taxes that directly affect the construction operations, which include Value Added Tax (VAT), Corporate Income Tax (CIT), Social Security Contribution Levy (SSCL) and other customs duties. Among them, SSCL received a significant amount of criticism as professionals in the industry claimed that the rate of 2.5 % significantly interferes with the feasibility of a project. Other than active taxes, the respondents also contemplated the Construction Industry Guarantee Fund Levy (CIGFL) that was suspended in 2011. Professional group P2 and P4 supported the reintroduction of such a duty that was previously charged at low rates of 0.25 to 1 per cent, arguing that such a duty would provide the benefits needed since small contractors would be able to obtain the required bonds and guarantees via the Construction Industry Development Authority (CIDA). Table 6 presents the specific tax categories identified by each participant during the study.

*Table 6: Applicable taxes for the construction industry*

| Participants | Identified Applicable Taxes |
|---|---|
| P1 | VAT, Corporate Income tax, SSCL, Custom duty |

| Participants | Identified Applicable Taxes |
|---|---|
| P2 | VAT, Corporate Income tax, SSCL, Custom duty |
| P3 | VAT, Corporate Income tax, SSCL, Custom duty |
| P4 | VAT, Corporate Income tax, SSCL, Custom duty, PAL, PAYE |
| P5 | VAT, Corporate Income tax, SSCL, Stamp duty |
| P6 | VAT, Corporate Income tax, SSCL |

## 4.4 DIRECT BENEFITS AND STAKEHOLDER IMPACT

One of the most important findings of the study is the lack of direct benefit reimbursements to the construction industry as a reward for paying taxes. Most of the respondents insisted that despite the act of collecting tax revenue in the industry, it is diverted to the general government spending instead of being invested in the industry. Even though agencies like CIDA are involved in the provision of indirect assistance in terms of skill-development workshops and training to students, the funding to such programs is not based on any form of explicit nexus of tax-benefit. Quantitative evidence also supports the fact that the burden of tax is so widespread; half of the respondents in the survey confirmed that the tax burden affects clients, contractors, and suppliers alike, and 30 per cent of those surveyed specifically claimed that the contractor is the most burdened. Figure 2 illustrates the distribution of stakeholder groups identified by respondents as being affected by tax obligations.

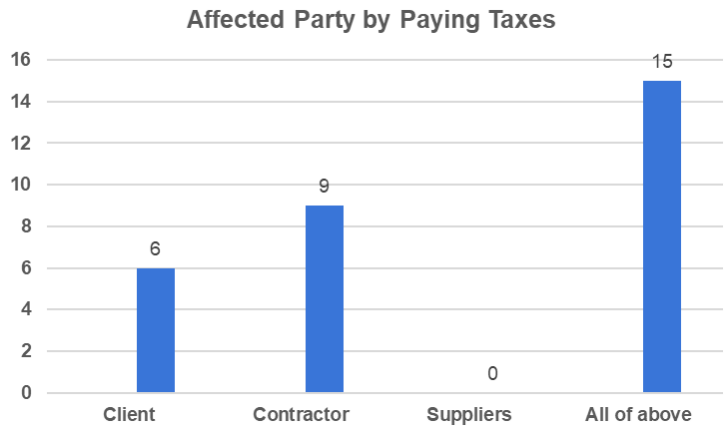



*Figure 2: Affected party by paying taxes*

## 4.5 EFFECTIVENESS OF TAX ADMINISTRATION PROCESS

According to the survey findings, the current system of tax administration is not satisfactory, as 77 per cent of the respondents reported that a proper system is not applicable in the construction industry. The causes of this negative perception can be divided into a lack of a clear administrative process, an overall failure to improve the current system, and the government's failure to cut taxes despite the increase in the cost of raw materials. According to the respondents, the constant change of tax rates and the appearance of new taxes like SSCL have a negative impact on the planning of a project in the long term. Experts P1 and others argued that they need an efficient, possibly

computerised system that will promote transparency in tax revenue management and its strategic use in developing the industry.

### 4.6 REINVESTMENT AND GOVERNMENT SUPPORT EXPECTATIONS

The study has investigated the topic of reinvestment of tax revenue; 60 per cent of interviewees were convinced that tax receivables acquired in the construction sector are not reinvested in its favour. The views about such reinvestment were mixed, and 53 per cent had a neutral position, and 27 per cent held that reinvestment is a necessity to the development of the industry. Regarding the future governmental assistance, 54 per cent of the respondents concurred that a hybrid approach that includes low-cost raw materials, unalterable tax rates, and low interest rates by the banks is essential. It was proposed by experts that the establishment of a fixed rate of tax over a specific type of project (such as five years) would alleviate the risks of unexpected cash-flow interruptions at the end of large-scale projects. Table 7 outlines the proposed support measures as identified by respondents, categorised by their percentage of preference.

*Table 7: Proposed government support for the construction industry*

| Proposed Support Measure | Respondents (%) |
|---|---|
| Reducing the cost of raw materials required by industry | 20% |
| Keeping tax rates unchanged and creating a fair tax system | 16% |
| Deduction of interest rates on bank loans (for tax-paying entities) | 10% |
| All of the above | 54% |

## 5. DISCUSSION

The current research demonstrates that there is a great discrepancy between the theoretical role of taxation and its practice in the Sri Lankan construction industry. The basic concept of a tax system is presented as the ability to pay to raise revenue and limit the economic disparities (Waidyasekera, 2016). Nonetheless, the results of the research expose a failure to uphold this principle; despite 100 % of the respondents admitting that taxes are necessary to develop the country (Vickneswaran, 2014), dissatisfaction with the current administration is high (77%), indicating that the perceived benefits of free healthcare and infrastructure no longer equate with the existing tax burden. This confirms the claim by Amirthalingam (2013) that tax structure is a sensitive macro-economic parameter that may either strangle or spur the growth of the sector.

One of the main arguments that has been found in the data relates to the Social Security Contribution Levy (SSCL). Although the Ministry of Finance (2022) states that levies like PAL and SSCL are working towards achieving the requisite government revenue, the results reveal a ripple effect where the taxation pressure is increased along the supply chain. Because 50% of respondents pointed out that the clients, contractors, and suppliers are all adversely affected, the current system is not as simplistic as Gangodawilage (2015) suggests. This is further complicated by the frequency with which the rates are changed, a point that Chandrasekera et al. (2021) validated when asserting that an unsustainable tax structure interferes with long-term industrial layout and investment. Furthermore, a notable operational challenge in the Sri Lankan construction supply chain arises when clients or main contractors procure goods and services from small-scale suppliers or

informal sub-contractors who are not VAT-liable due to falling below the statutory registration threshold. Because these transactions do not generate input tax invoices, VAT-registered construction entities are unable to claim input tax credits. This creates a tax cascading effect that drives up total project costs and compresses profit margins. This structural disadvantage directly aligns with the survey findings, where 50% of the respondents highlighted that the tax burden is not isolated but heavily impacts clients, contractors, and suppliers simultaneously. According to experts P2 and P4, a targeted, industry-specific levy is much more efficient than generalised taxes due to the way it offers a real-life safety net, that is, helping small-scale contractors to secure necessary bonds and guarantees. This implies that the industry adopts a model of fiscal reciprocity whereby a part of the taxation gets ring-fenced to reinvest into the sector instead of consumption by the general treasury.

Lastly, it becomes a pressing need to have fixed tax rates over the period a project is going to last. Since construction projects are typified by long-term construction services and fixed-pricing contracts, there should be a specialised approach to revenue collection (Engen & Skinner, 1996). The results prove that without a separate, stable, and computerised administration system, the construction industry, which is one of the main pillars of the national development (Dassanayake & Rathnayake, 2023), will remain in financial instability. To reinvigorate the sector, the government should go beyond collection and apply the supportive measures suggested by 54 per cent of the respondents, such as stabilised material costs and lower interest rates.

## 6. CONCLUSIONS

The research was effective in capturing the efficiency of tax administration in the construction sector of Sri Lanka, and thus, its three main goals were fulfilled. A review of the literature showed that the current taxation system (both direct and indirect taxes; VAT, Corporate Income Tax, and the Port Authority Levy) has had a considerable impact on the industry. It was analysed that the sudden rise of taxation rates in the recent past, along with the general economic difficulties within the land of Sri Lanka, has triggered the occurrence of a sharp rise in the price of raw materials and the general project expenses. Besides, the research noted the paramount significance of the effective system of the tax administration, pointing out that a well-designed and equitable system is indispensable to maximise the government revenue without simultaneously damaging the national industries and undermining the accumulation of capital. However, the analysis of the existing practices revealed a conspicuous gap: the construction sector does not have a specific tax administration system, which has irregularities and is significantly deficient in transparency when it comes to the distribution of the collected revenues to the development of the industry.

To deal with these problems, the research suggests that the government should introduce a fairer tax regime by ensuring that tax rates are stabilised and unnecessary frequent changes that destabilise industrial planning are checked. Such policy aspects as the decrease of the tax rates to reduce the cost of raw materials and the introduction of policies that will decrease the bank interest rates on the construction-related loans should also be viewed as important. Also, they recommend that the government and relevant agencies, like the Construction Industry Development Authority (CIDA), proceed with providing finances and running professional training workshops to boost the technical expertise and tax acumen of the workforce. To restore the healthy status of the construction sector, the

government must conduct an extensive review of industry-specific demands and provide some facilitating factors, such as a reduction of corporate income taxes to reduce the financial load experienced by contractors and consultants. Since the participants showed overall awareness of the tax requirements, the study pointed out that there is a knowledge gap that is related to tax administration, which necessitates future programs that will help to fill the information gap so that improved compliance and stability within the sector is achieved.

# 7. REFERENCES


Amirthalingam, K. (2010). Indirect taxation in Sri Lanka: The development challenge. *Economic Review*, *36*(7–8), 11–15. https://www.researchgate.net/publication/294729165_Sri_Lanka_Indirect_Taxation_in_Sri_Lanka_The_Development_Challenge

Amirthalingam, K. (2013). Importance and issues of taxation in Sri Lanka. *Colombo Business Journal*, *4*(1), 13–22. https://doi.org/10.4038/cbj.v4i1.30

Ashworth, A., & Perera, S. (2010). *Cost studies of buildings* (5th ed.). Routledge. https://doi.org/10.4324/9781315847122

Bird, R. M., Martinez-Vazquez, J., & Torgler, B. (2004). *Societal institutions and tax effort in developing countries* (CREMA Working Paper No. 2004-21). Center for Research in Economics, Management and the Arts (CREMA). https://www.econstor.eu/bitstream/10419/214307/1/2004-21.pdf

Central Bank of Sri Lanka. (2024). *Annual economic review 2024*. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-economic-review/annual-economic-review-2024

Central Bank of Sri Lanka. (2025). *Sri Lanka socio-economic data 2025*. Statistics Department, Central Bank of Sri Lanka. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/publications/otherpub/publication_sri_lanka_socio_economic_data_folder_2025_e.pdf

Central Bank of Sri Lanka. (2026). *Monthly economic indicators: January 2026*. https://www.cbsl.gov.lk/en/statistics/economic-indicators/monthly-indicators

Chandrasekera, A. D. D. J., Waidyasekara, K. G. A. S., & Sirimewan, D. C. (2021). The impact of frequent tax reforms on construction industry in Sri Lanka. *Sri Lankan Journal of Banking and Finance*, *4*(1), 124–140. https://www.researchgate.net/publication/354393588

Dassanayake, D. R. S., & Rathnayake, L. (2023). Cost of construction update for the year 2022: Position of Sri Lanka (Colombo) within the South Asian region. In P. S. Dissanayaka (Ed.), *IQSSL technical research proceedings 2023* (pp. 23–27). Institute of Quantity Surveyors Sri Lanka. https://iqssl.lk/docs/publications/publication-iqssl-2023-08-28-uid454.pdf

De Silva, N., Rajakaruna, R. W. D. W. C. A. B., & Bandara, K. A. T. N. (2008). Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors. In *Proceedings of the CIB W107 International Symposium on Innovation in Architecture, Engineering and Construction* (pp. 1–12). CIB. https://www.irbnet.de/daten/iconda/CIB11344.pdf

De Silva, S. S., Wijekoon, W. M. C. L. K., & Kalugala, C. (2023). Impact of economic crisis on employees of contractors' organisations in the Sri Lankan construction industry. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, & K. A. T. O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium* (pp. 557–568). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2023.46

Department of National Planning. (2024). *Annual performance report*. Ministry of Finance, Economic Stabilization and National Policies. https://npd.treasury.gov.lk/files/3.%20PP%20English.pdf

Engen, E. M., & Skinner, J. (1996). Taxation and economic growth. *National Tax Journal*, *49*(4), 617–642. https://doi.org/10.1086/NTJ41789231

Gangodawilage, D. (2015). *Business taxation*. The Institute of Chartered Accountants of Sri Lanka. https://www.casrilanka.com/casl/images/stories/EDBA/study%20text%20business%20taxation%20m1%204.pdf

James, S., & Edwards, A. (2008). Developing tax policy in a complex and changing world. *Economic Analysis and Policy*, *38*(1), 35–53. https://doi.org/10.1016/S0313-5926(08)50005-1

Kelegama, S. (Ed.). (2017). *Tax policy in Sri Lanka: Economic perspectives*. Institute of Policy Studies of Sri Lanka. https://www.ips.lk/wp-content/uploads/2017/10/Tax-Policy-in-Sri-Lanka-Economic-Perspectives_E_Book.pdf

McNabb, K. (2018). Tax structures and economic growth: New evidence from the government revenue dataset. *Journal of International Development*, *30*(2), 173–205. https://doi.org/10.1002/jid.3345

Ministry of Finance. (2022). *Fiscal management report 2023*. https://www.treasury.gov.lk/api/file/f3256b98-539f-4645-85a6-6fe50a7a865f

Panagodage, T. L., & De Silva, P. (2022). Critical supply chain problems in contractor - Subcontractor interface of Sri Lankan building construction projects. *In Proceedings of the SLIIT International Conference on Engineering and Technology*, 57–68. https://doi.org/10.54389/cjfm8214

Patel, M., & Patel, N. (2019). Exploring research methodology: Review article. *International Journal of Research and Review*, *6*(3), 48–55. https://www.ijrrjournal.com/IJRR_Vol.6_Issue.3_March2019/IJRR0011.pdf

Ranasinghe, S. R. S. H., & Kulathunga, K. M. M. C. B. (2016). Impact of the income tax system on tax payers' satisfaction: With special reference to Kegalle district income tax payers. *International Journal of Accounting and Business Finance*, *2*(2), 24–37. https://www.maco.jfn.ac.lk/ijabf/wp-content/uploads/2017/11/vol2_issue2_3.pdf

Taherdoost, H. (2022). What are different research approaches? Comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Thilanka, H. R. A. C., & Ranjith, J. G. S. (2021). The effect of tax composition on income inequality: Sri Lankan experience. *Sri Lanka Journal of Economic Research*, *8*(2), 3–20. https://doi.org/10.4038/sljer.v8i2.134

Vickneswaran, A. (2014). *Tax policy changes, tax revenue and budget deficit: A case in Sri Lanka* [Unpublished manuscript]. University of Jaffna. https://www.researchgate.net/publication/314116840

Waidyasekera, D. D. M. (2016). *Taxation in Sri Lanka: Current trends and perspectives* (Research Studies Series No. 25). Institute of Policy Studies of Sri Lanka. https://www.ips.lk/wp-content/uploads/2017/01/Taxation-in-Sri-Lanka.pdf

Silva, R.Y., Madhusanka, H.W.N. and Kahandawa, K.A.R.V.D., 2026. Enhancing building energy data management in Sri Lanka: Barriers, enablers, and strategic pathways. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 628-641. DOI: https://doi.org/10.31705/WCS.2026.47. Available from: https://ciobwcs.com/papers/

# ENHANCING BUILDING ENERGY DATA MANAGEMENT IN SRI LANKA: BARRIERS, ENABLERS, AND STRATEGIC PATHWAYS

**R.Y. Silva[1], H.W.N. Madhusanka[2] and K.A.R.V.D. Kahandawa[3]**

## *ABSTRACT*

*With the use of advanced technologies in the construction sector, buildings are producing numerous heterogeneous energy data, enabling more informed decision-making in energy management. However, Building Energy Data Management (BEDM) is vital to extract valuable and meaningful insights from building energy data. Therefore, several countries and energy-related institutes promote and regulate building energy data disclosure and management, aiming for energy data collection and advanced analytics for national, regional and international sustainability goals. However, Sri Lanka is still lacking research in BEDM. Therefore, this research focus to study barriers, enablers and strategies to strengthen BEDM in Sri Lanka. Along with an intensive literature review, 8 expert interviews were conducted with the qualitative approach adopted in this study. The experts were selected through a purposive sampling method to obtain more relevant insights. According to the findings, BEDM in Sri Lanka is in a primitive stage requiring considerable attention to collect and analyse building energy data for national-level energy policy formulation. Lack of consistent and accurate energy data and legislative support are the key barriers identified. Energy policies, building energy ratings and higher tariff rates were identified as key enablers in BEDM in Sri Lanka. Further, 13 strategies to promote BEDM were suggested using both literature findings and expert opinions. Introducing energy benchmarks, data disclosure laws and a centralised data collection platform were identified as promising strategies to promote BEDM. The findings of this research would be beneficial for the policy makers to develop a strategic framework to streamline BEDM in Sri Lanka.*

***Keywords:*** *Building Energy Data Management; Data-Driven Energy Management; Energy Data Barriers; Energy Data Enablers; Smart Energy Management.*

## 1. INTRODUCTION

Building energy consumption contributes a significant portion of the global energy supply and demand. With the rapid urbanisation due to population growth, building energy consumption has dramatically increased over the past few decades (Ali et al., 2020b). Buildings contribute to one-third of global energy consumption and 36% of global energy-related emissions (IEA, 2025). Further, building-related $CO_2$ emissions have increased by 1% since 2010 (Ali et al., 2020a). Therefore, energy consumption and its

[1] Temporary Lecturer, Department of Facilities Managament, University of Moratuwa, Sri Lanka, silvar@uom.lk
[2] Senior Lecturer, Department of Facilities Managament, University of Moratuwa, Sri Lanka, nandunm@uom.lk
[3] Lecturer, School of Built Environment, Massey University, New Zealand, R.Kahandawa@massey.ac.nz

impact on climate change are critical challenges in the building sector. Improperly maintained and controlled building systems might be the reason for the higher energy consumption in buildings (Ali et al., 2020b). According to Li et al. (2024), 15% -30% energy is wasted in buildings due to poor maintenance and inefficient operational practices. By monitoring energy consumption in buildings, detailed information related to individual equipment can be identified (Hannan et al., 2018).

Predicting and forecasting building energy consumption is essential for energy planning, energy optimisation, and management (Runge & Zmeureanu, 2021). In addition, building energy forecasting is used to measure and confirm the effectiveness of energy-saving practices, to estimate energy needs using trend analysis, and to identify event-specific variations in energy consumption (Mariano-Hernández et al., 2020). Due to the massive amount of building energy data, data-driven approaches are used to understand the building performance (Li et al., 2024). Currently, building operational data has been more accessible due to the utilisation of advanced technologies such as smart meters and sensors (Billanes et al., 2025).

Data-driven energy management refers to the systematic use of energy-related data, digital technologies and analytical methods to monitor, analyse and optimise energy performance within buildings and facilities (Marinakis, 2020). Unlike conventional energy management approaches that rely on periodic document reviews and manual analysis, data-driven energy management enables continuous and evidence-based decision making through historical and real-time energy data analysis (Billanes et al., 2025). Recent studies highlight that the increasing availability of smart meters, sensors, Internet of Things (IoT) devices, Building Management Systems (BMS) and Artificial Intelligence (AI) technologies has significantly increased the adoption of data-driven energy management in buildings (Elnour et al., 2024). Typically, data-driven approaches consist of several stages such as data collection, monitoring, analysis, reporting and optimisation. Initially, data is collected from various sources such as smart meters, sensors, BMS and other operational systems (Mantha et al., 2016). Subsequently, the collected data is continuously monitored to identify energy consumption patterns and abnormalities. The monitoring data are then analysed using statistical, machine learning, or predictive techniques to generate meaningful insights for decision-making (Liu et al., 2023). The analysed information is communicated through reporting and visualisation platforms to building operators and policymakers in understanding building energy performance. Finally, optimisation strategies are implemented to improve operational efficiency and reduce energy wastage(Han et al., 2023).

However, collecting detailed information in different building systems has been challenging for years (Hannan et al., 2018). Especially, the lack of public energy databases limits the ability to collect data for macro-level building energy analysis (Kazmi et al., 2023). Further, unreliable and unrealistic data can cause deviations of actual energy consumption from the prediction. (Mariano-Hernández et al., 2020). Data collection is also difficult because of manual data collection methods and a lack of novel technical solutions for energy data collection, such as smart meters (Krishnan et al., 2022). Manual data collection is prone to human errors, making the collected data irrelevant, incomplete, inconsistent and redundant (Ali et al., 2020a). High dependence on large historical data demands large data backups which can handle a large amount of heterogeneous data and information (Ali et al., 2021).

However, several authors have identified a range of technical and systematic enablers for building energy data management (BEDM). Several information and communication technologies, such as wireless sensor networks, Internet of Things (IoT), and cloud-based communication infrastructures, enable real-time data collection and seamless integration across heterogeneous building systems (Akbulut et al., 2025). Machine Learning (ML) and Artificial Intelligence (AI) became critical enablers in empowering building systems to transform raw energy data into more insightful findings. Currently, these technologies are being considered for accurate demand forecasting, fault detection and diagnosis and adaptive controlling of building systems (Gao, 2025).

To strengthen BEDM, some strategies are being introduced by several governments and international organisations. Some buildings utilised advanced technical solutions such as Big Data, IoT sensors and smart meters for real-time data collection analysis for informed decision making in building energy management (BEM) (Billanes et al., 2025). In addition, several standardised reporting practices have been introduced to ensure data quality and interoperability (Morewood, 2023). Further, advanced data analytics, machine learning and AI are used to extract valuable information from available building energy datasets (Gao, 2025).

Even though buildings account for a substantial share of global energy consumption, considerable attention has not been paid in some countries. Some research indicates that building energy data quality and availability are still underdeveloped in many regions due to poor BEDM (Gao, 2025; Lee et al., 2022). Especially, studies regarding centralised building energy data governance are lacking in Sri Lanka due to the resulting ignorance of the importance of building energy data in achieving sustainable development and mitigating climate change impacts. It causes the absence of building energy data required for the national-level building energy policymaking. Simultaneously, barriers and enablers for BEDM have not been studied in the Sri Lankan context. Therefore, this study aims to study barriers and enablers in BEDM in Sri Lanka and finally suggest strategies to strengthen BEDM in Sri Lanka.

This study consisted of a comprehensive literature review and a series of expert interviews to identify barriers, enablers and strategies in BEDM. Initially, this paper describes the adopted methodology, followed by literature findings on barriers, enablers and strategies in BEDM. Next, the data analysis and findings section will describe the findings of the expert interviews. Finally, the discussion section will explain how the literature findings will apply to the literature findings, comparing them with expert opinions.

## 2. METHODOLOGY

A comprehensive literature review was conducted to identify barriers, enablers and strategies to implement BEDM. Peer-reviewed journal articles, conference proceedings, books, and websites were used for the literature review to ensure the quality of the literature findings. Expert interviews were conducted to identify the most significant barriers, enablers and strategies to implement BEDM along with the literature findings. Interviewees were selected using a purposive sampling method. Experts were selected based on their years of experience and their roles in BEDM. Eight interviewees who are currently involved in national-level energy policy making and regulating energy consumption were selected for this study to obtain valuable and comprehensive insights

based on their experience. Eight experts were selected for interviews due to the highly limited population of professionals involved in building energy policy formulation in Sri Lanka. This limitation arises because the Sri Lanka Sustainable Energy Authority serves as the primary authority responsible for BEM and related policy development in the country. Consequently, the study targeted a substantial proportion of the available expert population, thereby ensuring the relevance and credibility of the collected insights. Even though the sample size of eight may appear limited, it is in line with the standards of the qualitative investigations, where quality is prioritised over the breadth of the study. Thematic saturation was reached by the sixth interview, and the seventh and eighth interviews confirmed that there were no new themes. Guest et al. (2020) confirmed that theoretical saturation is often reached by 6-12 interviews. The findings of the initial interviews were shared with followed by participants for further validation to ensure reliability. Finally, findings of interviews were validated through literature triangulation. Profiles of experts are shown in Table 1.

*Table 1: Profiles of experts*

| Expert Name | Description | Years of experience |
|---|---|---|
| E1 | Board member of the Sri Lanka Sustainable Energy Authority | 18 years |
| E2 | President of the Sri Lanka Energy Managers Association, board member of the Sri Lanka Sustainable Energy Authority | 30+ years |
| E3 | Director General of the Sri Lanka Sustainable Energy Authority | 25 years |
| E4 | Former president of the Sri Lanka Energy Managers Association, Former Director General of National Engineering Research and Development Centre (RERDC) | 35 years |
| E5 | Deputy Director (Energy Efficiency Improvement) in the Sri Lanka Sustainable Energy Authority | 10 years |
| E6 | Director (Energy Efficiency Improvement) in the Sri Lanka Sustainable Energy Authority | 25 years |
| E7 | Director (Demand Side Management) in the Sri Lanka Sustainable Energy Authority | 25+ years |
| E8 | PhD holder in BEM and a member of the Sri Lankan energy benchmarking portal development committee | 8 years |

A qualitative research approach was adopted in this study, which involves semi-structured interviews to examine experts' opinions and experiences more flexibly. The thematic analysis method was manually conducted to analyse data using pre-determined themes based on the literature review.

## 3. LITERATURE REVIEW

This section presents the findings of the literature survey conducted to study the existing knowledge in the field of data-driven BEM in the global context. Initially, an introduction to BEDM and the benefits of BEDM will be discussed. Subsequently, barriers and enablers in adopting BEDM will be discussed. Finally, strategies to overcome barriers and strengthen BEDM in the global context.

## 3.1 DATA-DRIVEN BUILDING ENERGY MANAGEMENT

Data-driven approaches are used in buildings to reduce energy consumption and to extract more practical energy-saving insights (Markus et al., 2022). Currently, several advanced technologies such as AI, Big Data, DT, and IoT are being used to strengthen the data-driven approaches in BEM (Adewale et al., 2024). To extract meaningful conclusions and insights, BEDM is imperative because an enormous volume of building energy data is generated from different data sources, such as smart meters, Internet of Things devices, and sensors (Billanes et al., 2025). Further to the authors, the building construction sector is shifting towards a smart building concept due to the rapid development of information and Communication Technologies such as AI, IoT, and blockchain. Several applications in data-driven approaches can be identified in the building energy sector, such as load profiling, energy forecasting, regional energy-consumption mapping, and energy performance benchmarking (Mariano-Hernández et al., 2020). Accurate prediction of building loads helps to identify future energy demands in buildings (C. Zhang et al., 2020). Building energy forecasting helps to confirm and measure the effectiveness of energy-saving initiatives (Mariano-Hernández et al., 2020). The effectiveness of energy saving initiatives can be measured by comparing the actual energy data with expected values ad take the necessary decisions based on minimum performance standards, energy policies and building energy codes. Markus et al. (2022) stated that various visualisations and Key Performance Indicators (KPIs) related to building HVAC systems, occupancy patterns and deficiencies in energy use can be produced using data analytics in buildings.

## 3.2 BARRIERS TO ADOPTING BUILDING ENERGY DATA MANAGEMENT

Building energy data disclosure and management has become challenging over the years due to several challenges associated with data collection, reporting, and analysis. Table 2 summarises the literature findings of challenges associated with BEDM.

*Table 2: Barriers to adopting building energy data management*

| Barriers | Citations |
|---|---|
| Issues related to data quality, availability and reliability | 1,2,3,4,7,8 |
| Challenges in handling a large amount of heterogeneous data | 5 |
| Data security and privacy concerns | 4,7,8 |
| Challenges in balancing multiple objectives | 5, 8 |
| Changes in building operation | 2,7 |
| Resistant to taking a challenge | 6,7 |
| Lack of human adaptation | 4,7 |
| Incorrect feature identification | 1,2,7 |
| Lack of interpretability of data | 1,2,3,7,8 |
| Lack of expertise | 1,3,4,5,6 |
| Lack of research and development | 7 |
| Lack of interoperability with building systems | 3,4,7 |
| Complex technologies | 1,5,7,8 |
| Lack of policy support | 1,4 |
| Lack of standard methods | 2,3,4 |

| Barriers | Citations |
|---|---|
| Higher implementation costs | 4,5 |
| Lack of funding and incentives | 9,10 |
| 1-(Clauß et al., 2024); 2-(Alrobaie & Krarti, 2022); 3-(Manfren et al., 2022) ; 4-(Adewale et al., 2024); 5-(Kiavarz et al., 2024); 6-(Markus et al., 2022); 7-(Krishnan et al., 2022); 8-(Zhang et al., 2022), 9-(Onile et al., 2021); 10-(Kazmi et al., 2023) | |

## 3.3 ENABLERS OF ADOPTING BUILDING ENERGY DATA MANAGEMENT

According to Shang et al. (2020), buildings that disclose building energy data are performing well in the real estate market. Further to the authors, the energy efficiency and marketability of buildings have substantially increased with the implementation of building energy data disclosure laws. In addition, BEDM enables sustainability certification and public policy adoption (Lee et al., 2022). Further, higher tariff rates encourage energy-conscious behaviour of building owners by monitoring real-time building energy (Nahiduzzaman et al., 2023). Especially, monitoring building energy demand helps to reduce the energy cost through demand response (Guo & Weeks, 2022). Further, some energy service providers have introduced dynamic tariff rates and incentives based on energy demand and consumption, encouraging building operators and facility managers to track their energy consumption. With the introduction of different rating scales, such as the star rating introduced by the mandatory building disclosure program (NABERS) in Australia, higher-rated buildings have delivered a higher investment return, demonstrating the impact of transparent energy performance on the market value of properties (Lee et al., 2022). Since buyers analyse energy data, energy performance certificates, and clear disclosure of energy performance increases property value and competitiveness in the real estate market (Wilhelmsson, 2023). A summary of enablers of adopting BEDM is shown in Table 3.

*Table 3: Enablers of adopting building energy data management*

| Enablers | Citations |
|---|---|
| Increased Marketability of Buildings | (Wilhelmsson, 2023) |
| Improved energy efficiency in buildings | (Shang et al., 2020) |
| Sustainability certification requirements | (Lee et al., 2022) |
| National and international-level energy policies | (Lee et al., 2022) |
| Higher tariff rates | (Nahiduzzaman et al., 2023) |
| Easy identification of energy-saving opportunities | (Guo & Weeks, 2022) |
| Dynamic tariff rates and incentives | (Guo & Weeks, 2022) |
| Building energy ratings | (Lee et al., 2022) |
| Increasing public awareness | (Wilhelmsson, 2023) |
| Advancement in digital technologies | (Elnour et al., 2024) |

## 3.4 STRATEGIES TO PROMOTE BUILDING ENERGY DATA MANAGEMENT

Das (2025) emphasised that strict building codes and mandatory disclosure of building energy efficiency data must be implemented as policy instruments to address constraints related to data and information to verify the policy outcomes. According to Jin et al.

(2023), energy data disclosure enhances the collaboration between scientific and policy fields, increasing productivity through collaboration and burden sharing. As a pioneer in promoting building energy efficiency, the US is rapidly passing laws to mandate the collection and disclosure of energy usage data. The energy consumption of the US building sector has reduced by 3-8% after energy disclosure. The energy consumption of large Australian buildings has decreased by up to 35% within 9 years after the introduction of building energy disclosure laws. Moreover, 14% of the energy consumption has been reduced within 4 years with energy disclosure along with the New York City benchmarking program. Some local governments in the US, such as New York, San Francisco and Seattle, have mandated Annual disclosure of total energy use and building characteristics as a benchmarking requirement by law or ordinance. Policies related to cybersecurity, privacy, confidentiality and ownership ensure reliable data flow and stakeholder trust in energy data sharing (Das, 2025). Energy performance standards and financial incentives play a crucial role in promoting energy-saving initiatives, where measurable indicators do not effectively impact (Morewood, 2023). Further, Mustapha et al. (2025) identified a few strategies to promote energy data disclosure and management in buildings, including supportive government policies, financial incentives, clear energy management goals, financial support, technological integration, stakeholder engagement, and practical policy frameworks. Iyer et al. (2016) demonstrated the need for a country-level data collection framework and identification of institutional roles and responsibilities in BEDM. In addition, Marinakis (2020) suggests a data-driven architecture for building energy data exchange, management, and real-time processing as a suggestion to promote BEDM.

# 4. DATA ANALYSIS AND FINDINGS

## 4.1 CURRENT STATE OF BUILDING ENERGY DATA MANAGEMENT IN SRI LANKA

According to the findings, Sri Lanka is in a preliminary stage of implementing BEDM. All professionals emphasised that Sri Lanka didn't use building energy data analysis for national-level policy making. Especially, E1 and E3 pointed out the lack of awareness and energy data required for BEDM in the Sri Lankan context. E1 stated, *"At least, many organisations do not maintain regular energy performance metrics in their buildings"*. In addition, E3 highlighted the absence of proper protocols or procedures to disclose and manage building energy data. However, it is noted that the Sri Lanka Sustainable Energy Authority is planning to promote BEDM, aiming at energy data collection and management for national-level energy policy making. E7 stated, "*Now, we are collecting building energy data from financial institutes and supermarkets and hope to expand to other sectors in future"* Substantially, the current focus is only to develop specific energy benchmarks using building energy consumption, floor area, product output, etc.

## 4.2 BARRIERS TO ADOPTING BUILDING ENERGY DATA MANAGEMENT

According to the findings, several barriers in BEDM were identified by the professionals. All professionals identified the issues in data availability, quality and reliability and lack of policy support as significant barriers in BEDM. E1 and E3 stated that even though they needed to access energy data in national building energy policy making, they didn't have a reliable data source to collect data. E3 mentioned, "*building energy disclosure and management has not yet been enforced in Sri Lanka, even though there are some statutory*

*provisions* available *in the Sustainable Energy Authority Act, 2007"*. According to E2, Sri Lanka is facing a severe skill shortage due to a higher rate of migration of experts in BEDM. He further illustrated that *"it's very difficult to retain knowledgeable and skilled professionals to sustain national-level energy data disclosure initiatives"*. Moreover, seven professionals highlighted issues related to standardisation in BEDM. E4 mentioned that Sri Lanka didn't have a standardised data platform to collect building energy data. E3 stated, *"even though we are requested to provide data for energy census in buildings, building operators don't disclose their energy data due to data privacy concerns"*. Cost-related barriers, such as a lack of funding for BEDM and higher implementation costs, have also been highlighted by 6 and 5 professionals, respectively. E3 and E6 stated that Sri Lanka couldn't afford higher implementation costs and funding for BEDM projects with the prevailing economic crisis. Table 4 demonstrates the summary of the barriers identified.

*Table 4: Summary of expert opinions regarding barriers in building energy data management*

| Barriers | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 |
|---|---|---|---|---|---|---|---|---|
| Issues related to data quality, availability and reliability | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Data security and privacy concerns | | | ✓ | ✓ | ✓ | ✓ | | |
| Resistant to taking challenges | | | ✓ | | ✓ | | | |
| Lack of technical infrastructure | | | ✓ | | ✓ | | | |
| Lack of human adaptation | ✓ | | ✓ | | ✓ | ✓ | | |
| Lack of expertise | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Lack of policy support | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lack of standard methods | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Higher implementation costs | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| Lack of funding and incentives | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ |

## 4.3 ENABLERS OF ADOPTING BUILDING ENERGY DATA MANAGEMENT

Considering the enablers in BEDM, the highest number of professionals identified the policy adoption. According to A3, some buildings disclose energy data due to mandatory energy data disclosure regulations. Further, E1 stated, *"Currently, financial institutions and supermarkets are disclosing building energy data because of mandatory energy data disclosure regulations for benchmarks. Without regulations, they do not provide data voluntarily"*. Further, 6 professionals mentioned that sustainability certificates, higher energy tariff rates and building rating systems motivate building owners for BEDM. E3 stated that more building owners would tend to manage data if it could be considered as a plus point in obtaining sustainability certification. Moreover, E5 stated, *"if we can rate buildings based on their energy consumption considering reported energy data, companies will tend to voluntarily disclose and manage data because the energy rating can be used for marketing purposes"*. Additionally, E4 stated that some buildings tend to manage and report energy data, aiming for some incentives and tax reductions through energy saving. Simultaneously, five professionals identified incentives and rewards as enablers in BEDM. Four professionals identified the higher market value and competitive

advantage of buildings due to their energy rating. E3 stated, *"buildings can use their energy ratings and attempts for energy conservation to promote their properties"*. Table 5 summarises the enablers of BEDM identified through expert interviews.

*Table 5: Summary of Expert Opinions regarding Enablers in Building Energy Data Management*

| Enablers | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 |
|---|---|---|---|---|---|---|---|---|
| Higher market value | | ✓ | ✓ | | ✓ | ✓ | | |
| Sustainability certifications | | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Public policy adoption | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Higher energy tariff rates | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Incentives and rewards | | ✓ | ✓ | ✓ | | ✓ | ✓ | |
| Building rating systems | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | |
| Building energy-saving | ✓ | | | | | | | ✓ |
| Company reputation and competitiveness | | | ✓ | ✓ | | ✓ | ✓ | |

## 4.4 STRATEGIES TO PROMOTE BUILDING ENERGY DATA MANAGEMENT

Based on the findings, introducing building energy benchmarks was mentioned by all professionals, highlighting its impact on strengthening BEDM. According to E3, energy benchmarks motivate building owners and operators to effectively utilise building energy data to identify energy-saving opportunities. Seven professionals mentioned that energy data disclosure laws regulate energy data reporting. Specifically, E3 stated, "*introducing mandatory energy reporting regulations is the only way of collecting required energy data for national-level energy policy making"*. Six professionals highlighted the need of centralized energy data platform and training industry professionals to manage energy data effectively. E2 stated that having centralized location ensuring data privacy and confidentiality to collect energy data of the Sri Lankan building stock was a preliminary requirement of national-level BEDM. E7 highlighted the training requirement of professionals to deal with advanced digital technologies in BEDM. Moreover, five professionals identified introducing rewarding systems and building rating systems. Further, E3 mentioned, *"we can obtain a significant participation of industry practitioners for BEDM through rewards, incentives and building ratings".* In addition, experts suggested financial relief for buildings having an effective BEDM system, such as tax reduction and incentives. Finally, 2 experts mentioned the requirement of awareness programs to promote BEDM in the building sector. Table 6 illustrates the summary of the findings of expert interviews on strategies to strengthen BEDM.

*Table 6: Summary of expert suggestions regarding Strategies in Building Energy Data Management*

| Strategies | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 |
|---|---|---|---|---|---|---|---|---|
| Imposing energy data disclosure laws | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| Developing a centralised energy data platform | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Introducing a rewarding system | ✓ | | ✓ | ✓ | ✓ | ✓ | | |

| Strategies | E1 | E2 | E3 | E4 | E5 | E6 | E7 | E8 |
|---|---|---|---|---|---|---|---|---|
| Introducing tax reduction policies | ✓ | | ✓ | | | ✓ | | |
| Introducing energy performance incentives | ✓ | | ✓ | | | ✓ | | |
| Introducing a building rating system | | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Introducing energy benchmarks | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Training industry professionals | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ |
| Conducting awareness programs | | | ✓ | | | | | ✓ |

## 5. DISCUSSION

Both literature findings and expert interviews confirmed that Sri Lanka is still in a preliminary stage in BEDM, whereas it is gaining considerable attention in the global context. Sri Lanka is focusing on collecting fundamental data points required for specific energy consumption, while the global context is thriving towards more advanced analytics and AI-driven decision-making in BEDM. Further, even though 17 barriers in BEDM were identified through the literature review, experts identified only the 10 most significant barriers for the Sri Lankan context. Issues related to heterogeneous data handling, balancing multiple objectives, model and parameter selection, operational changes, system interoperability, research and development, and technological complexity have been identified by none of the experts. Those barriers are associated with advanced BEDM systems, which involve advanced system integration and data analytics. Lack of data quality, availability and reliability and policy support are the highly noted barriers in both literature and expert interviews. Standardisation in BEDM is another highly notable barrier from expert interviews, while literature also emphasised the standardisation issues in BEDM in the global context. Similar to the global context, Sri Lanka is also facing a severe knowledge and skill shortage in BEDM. In addition, cost-related issues such as implementation cost and incentives were also verified in the Sri Lankan context through expert interviews due to the economic condition of the country. Issues related to confidentiality, lack of technical infrastructure, stakeholder resistance and adoption are the least mentioned barriers in Sri Lanka, although they were highly concerned in the global context. A summary of the findings is shown in Figure 1.

In addition, several enablers for BEDM were identified using both the literature review and the expert interviews. Both confirmed that higher marketability and property value due to sustainable efforts to conserve energy would encourage stakeholders to invest in BEDM. Currently, investors look for sustainable features due to a higher focus on sustainable development. In addition, due to higher energy tariff rates in Sri Lanka, people are motivated to be more concerned about energy consumption in buildings. Simultaneously, building management companies try to obtain different sustainability certifications and energy ratings to improve the market value of their property. Therefore, these factors enable BEDM in the Sri Lankan context to some extent. Nevertheless, expert interviews pointed out that some buildings are still not aware of the energy cost because that cost is incurred by the tenants or the residents in the building. In such cases, data disclosure laws must be enforced to influence stakeholders to disclose and manage data.

Considering both barriers and enablers, strategies to promote BEDM in Sri Lanka were identified. As mentioned in the literature, experts also confirmed that strong legislative provisions, such as laws and regulations, must be introduced to force stakeholders to disclose and manage building energy data. Further, experts emphasised that a building energy data platform must be introduced to standardise building energy data disclosure to enable data-driven decision-making in national energy policy formulation, which was also discussed in the literature. However, experts suggested introducing energy benchmarks to strengthen BEDM, allowing building stakeholders to analyse energy data for better energy efficiency opportunities, although this was not found in the literature. Experts agreed with providing incentives, rewarding systems and tax reductions to encourage BEDM as mentioned in the literature. However, it was found that novel suggestions from experts, such as providing training for building stakeholders, conducting awareness programs and introducing rating systems, are more effective strategies to promote BEDM in Sri Lankan buildings.

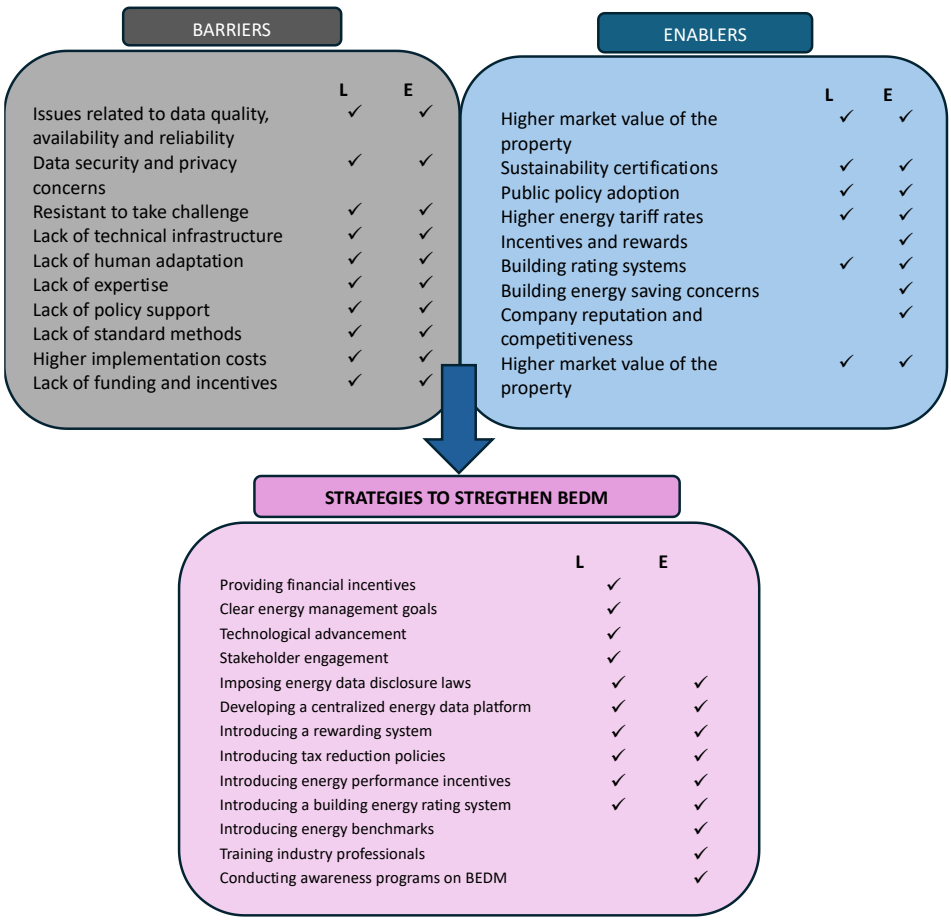



*Figure 1: Summary of findings*

*[L*- Literature; E *- Expert Interviews]*

Due to the number of constraints, Sri Lanka consists of a special setting for researching BEDM. While there is a growing tendency to adopt data-driven energy management in developed countries, Sri Lanka continues to face challenges in BEDM due to fragmented data collection, limited interoperability among stakeholders and low digital integration within building operations. Therefore, examining BEDM within the Sri Lankan context

provides valuable insights into how developing economies can overcome institutional, technological, and operational barriers in achieving sustainability and low-carbonisation goals. Further, the study provides a broader contribution to BEDM by offering a framework that may support other developing countries experiencing similar constraints in BEDM.

## 6. CONCUSIONS

This study focused on identifying the barriers, enablers and strategies to strengthen BEDM in the Sri Lankan context. According to the literature review, advanced data analytics and technologies are used for BEDM and decision-making in BEM in the global context. Even though the literature review identified multiple barriers, enablers and strategies in BEDM in the global context, few of them are highly applicable in the Sri Lankan context. According to the findings of the expert interviews, even though a constructive attempt has been initiated to collect and manage building energy data, BEDM is still in the early stages in the Sri Lankan context. In addition, 10 barriers which hinder the approaches for a BEDM, 8 enablers which motivate BEDM and 9 strategies to promote BEDM, which are applicable for the Sri Lankan context. Lack of data availability, quality, reliability and policy support were the highly noted barriers in Sri Lanka. Data disclosure laws and building energy rating were the highly noted enablers in Sri Lanka. Further, introducing energy benchmarks and statutory provisions, such as laws and regulations, were highly suggested strategies to promote BEDM. The results provide important insights for policymakers regarding the need for national policies and regulatory frameworks for building energy data disclosure and reporting. Industry practitioners can use the identified strategies to improve internal energy data management practices. Finally, this study contributes to the growing knowledge on BEDM, particularly in the context of developing countries. Since this study is directly focused on the Sri Lankan context, the findings of this study might not be directly applicable to other developing contexts with different environmental, regulatory and market conditions.

## 7. REFERENCES

Adewale, B. A., Ene, V. O., Ogunbayo, B. F., & Aigbavboa, C. O. (2024). A systematic review of the applications of AI in a sustainable building's lifecycle. *Buildings*, *14*(7), 2137. https://doi.org/10.3390/buildings14072137

Akbulut, L., Taşdelen, K., Atılgan, A., Malinowski, M., Coşgun, A., Şenol, R., Akbulut, A., & Petryk, A. (2025). A systematic review of building energy management systems (BEMSs): Sensors, IoT, and AI integration. *Energies*, *18*(24), 6522. https://doi.org/10.3390/en18246522

Ali, U., Shamsi, M. H., Bohacek, M., Hoare, C., Purcell, K., Mangina, E., & O'Donnell, J. (2020a). A data-driven approach to optimize urban scale energy retrofit decisions for residential buildings. *Applied Energy*, *267*, 114861. https://doi.org/10.1016/J.APENERGY.2020.114861

Ali, U., Shamsi, M. H., Bohacek, M., Purcell, K., Hoare, C., Mangina, E., & O'Donnell, J. (2020b). A data-driven approach for multi-scale GIS-based building energy modeling for analysis, planning and support decision making. *Applied Energy*, *279*, 115834. https://doi.org/10.1016/j.apenergy.2020.115834

Ali, U., Shamsi, M. H., Hoare, C., Mangina, E., & O'Donnell, J. (2021). Review of urban building energy modeling (UBEM) approaches, methods and tools using qualitative and quantitative analysis. *Energy and Buildings*, *246*, 111073. https://doi.org/10.1016/J.ENBUILD.2021.111073

Alrobaie, A., & Krarti, M. (2022). A Review of data-driven approaches for measurement and verification analysis of building energy retrofits. *Energies*, *15*(21), 7824. https://doi.org/10.3390/EN15217824

Billanes, J. D., Ma, Z. G., & Jørgensen, B. N. (2025). Data-Driven Technologies for Energy Optimization in Smart Buildings: A Scoping Review. *Energies*, *18*(2), 290. https://doi.org/10.3390/en18020290

International Energy Agency (IEA). (2025). Buildings - Energy System. https://www.iea.org/energy-system/buildings

Clauß, J., Caetano, L., & Bror Svinndal, Å. (2024). Impact of practical challenges on the implementation of data-driven services for building operation: Insights from a real-life case study. *Energy and Buildings*, *316*, 114310. https://doi.org/10.1016/J.ENBUILD.2024.114310

Das, D. K. (2025). integrating iot and ai for sustainable energy-efficient smart building: potential, barriers and strategic pathways. *Sustainability*, *17*(22), 10313, https://doi.org/10.3390/su172210313

Elnour, M., Ahmad, A. M., Abdelkarim, S., Fadli, F., & Naji, K. (2024). Empowering smart cities with digital twins of buildings: Applications and implementation considerations of data-driven energy modelling in building management. *Building Services Engineering Research and Technology*, *45*(4), 475–498. https://doi.org/10.1177/01436244241239290

Gao, D. (2025). A deep learning approach for energy management systems in smart buildings towards a low-carbon economy. *International Journal of Low-Carbon Technologies*, *20*, 1136–1142. https://doi.org/10.1093/ijlct/ctaf063

Guest, G., Namey, E., & Chen, M. (2020). A simple method to assess and report thematic saturation in qualitative research. *PLOS One*, *15*(5), e0232076. https://doi.org/10.1371/JOURNAL.PONE.0232076

Guo, B., & Weeks, M. (2022). Dynamic tariffs, demand response, and regulation in retail electricity markets. *Energy Economics*, *106*, 105774. https://doi.org/10.1016/j.eneco.2021.105774

Han, J. M., Lim, S., Malkawi, A., Han, X., Chen, E. X., Salimi, S., Dokka, T. H., Hegli, T., & Edwards, K. (2023). Data-informed building energy management (DiBEM) towards ultra-low energy buildings. *Energy and Buildings*, *281*, 112761. https://doi.org/10.1016/J.ENBUILD.2022.112761

Hannan, M. A., Faisal, M., Ker, P. J., Mun, L. H., Parvin, K., Mahlia, T. M. I., & Blaabjerg, F. (2018). A review of internet of energy based building energy management systems: Issues and recommendations. *IEEE Access*, *6*, 38997–39014. https://doi.org/10.1109/ACCESS.2018.2852811

Iyer, M., Kumar, S., Mathew, S., Stratton, H., Mathew, P., & Singh, M. (2016). *Establishing a Commercial Buildings Energy Data Framework for India: A Comprehensive Look at Data Collection Approaches, Use Cases and Institutions*. (DE-AC02- 05CH11231), Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/lbnl-1006427.pdf

Jin, X., Zhang, C., Xiao, F., Li, A., & Miller, C. (2023). A review and reflection on open datasets of city-level building energy use and their applications. *Energy and Buildings*, *285*, 112911. https://doi.org/10.1016/J.ENBUILD.2023.112911

Kazmi, H., Fu, C., & Miller, C. (2023). Ten questions concerning data-driven modelling and forecasting of operational energy demand at building and urban scale. *Building and Environment*, *239*, 110407. https://doi.org/10.1016/J.BUILDENV.2023.110407

Kiavarz, H., Jadidi, M., Rajabifard, A., & Sohn, G. (2024). An explainable & prescriptive solution for space-based energy consumption optimization using BIM data & genetic algorithm. *Journal of Building Engineering*, *92*, 109763. https://doi.org/10.1016/J.JOBE.2024.109763

Krishnan, D., Kelly, S., & Kim, Y. (2022). A meta-analysis review of occupant behaviour models for assessing demand-side energy consumption. *Energies*, *15*(3), 1219. https://doi.org/10.3390/EN15031219

Lee, C. L., Gumulya, N., & Bangura, M. (2022). The role of mandatory building efficiency disclosure on green building price premium: Evidence from Australia. *Buildings*, *12*(3), 297. https://doi.org/10.3390/buildings12030297

Li, A., Xiao, F., Xiao, Z., Yan, R., Li, A., Lv, Y., & Su, B. (2024). Active learning concerning sampling cost for enhancing AI-enabled building energy system modeling. *Advances in Applied Energy*, *16*, 100189. https://doi.org/10.1016/J.ADAPEN.2024.100189

Liu, H., Liang, J., Liu, Y., & Wu, H. (2023). A review of data-driven building energy prediction. *Buildings*, *13*(2), 532. https://doi.org/10.3390/BUILDINGS13020532

Manfren, M., James, P. A., & Tronchin, L. (2022). Data-driven building energy modelling: An analysis of the potential for generalisation through interpretable machine learning. *Renewable and Sustainable Energy Reviews*, *167*, 112686. https://doi.org/10.1016/J.RSER.2022.112686

Mantha, B. R. K., Menassa, C. C., & Kamat, V. R. (2016). A taxonomy of data types and data collection methods for building energy monitoring and performance simulation. *Advances in Building Energy Research*, *10*(2), 263–293. https://doi.org/10.1080/17512549.2015.1103665

Mariano-Hernández, D., Hernández-Callejo, L., García, F. S., Duque-Perez, O., & Zorita-Lamadrid, A. L. (2020). A review of energy consumption forecasting in smart buildings: Methods, input variables, forecasting horizon and metrics. *Applied Sciences (Switzerland)*, *10*(23), 1–27. https://doi.org/10.3390/APP10238323

Marinakis, V. (2020). Big Data for energy management and energy-efficient buildings. *Energies*, *13*(7), 1555. https://doi.org/10.3390/EN13071555

Markus, A. A., Hobson, B. W., Gunay, H. B., & Bucking, S. (2022). Does a knowledge gap contribute to the performance gap? Interviews with building operators to identify how data-driven insights are interpreted. *Energy and Buildings*, *268*, 112238. https://doi.org/10.1016/J.ENBUILD.2022.112238

Morewood, J. (2023). Building energy performance monitoring through the lens of data quality: A review. *Energy and Buildings*, *279*, 112701. https://doi.org/10.1016/j.enbuild.2022.112701

Mustapha, Z., Akomah, B. B., Abilgah, T., & Tieru, C. K. (2025). Enhancing energy efficiency and management in smart buildings: A holistic approach. *Journal of Applied Science and Technology Trends*, *6*(1), 16–24. https://doi.org/10.38094/jastt61206

Nahiduzzaman, K. M., Said Abdallah, A., Moradzadeh, A., Mohammadpour Shotorbani, A., Hewage, K., & Sadiq, R. (2023). Impacts of tariffs on energy conscious behavior with respect to household attributes in Saudi Arabia. *Energies*, *16*(3), 1458. https://doi.org/10.3390/en16031458

Onile, A. E., Machlev, R., Petlenkov, E., Levron, Y., & Belikov, J. (2021). Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review. *Energy Reports*, *7*, 997–1015. https://doi.org/10.1016/J.EGYR.2021.01.090

Runge, J., & Zmeureanu, R. (2021). A review of deep learning techniques for forecasting energy use in buildings. *Energies*, *14*(3), 608. https://doi.org/10.3390/EN14030608

Shang, L., Lee, H. W., Dermisi, S., & Choe, Y. (2020). Impact of energy benchmarking and disclosure policy on office buildings. *Journal of Cleaner Production*, *250*, 119500. https://doi.org/10.1016/j.jclepro.2019.119500

Wilhelmsson, M. (2023). How does the presentation of energy performance affect the price of houses? A case study of detached houses in stockholm, Sweden. *Buildings*, *13*(6), 1367. https://doi.org/10.3390/buildings13061367

Zhang, C., Li, J., Zhao, Y., Li, T., Chen, Q., & Zhang, X. (2020). A hybrid deep learning-based method for short-term building energy load prediction combined with an interpretation process. *Energy and Buildings*, *225*, 110301. https://doi.org/10.1016/J.ENBUILD.2020.110301

Zhang, H., Seal, S., Wu, D., Bouffard, F., & Boulet, B. (2022). Building energy management with reinforcement learning and model predictive control: A Survey. *IEEE Access*, *10*, 27853–27862. https://doi.org/10.1109/ACCESS.2022.3156581

Veenadhi, A.P.G.K., Waidyasekara, K.G.A.S., Manewa, R.M.A.S. and Jayasena H.S., 2026. Enhancing circularity in steel structures through design for decosntruction: Information needs. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 642-656. DOI: https://doi.org/10.31705/WCS.2026.48. Available from: https://ciobwcs.com/papers/

# ENHANCING CIRCULARITY IN STEEL STRUCTURES THROUGH DESIGN FOR DECOSNTRUCTION: INFORMATION NEEDS

**A.P.G.K.Veenadhi[1], K.G.A.S. Waidyasekara[2], R.M.A.S. Manewa[3] and H.S.Jayasena[4]**

## *ABSTRACT*

*Design for Deconstruction (DfD) is identified as a key strategy for improving circularity in the construction industry. It mainly considers the integration of R principles into the building components and processes at the end of their life cycles. During the implementing the DfD for the building or infrastructure the material selection process plays a significant role. Having observed some of the building and infrastructure projects in Sri Lanka, the structure/frames represent a significant portion of the overall cost. However less attention had been paid on their end of lifecycle considerations (economic, social and environmental). As the first step, this study explores the potential of DfD steel structures in enhancing circularity. The research is based on a literature review examining on design phase deconstruction information requirement for enhancing circularity in construction products. The review identifies key factors influencing DfD, including durability, connection methods, structural characteristics, and ease of separation during deconstruction in general and the ability of material traceability, selective disassembly, and integration with digital technologies like Building Information Modelling for Deconstruction (BIMfD) in specific to steel structures. Large-scale deployment is nevertheless hampered by issues including certification requirements, market uncertainties, logistical limitations, and the absence of standardised reuse protocols, notwithstanding these benefits. In order to optimise the reuse potential of steel structures and facilitate the shift to a circular construction. The conceptual framework explains the integration between DfD principles, information requirements (product. process) and circularity dimensions for sustainable product delivery.*

***Keywords:*** *Circular Construction; Conceptual framework; Design for Deconstruction; Information Requirement; Steel.*

## 1. INTRODUCTION

Sustainability is an essential consideration in the current practice of every industry especially construction industry (Mhatre et al., 2021) due to its products and processes

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, kaviniveenadhi1997@gmail.com ,
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Senior Lecturer, School of Civil Engineering and Built Environment, Liverpool John Moores University, UK, R.M.Manewa@ljmu.ac.uk
[4] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk

consume high volume of scarce resources and in general products are designed for long lifecycles. Circular construction is identified as one of effective solutions for improving sustainability within construction. It has been discussed with several practices, such as waste-to-energy supply chain (Pan et al., 2015) , eco-industrial park, waste-to-resource supply chain, cradle-to-cradle, industrial ecology regenerative design (Mahpour, 2018). Design for Deconstruction (DfD) has gained more global attention in recent past , for effective waste and resource management (Benachio et al., 2020). The concept of Design for Deconstruction (DfD) seeks to create construction assets such as buildings and infrastructure that can easily be reused or repurposed, utilizing recycled materials and elements, as well as reducing construction and demolition waste (Akanbi et al., 2019). Aligning with that, implementing DfD in construction industry can make a massive impact on sustainable practices, which is one of the important tasks to be achieved according to the past studies (Yates, 2013). Therefore, identifying practical techniques and suitable material applications for implementing DfD has become increasingly important. Literature explains several construction materials that are fit for DfD purposes. Among them steel is often pointed out as one of the most promising materials due to its recyclability, reusability, adaptability and ease of disassembly. Steel structures possess a number of attributes that are well suited to the circular economy principles of the built environment, and hence demonstrate a high degree of compatibility with DfD approaches.

Furthermore, some studies have comprehensively synthesised the applicability, advantages, implementation considerations and deconstruction potential of steel structures (Akanbi et al., 2019). However, no study was explained its design considerations (proactive information requirement) to make the steel as more DfD structure to enhance its circularity potentials. This led to a research gap in the development of a clear and integrated understanding on the role of steel in enabling DfD implementation. The study therefore aims to explore the potential of steel as a material for Design for Deconstruction by critically reviewing and consolidating the diverse perspectives available in existing literature. This study is carried out as part of a larger research initiative for MPhil study which is aimed at the development of a deconstruction information model for steel structures and therefore is a necessary preliminary investigation to understand the appropriateness and feasibility of implementation of steel in DfD practices.

## 2. RESEARCH METHODOLOGY

This paper derives from an extensive literature review that is part of an ongoing MPhil research project, which aimed at developing a Deconstruction Information Model (DIM) for Steel Structures by incorporating Design-for-Deconstruction (DfD) Data Features to Improve Circular Economy Decision-Making. Since the research is still at its preliminary phase, the examination relies solely on a review of existing literature that explained the current gap in understanding principles, and practices of DfD and its role in improving CE. Accordingly, the literature review has been utilized narrative review, where the past literature has interpreted in more descriptive way. In that case, literature evidence was sourced from journal articles, books, both published and unpublished bibliographies, conference proceedings, and various documents. In the literature review, essential terms such as circular economy, design for deconstruction, design for disassembly, Steel Construction, Steel Reuse, advantages, obstacles, and construction were examined (Sylvester et al., 2011).

# 3. DESIGN FOR DECONSTRUCTION

Tleuken et al., (2022) stated that Design for Deconstruction (DfD) is the concept that considers the final demolition stage during initial design and planning. And also, it focuses on increasing the value that has been input into the building material or structural element even after the building's end-of-use. Kanters (2018) identified DfD is a method where a design team designs a building that facilitates not only adaptation and renovation, but also the reuse of building materials and components. As mentioned previously, deconstruction process can be predicted at the design stage of a construction process (Akanbi et al., 2019). Therefore, this concept can outbreak with number of advantages economically, environmentally and socially (Akinade et al., 2020). For an example, if the buildings are initially designed for deconstruction, it will significantly improve the environmental effect due to the possible recovery of almost 95% savings of the embodied energy of the construction materials and up to 50% of the total building's life cycle energy (Tleuken et al., 2022). Moreover, it also massively improves the waste management issues.

DfD has its own set of principles which is supposed to follow when the practices of it implemented (Rios et al., 2015) it includes reducing the number of materials and components used; Choosing materials that are possible for reusing and recycling; Using visible and reachable building elements connections; Using simple (yet strong) and connections that are easy to deconstruct, (e.g. dry connections, dissolvable chemical or reversible welding connections); and practicing utilization of building modules that are robust, substitutable and convenient for transportation (Akinade et al., 2020). Supportively, Rios et al., (2015) also provided a similar definition with addressing the key principles as above mentioned.

Tleuken et al., (2022), identify some benefits of DfD in the industrial market such as, reducing the time required for building demolition and labour involved in demolition works. DfD could bring some economic incentives. Meanwhile, uncertainty about the quality of the reused material; low demand due to users' negative perception; financial profitability of demolition practices rather than disassembly; earthquake risks when using bolting connections; high risks of reinforced concrete corrosion can identify as basic shortcomings (Tleuken et al., 2022).

## 3.1 IMPLEMENTATION OF DFD IN THE CONSTRUCTION INDUSTRY

DfD is still in its early stage of implementation globally (Akinade et al., 2017). Nevertheless, researchers have examined various aspects of DfD from different perspectives (Akanbi et al., 2019). According to Kanters (2018), general construction principles that support the design for deconstruction are, (a) the overall building design, (b) materials and connections, (c) the construction and deconstruction phases, and (d) communication, competence, and knowledge. Moreover, in the same study, the author mentioned about major categories to be considered when implementing DfD in the construction industry. They are as; (a) general design and construction principles, (b) Specific materials' potential for DfD, (c) DfD throughout the design process, (d) Tools for DfD, (e) Existing building stock potential and (f) Barriers and drivers for DfD.

### 3.2 FACTORS TO BE CONSIDERED IN SELECTING MATERIALS FOR DFD

Material selection has a major consideration on the DfD implementations (Ranasinghe et al., 2025; Zoghi et al., 2022). Tzourmakliotou (2021) has reviewed the number of past literature and identified following list of factors to be considered specifically for the material selection for DfD implementation for building construction which is summarised in Table 1.

*Table 1: Material related factors involved in the DfD*

| No | Material Related Factors |
|---|---|
| 1 | Use of durable reusable materials |
| 2 | Use as connections nut/bolt that can be easily removed instead of nails and gluing |
| 3 | Use prefabricated, modular assemblies |
| 4 | Avoid composite materials during design specification |
| 5 | Minimize number of connectors and limit the different types |
| 6 | Minimize number and types of building components |
| 7 | Avoid toxic and hazardous materials |
| 8 | Use of recyclable materials |
| 9 | Avoid materials with secondary finishes, such as coating which compromise reuse potential |
| 10 | Select easily separable materials with reuse potential |
| 11 | Use lightweight materials |

*Source - (Tzourmaklioutou, 2021)*

The aim of DfD for buildings/infrastructure is to find solutions for the problems of reusing and recycling building materials when their useful lives are coming to an end (Tzourmakliotou, 2021). As previously mentioned, DfD envisions a closed cycle of resource use and reuse as opposed to the conventional linear material flow, which starts with the extraction of raw materials and ends with the disposal of garbage in landfills (Akinade et al., 2020). DfD strategy uses fewer virgin materials and produce less waste during construction, renovation, and demolition; it also wants to build structures that are "material banks" of future building materials and prolong building lives in situ (Mahpour, 2018). For the design team to achieve a high degree of DfD, choosing the appropriate materials, connections, and components is arguably the most significant task to be completed (Akbarnezhad, 2014). Before determining whether a material is durable enough to be reused in its current form or, if it cannot be reused, whether it can be readily recycled, consideration should be given to issues like whether the specific material or its component is suitable for reuse, recycling, and disposal procedures (Crowther, 1999).

## 4. ANALYSIS OF STRUCTURAL MATERIALS FOR DFD POTENTIALS

Material selection plays a vital role in the successful implementation of Design for Deconstruction (DfD). Kanters (2018) explained that choosing materials that are easily dismantled, reused, or recycled is one of the most important parts of designing for deconstruction. Table 2 presents a summary of literature during last two decades that have identified the structural materials that have high potentials for DfD.

*Table 2: Potential materials for DfD*

| Materials / Authors | Steel | Timber | Concrete | Masonry | Prefabricated Structures | (Roofing materials, Architectural elements) |
|---|---|---|---|---|---|---|
| A1 | ✔ | ✔ | ✔ | ✔ | | ✔ |
| A2 | ✔ | ✔ | | ✔ | | ✔ |
| A3 | ✔ | ✔ | | ✔ | | |
| A4 | ✔ | ✔ | | | ✔ | |
| A5 | ✔ | ✔ | ✔ | ✔ | | |
| A6 | ✔ | | | | | |
| A7 | ✔ | ✔ | ✔ | | ✔ | |
| A8 | ✔ | ✔ | ✔ | | | |
| A9 | ✔ | | | | | |
| A11 | ✔ | | | | | |
| A12 | ✔ | ✔ | | | ✔ | |
| A13 | ✔ | ✔ | ✔ | ✔ | | |
| A14 | ✔ | ✔ | | | | |
| A15 | ✔ | ✔ | | | | |
| A16 | | ✔ | | | | |
| A17 | ✔ | ✔ | ✔ | | | |
| A18 | ✔ | ✔ | | | ✔ | |
| A19 | ✔ | ✔ | | | ✔ | |
| A20 | | ✔ | | | | |

A1-(Guy & Shell, 2002), A2-(Chini & Bruening, 2003), A3-(Crowther, 1999), A4-(Webster & Costello, 2006), A5-(Addis, 2012), A6- (Durmisevic, 2006), A7-(Gorgolewski, 2008), A8-(Guy & Ciarimboli, 2005), A9-(Tingley & Davison, 2011), A10-(Tingley, 2013), A11- (Rios et al., 2015), A12-(Kibert, 2016), A13-(Kanters, 2018), A14-(Akanbi et al., 2019), A15- (Tleuken et al., 2022), A16-(Passarelli et al., 2025), A17-(Daly, 2023), A18-(Ostapska et al., 2024), A19-(Pristerà et al., 2024), A20- (Patrizi et al., 2026).

The durability, connection techniques, and structural behaviour of the materials used have a significant impact on the viability of deconstruction at the end of a building's life (Kanters, 2018). These characteristics make some materials more reusable by nature, while others present challenges with deterioration, separation, or recycling. Moreover, Kanters (2018) emphasizes that materials like steel, masonry, and wood can facilitate reuse within a circular construction framework. Among these, steel and wood are regarded as closed-loop cycle materials since they have the potential to be repeatedly processed and reused (Ostapska et al., 2024). On the other hand, because of restrictions on recycling and reuse, materials like roof tiles, thermosetting plastic insulation, plasterboard, foundations, and masonry components are typically not categorized as closed-loop materials (Guy & Shell, 2002).

In a similar vein, Tingley (2013) investigated the viability of deconstruction for materials such as steel, concrete, masonry, and wood. Accordingly, timber structures' uniform sizes and straightforward construction techniques make them ideal for deconstruction. Deconstruction potential is also greatly influenced by the type of jointing system, with mechanical connectors like bolts or metal plate connectors facilitating simpler disassembly (Hopkinson et al., 2018). Masonry components, such as bricks and blocks, are frequently reusable, but the kind of mortar used is important because lime mortar is easier to separate and clean than cement mortar (Addis, 2012). In contrast, because of the strong bonding produced by cement-based joints, reinforced concrete structures are more challenging to disassemble. Because steel is highly recyclable and steel connections are versatile, steel structures are widely recycled even though they are not directly reused (Tingley & Davison, 2011).

Hybrid structural systems have also been studied recently. The potential of timber-concrete composite (TCC) floors for DfD applications is explained by Holly et al. (2023). The study shows that using deconstructable connectors can make it easier to disassemble and reassemble TCC components while preserving structural integrity. TCC flooring that incorporates DfD principles can increase carbon storage capacity and encourage material reuse (Chini & Bruening, 2003). However, in order to overcome technical and financial obstacles, such systems must be designed, built, and disassembled using a multidisciplinary approach (Rose et al., 2018). In order to facilitate broader adoption, the study recommends that future research concentrate on commercializing deconstructable connectors and lowering additional costs (Smeets et al., 2019).

Also, the information needs for reusable concrete components within DfD frameworks were investigated by Uotila et al. (2024). Accordingly, concrete components have a major impact on emissions during construction, but they also present a significant opportunity for CO2 reduction through reuse. The researchers created a thorough list of data requirements pertaining to the characteristics and potential for reuse of concrete components through expert workshops (Xia et al., 2022). These findings provide valuable guidance for designers and construction professionals during the early stages of projects and support the broader implementation of DfD principles in concrete construction (Daly, 2023). As the literature has increasingly recognised steel as a prominent material for DfD, and preliminary observations confirm its cost significance, this paper further investigates the design stage information requirement to enable the deconstruction of steel structures at the end of their physical or economic life.

## 5. STEEL FOR DESIGN FOR DECONSTRUCTION

Steel structure deconstruction is an innovative shift within the construction industry (Yeung et al., 2017). Which is also centered on selective disassembly techniques to preserve significant structural steel members intact for reuse, rather than re-melting or downcycling (Price, 2025). Contrary to the conventional demolition process, deconstruction aims at longer material lifecycles, less landfill wastes, and making significant reductions in embodied greenhouse gas (GHG) emissions (Andisheh, 2024). This paradigm is consistent with the principles of circular economy and sustainability, particularly if DfD methods are used in the early phases of the design process (Berglund-Brown & Ochsendorf, 2025). Empirical research has indicated that even in structures originally not designed for disassembly, steel components can be recovered satisfactorily and reused in new construction activities if adequate documentation, procurement

planning, and fabrication procedures are adopted (Gorgolewski et al., 2008). Such research has shifted the academic discussion from feasibility assessment to optimization and upscaling of steel reuse systems.

## 5.1 CIRCULAR CONSTRUCTION POTENTIALS OF STEEL

The current literature explains the fact that steel has a great potential for supporting circular construction practices thanks to its recyclability, reusability, adaptability and high material recovery value (Hradil et al., 2024). The environmental benefits of reusing and recycling steel have been clearly established, particularly its capacity to reduce greenhouse gas emissions, save embodied energy, and support the construction sector's carbon neutrality targets (Berglund-Brown & Ochsendorf, 2025).

Furthermore, the literature identifies the successful implementation of steel deconstruction being influenced not only by the material properties of steel but also by supportive design, technological and market-based approaches (Dunant, 2018). Design for disassembly principles, such as modularity, standardisation and use of dismountable connections, allow for efficient dismantling and material recovery (Tleuken et al., 2022). Simultaneously, digital technologies such as BIMfD (Building Information Modelling for Deconstruction), enhance the traceability, documentation of materials, and deconstructability assessment, allowing for improved decision-making throughout the building lifecycle (Jayasinghe & Waldmann, 2020).

Moreover, prior research highlights a range of economic and industrial applications linked to steel deconstruction, including the establishment of certification systems, circular supply chains, and digital platforms for trading reclaimed steel components (Basta et al., 2020; Davis et al., 2024). The literature reviewed therefore shows that steel deconstruction is an integrated strategy that combines environmental sustainability, (Rios et al., 2015) technological innovation and circular material management in the built environment (Gorgolewski, 2006). Table 3 summarises the advantages and applications of steel DfD reported by various authors.

*Table 3: Advantages and applications of steel DfD*

| Category | Advantages / Applications of Steel Deconstruction and DfD | References |
|---|---|---|
| Environmental Benefits | Steel recycling and reuse through deconstruction significantly reduce greenhouse gas (GHG) emissions and environmental impacts compared to conventional recycling and landfilling methods. | (Yellishetty et al., 2011), (Berglund-Brown & Ochsendorf, 2025), (Ranasinghe et al., 2025), (Zoghi et al., 2022) |
| Embodied Energy Conservation | Reuse preserves the embodied energy and material value associated with rolling, fabrication, and machining processes, achieving greater carbon and energy savings than recycling. | (Dunant, 2018), (Davis et al., 2024) |
| Contribution to carbon neutrality | Steel deconstruction supports carbon neutrality goals in the construction industry by minimizing embodied carbon emissions and maximizing material recovery. | (Dunant, 2018), (Yellishetty et al., 2011) |

| Category | Advantages / Applications of Steel Deconstruction and DfD | References |
|---|---|---|
| Circular economy integration | Steel structures support circular economy principles through recyclability, reusability, adaptability, and material value retention. | (Gorgolewski, 2006), (Basta et al., 2020) |
| Design application under DfD | DfD promotes modular construction, standardized components, and bolted/dismountable connections that facilitate easier dismantling and reuse. | (Bartsch, 2025) |
| Digital application | BIM for Deconstruction (BIMfD) enables material tracking, salvage value assessment, traceability, and deconstructability evaluation for optimized recovery solutions. | (Jayasinghe & Waldmann, 2020) |
| Quality assurance applications | Steel reuse requires documentation, provenance tracing, inspection, and non-destructive testing to ensure structural performance and safety compliance. | (Kanyilmaz et al., 2023), |
| Economic benefits | Reused steel can become cost-competitive under favourable conditions such as shorter transportation distances and limited testing requirements. | (Dunant, 2018), (Basta et al., 2020) |
| Market and supply chain applications | Development of digital marketplaces, certification systems, and circular supply chains can normalize steel reuse practices within the construction industry. | (Kanyilmaz et al., 2023), (Dunant, 2018) |
| Industry transformation | Steel deconstruction supports the transformation of the construction industry towards sustainable and circular material economies. | (Bartsch, 2025) |

## 5.2 DEMAND OF REUSING STEEL IN CONSTRUCTION

The reuse of structural steel presents a distinct opportunity to minimize embodied carbon in buildings, as direct reuse bypasses the energy and heavy emission processes of remelting and re-rolling scrap (DBM Vircon, 2024). Current studies highlight that reuse often results in greater life-cycle environmental advantages compared to recycling, as long as reuse recovery rates and transportation and processing impacts are effectively handled (Bartsch, 2025).

The demand for recycled steel is influenced by three interconnected factors (Hart et al., 2019). Initially, regulations and corporate decarbonization goals enhance the motivation to obtain materials with lower embodied carbon. Research modelling the circularity of steel indicates that policy; procurement regulations, reuse objectives are crucial for generating consistent demand (Davis et al., 2024). Secondly, cost indicators, when the expenses of demolition, deconstruction, and refurbishing are on par with new production or when new steel prices increase, reuse gains commercial appeal, yet studies indicate this is significantly influenced by context and is sensitive to logistics and labour expenses (Temmerman et al., 2012). Client preferences and sustainable procurement in construction are generating a specialized demand for verified reused materials, encouraging supply-chain investment and intermediary entities that can facilitate the exchange of reclaimed inventory (Tingley et al., 2017).

### 5.3 PRACTICALITIES AND BARRIERS TO IMPLEMENTATION

Research and project case studies highlight various persistent practical obstacles that hinder extensive reuse of steel. Some of the major barriers can identify as inventory and alignment, salvaged pieces from demolition vary in size, quality, and state, complicating their alignment with designers' standard specifications without considerable refabrication or innovative design adjustments (Bartsch, 2025). Deconstruction compared to demolition methods influences yields: meticulous deconstruction enhances reusable yield but raises time and labour expenses (Yeung et al., 2017).

According to Bartsch (2025), standards, certification, and structural traceability present significant challenges. The absence of standardized guidelines for certifying the suitability of reclaimed components (bolt configurations, remaining section capacity, connection details, fatigue lifespan) creates liability issues for engineers and insurers. Recent evaluations urge the establishment of standardized assessment protocols and material passports to record history, grading, and testing to close trust gaps (Akbarnezhad, 2014).

Additionally, in the perspective of economical practicalities, several life-cycle assessments (LCAs) and business-case studies indicate that the environmental advantages of reuse may be diminished if transport distances are extensive, if significant reconditioning is necessary (such as sandblasting, re-coating, non-destructive testing), or if extra embodied emissions result from changed structural details. Therefore, local supply chains, disassembly-focused reversible design, and prefabrication methods enhance practicality (Bartsch, 2025).

Past studies also indicate that reuse of steel is still low across countries and markets. The survey and case-study research by (Tingley et al., 2017) measured the low historical rates of reuse while also identifying technical and institutional factors that enhanced reuse in particular projects. Recent studies support the use of digital tools such as; material passports, searchable reclaimed inventories and procurement incentives to consolidate demand and lower transaction expenses. Summary of identified barriers and challenges to implement DfD for steel structures has provided in Table 4.

*Table 4: Practicalities and barriers to implementation of DfD in steel*

| Category | Identified Barriers / Challenges in Steel Reuse and Deconstruction | References |
|---|---|---|
| Inventory and Component Compatibility | Salvaged steel components vary in size, quality, and condition, making it difficult to align them with standard design specifications without additional refabrication or design modifications. | (Bartsch, 2025) |
| Time and Labour Requirements | Careful deconstruction methods improve reusable material yield; however, they increase time consumption and labour costs compared to conventional demolition practices. | (Yeung et al., 2017) |
| Standards and Certification Issues | The absence of standardized certification guidelines for reclaimed steel components creates uncertainty regarding structural suitability, safety, and liability among engineers and insurers. | (Dunant, 2018), (Bartsch, 2025) |

| Category | Identified Barriers / Challenges in Steel Reuse and Deconstruction | References |
|---|---|---|
| Lack of Structural Traceability | Limited availability of material history, grading records, and testing documentation reduces confidence in the reuse of reclaimed steel components. | (Akbarnezhad et al., 2014) |
| Need for Material Passports and Assessment Protocols | Existing studies emphasize the importance of standardized assessment protocols and material passports to improve trust, traceability, and quality assurance in reclaimed steel reuse. | (Bartsch, 2025), (Akbarnezhad et al., 2014) |
| Transportation and Reconditioning Costs | Environmental and economic benefits of reuse can decrease when transport distances are high or when extensive reconditioning processes such as sandblasting, recoating, and testing are required. | (Bartsch, 2025) |
| Supply chain limitations | Lack of localized supply chains and inadequate disassembly-oriented design practices reduce the practical feasibility of steel reuse. | (Bartsch, 2025) |
| Low market adoption | Historical reuse rates of steel remain low across many countries and construction markets despite the recognized benefits of reuse practices. | (Dunant, 2018), (Tingley et al., 2017) |
| Technical and institutional constraints | Technical limitations and institutional barriers continue to hinder the wider adoption of reclaimed steel reuse practices. | (Dunant, 2018), (Tingley et al., 2017) |
| Limited digital integration | Insufficient use of digital tools such as material passports, searchable reclaimed inventories, and procurement incentive systems limits efficient material recovery and market coordination. | (Bartsch, 2025), (Tingley et al., 2017) |

## 5.4 DECONSTRUCTION INFORMATION REQUIREMENT FOR STEEL TOWARDS ENHANCING CIRCULARITY

Figure 1 shows the conceptual framework for DfD information requirement for CE while Figure 2 shows the theoretical framework that explains the link between DfD principles, information requirements for sustainable deconstruction and how this contributes in circularity (circularity dimensions). However, this is high end framework and component level information is required to develop a more accurate material passport. The process model mainly consists with three sections. DFD principles need to be considered at the design stage and then key information requirement for DFD. Having designed the product by using appropriate deconstruction information the product will achieve circularity dimensions at the end of its effective lifecycle. This framework needs further development in components level and also needs its usability in Sri Lankan context which are yet to undertake during the MPhil.

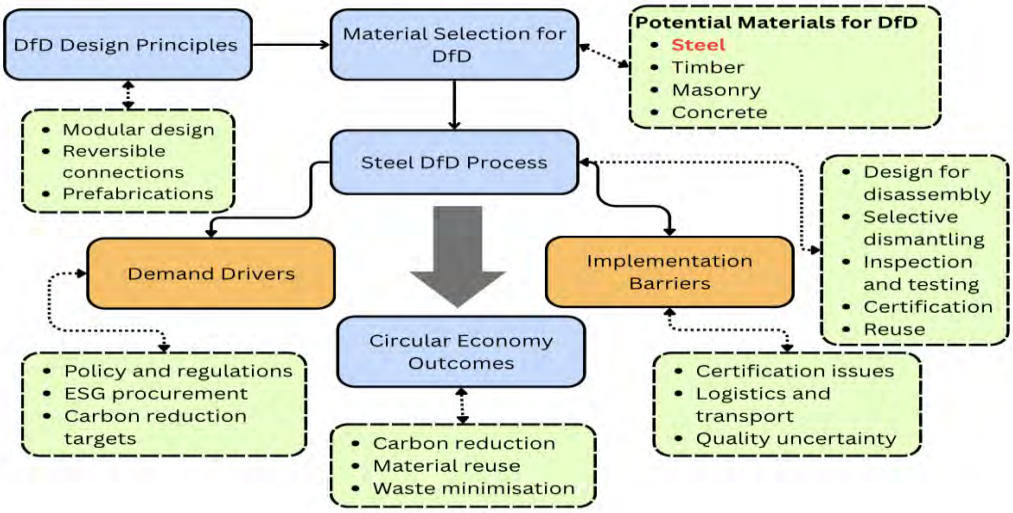



*Figure 1: Conceptual framework for DfD information requirement for circular construction*

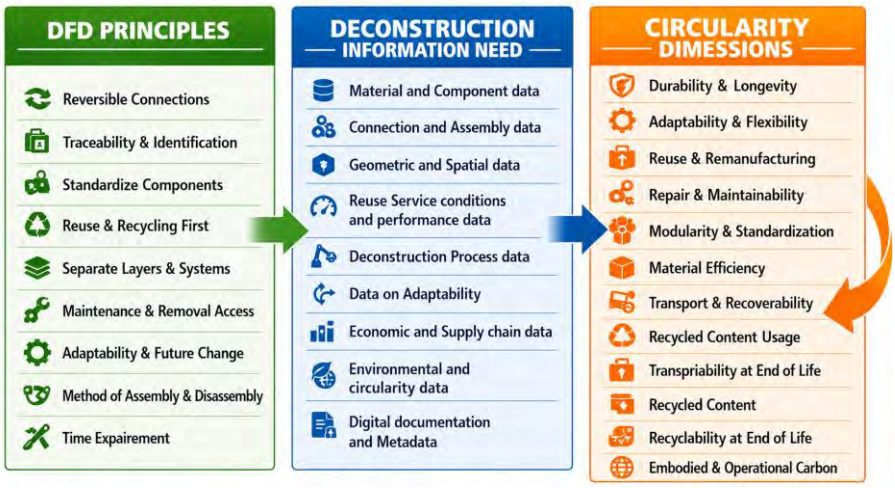



*Figure 2: Theoretical framework for DfD information requirement for circular construction*

## 6. DISCUSSION

The study explains deconstruction information needs of steel structure towards achieving a circular construction. Steel structure is used in the preliminary framework development as it covers most of the DfD principles such as recyclability, reusability, structural adaptability and compatibility with reversible connections, thus contributing to circular economy goals as illustrate in figure 2. Steel reuse is improved by integrating DfD with technologies such as digital traceability, material passports, and Building Information Modelling for Deconstruction (BIMfD). This emphasises that for steel DfD deployment to be successful, digital systems, standardised documentation, and integrated supply chains are essential. However, there are obstacles, such as the need for certification, the uneven quality of recycled parts, the absence of standard procedures, the expense of transportation, and the lack of market trust. The economic feasibility of salvaged steel applications is further reduced by the lack of regional supply chains and insufficient market infrastructure. According to this study, earlier studies on steel for DfD have been dispersed among a number of viewpoints, including economic and environmental ones. By consolidating these viewpoints, the study provides a comprehensive understanding of

the applicability of steel structures in DfD, serving as a critical foundation for future research in deconstruction-oriented design and circular construction practices.

## 7. CONCLUSIONS

This research explored the capability of steel frameworks for Design for Deconstruction (DfD) and their role in circular construction. The results show that steel ranks among the best materials for DfD because of its strength, ability to be reused, recyclability, flexibility, and suitability for reversible connection systems. Alongside its ecological and financial advantages, steel reuse can greatly enhance carbon reduction and resource efficiency in the constructed environment. The review results emphasizes that effective steel deconstruction relies on both material characteristics and efficient information management, digital traceability, along with the incorporation of DfD principles in the design phase. As regulatory pressure intensifies, procurement driven by ESG principles and decarbonization goals is generating demand for reused steel; however, obstacles like certification demands, traceability problems, logistical limitations, and market unpredictability persist in obstructing extensive acceptance. Consequently, the research suggests a conceptual framework connecting DfD principles, deconstruction data needs, and circular economy results. Moreover, this study is limited to the review of steel structures. Therefore, the findings may not fully represent the technical, regulatory, and market conditions associated with other construction materials or different geographical contexts. This paper lays the groundwork for creating a Deconstruction Information Model (DIM) for steel structures and facilitate upcoming studies on component-specific information needs and digital resources to improve steel reuse and circularity in the construction industry.

## 8. ACKNOWLEDGEMENT

The authors acknowledge the financial support provided by the Senate Research Committee of the University of Moratuwa under the Grant SRC/LT/2026/19

## 9. REFERENCES

Addis, B. (2012). *Building with reclaimed components and materials.* https://doi.org/10.4324/9781849770637

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., Davila Delgado, J. M., & Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production*, *223*, 386–396. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.172

Akbarnezhad, A., Ong, K. C. G., & Chandra, L. R. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction*, *37*, 131–144. https://doi.org/10.1016/j.autcon.2013.10.017

Akinade, O., Oyedele, L., Oyedele, A., Delgado, L. M. D., Bilal, M., Akanbi, L., Ajayi, A., & owolabi, H. (2020). Design for deconstruction using a circular ec onomy approach: Barriers and strategies for improvement. *Production Planning & Control*, *31*(10), 829–840. https://doi.org/10.1080/09537287.2019.1695006

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., Bello, S. A., Jaiyeoba, B. E., & Kadiri, K. O. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, *60*, 3–13. https://doi.org/10.1016/j.wasman.2016.08.017

Andisheh, K. (2024). Development of steel circularity passports: Literature review, research gaps, and program rules in New Zealand *Waste Management Bulletin*, *2*(3), 11-27 https://doi.org/10.1016/j.wmb.2024.06.003

Bartsch, H. (2025). Reuse of reclaimed steel components in construction: A systematic review of potential, challenges and future directions. *Structures*, *80*, 110057. https://doi.org/10.1016/j.istruc.2025.110057

Basta, A., Serror, M. H., & Marzouk, M. (2020). A BIM-based framework for quantitative assessment of steel structure deconstructability. *Automation in Construction*, *111*, 103064. https://doi.org/10.1016/j.autcon.2019.103064

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F., (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, https://doi.org/10.1016/j.jclepro.2020.121046

Berglund-Brown, J., & Ochsendorf, J. (2025). Reusing heavy-section steel in buildings: Carbon reduction potential and material availability. *Journal of Architectural Engineering*, *31*(2), https://doi.org/10.1061/JAEIED.AEENG-1918

Chini, A., & Bruening, S. (2003*). Deconstruction and materials reuse in the United States*. The Future of Sustainable Construction. https://www.researchgate.net/publication/228759250_Deconstruction_and_materials_reuse_in_the_United_States

Crowther, P. (1999). *Design for disassembly to extend service life and increase sustainability*. 8th International Conference on Durability of Building Materials and Components. https://eprints.qut.edu.au/2471/1/Crowther-8dbmc.PDF

Daly, P. (2023). A critical review of circularity - 'Design for disassembly' assessment methods applied in the development of modular construction panels - an Irish case study. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, *5*, 100252. https://doi.org/https://doi.org/10.1016/j.prime.2023.100252

Davis, C., Hall, R., Hazra, S., Debattista, K., Zhuang, S., Duan, J., Li, Z., Shenton, J., Panni, D., & Halfpenny, A. (2024). Reuse, remanufacturing and recycling in the steel sector. *Philos Trans A Math Phys Eng Sci*, *382*(2284). https://doi.org/10.1098/rsta.2023.0244

DBM Vircon (2024). *From scrap to structure: Reusing structural steel in construction*. https://www.dbmvircon.com/from-scrap-to-structure-reusing-structural-steel-in-construction/

Dunant, C. F. (2018). Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain. *Journal of Cleaner Production*, *183*, 102–111. https://doi.org/10.1016/j.jclepro.2018.02.141

Durmisevic, E. (2006). Transformable building structures: Design for disassembly as a way to introduce sustainable engineering to building design & construction. https://resolver.tudelft.nl/uuid:9d2406e5-0cce-4788-8ee0-c19cbf38ea9a

Gorgolewski, M. (2006). The implications of reuse and recycling for the design of steel buildings. *Canadian Journal of Civil Engineering*, *33*(4), 489–496. https://doi.org/10.1139/L06-006

Gorgolewski, M. (2008). Designing with reused building components: Some challenges. *Building Research & Information*, *36*(2), 175–188. https://doi.org/10.1080/09613210701559499

Gorgolewski, M., Straka, V., Edmonds, J., & Sergio-Dzoutzidis, C. (2008). Designing buildings using reclaimed steel components. *Journal of Green Building*, *3*(3), 97–107. https://doi.org/10.3992/jgb.3.3.97

Guy, B., & Ciarimboli, N. (2005). DfD: Design for disassembly in the built environment—A guide to closed-loop design and building. Hamer Center for Community Design, Pennsylvania State University. https://www.lifecyclebuilding.org/docs/DfDseattle.pdf

Guy, B., & Shell, S. (2002). Design for deconstruction and materials reuse. *Proceedings of the CIB Task Group 39 – Deconstriuction Meeting*. https://www.iip.kit.edu/downloads/CIB_Publication_272.pdf

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: The case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Holly, F., Kolar, G., Berger, M., Fink, S., Ogonowski, P., & Schlund, S. (2023). Challenges on the way to a circular economy from the perspective of the Austrian manufacturing industry. *Front. Sustain*, *4*, 1243374. https://doi.org/10.3389/frsus.2023.1243374

Hopkinson, P., Chen, H., Zhou, K., Ba, Y. W., & Lam, D.(2018). Recovery and reuse of structural products from end-of-life buildings. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability*, *172*(3), 119–128. https://doi.org/10.1680/jcoma.17.00012

Hradil, P., Vainio-Kaila, T., Ungureanu, V., del Castillo, C., Gervásio, H., Lüdecke, M., Ilomäki, A., Sansom, M., Girão-Coelho, A., Matias de Paula Filho, J. H., & Yang, J. (2024). *Environmental assessment of constructional steel reuse: Deliverable D4.1 methodology report*. ADVANCE Project. https://www.steelconstruct.com/wp-content/uploads/ADVANCE-D4.1-Methodology-report.pdf

Jayasinghe, L. B., & Waldmann, D., (2020). Development of a BIM-based web tool as a material and component bank for a sustainable construction industry. *Sustainability*, *12*(5), 1766. https://doi.org/10.3390/su12051766

Kanters, J. (2018). Design for deconstruction in the design process: State of the art. *Buildings*, *8*(11), 150. https://doi.org/10.3390/buildings8110150

Kanyilmaz, A., Birhane, M., Fishwick, R., & del Castillo, C. (2023). Reuse of steel in the construction industry: challenges and opportunities. *International Journal of Steel Structures*, *23*, 1399–1416. https://doi.org/10.1007/s13296-023-00778-4

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*. John Wiley & Sons. https://download.e-bookshelf.de/download/0007/6913/92/L-G-0007691392-0013787786.pdf

Mahpour, A. (2018). Prioritizing barriers to adopt circular economy in construction and demolition waste management. *Resources, Conservation and Recycling*, *134*, 216–227. https://doi.org/10.1016/j.resconrec.2018.01.026

Mhatre, P., Gedam, V., Unnikrishnan, S., & Verma, S. (2021). Circular economy in built environment – Literature review and theory development. *Journal of Building Engineering*, *35*, 101995. https://doi.org/10.1016/j.jobe.2020.101995

Ostapska, K., Rüther, P., Loli, A., & Gradeci, K. (2024). Design for disassembly: A systematic scoping review and analysis of built structures designed for disassembly. *Sustainable Production and Consumption*, *48*, 377–395. https://doi.org/10.1016/j.spc.2024.05.014

Passarelli, R. N., Chiletto, T. D. O., Brandner, R., & Ottenhaus, L.-M. (2025). Circulation of structural timber for structural purposes: A review of opportunities and challenges. *Wood Material Science & Engineering*, *20*(4), 778–799. https://doi.org/10.1080/17480272.2025.2493711

Pan, S. Y., Du, M. A., Huang, I. Te, Liu, I. H., Chang, E. E., & Chiang, P. C. (2015). Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: A review. *Journal of Cleaner Production*, 108, 409–421. https://doi.org/10.1016/j.jclepro.2015.06.124

Patrizi, N., Sporchia, F., Ruini, A., Neri, E., Bruno, M., Zarroli, G., Bastianoni, S., & Marchettini, N. (2026). Designing for reuse in timber buildings: The environmental benefits of aligning the time of nature and time of use. *Resources, Conservation and Recycling*, *225*, 108638. https://doi.org/10.1016/j.resconrec.2025.108638

Price, K. (2025). Supplying reusable steel from UK deconstruction: A dynamic material flow analysis approach. Sustainable Built Environment Conference Series, Zurich, Switzerland. https://www.research-collection.ethz.ch/server/api/core/bitstreams/7faa2038-4e73-416d-a8b3-7a2b7ebcf491/content

Pristerà, G., Tonini, D., Tornaghi, M. L., Caro, D., & Sala, S. (2024). Taxonomy of design for deconstruction options to enable circular economy in buildings. *Resources, Environment and Sustainability*, 15, 100153. https://doi.org/10.1016/j.resenv.2024.100153

Ranasinghe, P. H. G. M. A., Waidyasekara, K. G. A. S., & Uduwage, D. N. L. S. (2025). Optimising material selection for design for deconstruction: A Kano model-based evaluation of doors and windows. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium (pp. 1043–1056). Colombo, Sri Lanka: CIOB World Construction Symposium.* https://ciobwcs.com/downloads/papers25/S17043.pdf

Rios, F. C., Chong, W., & Grau, D. (2015). Design for disassembly and deconstruction - Challenges and opportunities. *Procedia Engineering*, *118*, 1296–1304. https://doi.org/10.1016/j.proeng.2015.08.485

Rose, C., Stegemann, J., Rose, C. M., & Stegemann, J. A. (2018). From waste management to component management in the construction industry. *Sustainability 10*(1), 229. https://doi.org/10.3390/su10010229

Smeets, P., & Wang, K., & Drewniok, M. P. (2019). *Can material passports lower financial barriers for structural steel reuse?* IOP Conference Series Earth and Environmental Science. https://doi.org/10.1088/1755-1315/225/1/012006

Sylvester, A., Tate, M., & Johnstone, D. (2011). Beyond synthesis: Re-presenting heterogeneous research literature. *Behaviour & Information Technology,* 32(12), 1-17. https://doi.org/10.1080/0144929X.2011.624633

Temmerman, N., Alegria Mira, L., Vergauwen, A., Hendrickx, H., & De Wilde, W. P. (2012). Transformable structures in architectural engineering. *High Performance Structures and Materials VI*.(pp: 457-468). WIT Press. https://doi.org/10.2495/HPSM120411

Tingley, D. (2013). *Design for Deconstruction: an appraisal*. University of Sheffield. https://etheses.whiterose.ac.uk/3771/

Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and Overcoming the barriers to structural steel reuse, a UK perspectice. *Journal of Cleaner Production, 148*, 642-652. https://doi.org/10.1016/j.jclepro.2017.02.006

Tingley, D. D., & Davison, B. (2011). Design for deconstruction and material reuse. *Proceedings of the Institution of Civil Engineers - Energy*, *164*(4), 195–204. https://doi.org/10.1680/ener.2011.164.4.195

Tleuken, A., Torgautov, B., Zhanabayev, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2022). Design for deconstruction and disassembly: Barriers, opportunities, and practices in developing economies of Central Asia. *Procedia CIRP*, *106*, 15–20. https://doi.org/10.1016/j.procir.2022.02.148

Tzourmakliotou, D. (2021). Modular disruption in construction industry—The environmental benefits. *Journal of Civil Engineering and Architecture*, 15, 318–329. https://doi.org/10.17265/1934-7359/2021.06.004

Tzourmakliotou, D. (2021). Designing for deconstruction—The related factors. *Journal of Civil Engineering and Architecture*, 15, 489–499. https://doi.org/10.17265/1934-7359/2021.09.002

Uotila, U., Saari, A., & Joensuu, T. (2024). Demands for DfD data characteristics: A step towards enabling reuse of prefabricated concrete components. *Environmental Research: Infrastructure and Sustainability*, *4*(1), 015014. https://doi.org/10.1088/2634-4505/ad1f4e

Webster, M. D., & Costello, D. T. (2006). Designing structural systems for deconstruction. *In Proceedings of the Greenbuild International Conference and Expo.* https://www.eurogypsum.org/wp-content/uploads/2015/05/N155.pdf

Xia, B., Xiao, J., & Li, S. (2022). Sustainability-based reliability design for reuse of concrete components. *Structural Safety*, 98, 102241. https://doi.org/10.1016/j.strusafe.2022.102241

Yates, J. K. (2013). Sustainable methods for waste minimisation in construction. *13*(3), 281–301. https://doi.org/10.1108/CI-Nov-2011-0054

Yellishetty, M., Mudd, G. M., Ranjith, P. G., & Tharumarajah, A. (2011). Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. *Environmental Science & Policy*, *14*(6), 650–663. https://doi.org/10.1016/j.envsci.2011.04.008

Yeung, J., Walbridge, S., Haas, C., & Saari, R. (2017). Understanding the total life cycle cost implications of reusing structural steel. *Environmental Systems and Decisions*, *37*, 101–120. https://doi.org/10.1007/s10669-016-9621-6

Zoghi, M., Rostami, G., Khoshand, A., & Motalleb, F. (2022). Material selection in design for deconstruction using Kano model, fuzzy-AHP and TOPSIS methodology. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *40*(4), https://doi.org/https://doi.org/10.1177/0734242X211013904

Kavindi, S.A.C., Ramachandra, T. and Gheethanjali, B., 2026. Enhancing green achievement: An emphasis on design features. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 657-671. DOI: https://doi.org/10.31705/WCS.2026.49. Available from: https://ciobwcs.com/papers/

# ENHANCING GREEN ACHIEVEMENT: AN EMPHASIS ON DESIGN FEATURES

**S. A. Chathuni Kavindi[1], T. Ramachandra[2] and B. Gheethanjali[3]**

## *ABSTRACT*

*The increasing sustainability challenges have prompted the construction industry to shift towards Green building practices globally. Despite the introduction of numerous rating systems aimed at promoting environmentally responsible construction, their adoption remains limited due to various contextual challenges. This study investigates the role of design features in enhancing Green achievement within the framework of these rating systems. A case study research method was employed through a comparative analysis of three buildings certified under the GREENSL rating system in Sri Lanka. The study aimed to identify key design strategies that enhance building performance in terms of Indoor Environment Quality (IEQ), Sustainable Sites (SS), and Energy and Atmosphere (EA). Primary data were collected through document analysis and formal discussions with Architects involved in the selected projects. The findings indicate that all three buildings prioritised natural ventilation, optimal daylight penetration, minimal water consumption, and strategies to reduce energy use and site disturbance, which significantly contributed to credits under Indoor Environment Quality, Sustainable Sites, Water Efficiency, and Energy and Atmosphere. Specific measures included the use of central atriums for passive ventilation, appropriate building orientation to reduce solar heat gain, incorporation of drought-tolerant native landscaping, and integration of renewable energy systems. The study further highlights the need to educate stakeholders on green practices and the technologies available worldwide to increase their adoption.*

***Keywords:*** *Design Features; Green Building; Green Features; Green Rating; Sri Lanka.*

## 1. INTRODUCTION

Accelerated urbanisation, coupled with sustained population growth, continues to exert pressure on the rapid expansion of the construction industry. The buildings and construction sector are responsible for approximately 38% of global energy-related $CO_2$ emissions and consumes nearly 40% of the world's raw materials (United Nations Environmental Programme [UNEP], 2022). In response, the construction industry is increasingly moving towards sustainable and green building approaches that focus on lowering environmental footprints and optimising the use of natural resources (Sachchithananthan & Thayaparan, 2024).

[1] Quantity Surveyor, Engineering Contracting Company LLC, Dubai, UAE, chathuni.kavindisa@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, thanujar@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anjana122000@gmail.com

Green buildings focus on resource efficiency, including energy, water, and materials, while providing healthy and productive environments for occupants (Periyannan et al., 2023). To systematically measure and promote these attributes, several internationally recognised Green building rating systems have been developed, including Leadership in Energy and Environmental Design (LEED), the Building Research Establishment Environmental Assessment Method (BREEAM), and the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (Sachchithananthan et al., 2024). These initiatives have enhanced the interest of developers and building owners in Green building construction. Moreover, certifications provided by relevant regulatory bodies add value to buildings in the market and society (Doan et al., 2017). The certification frameworks provide standard criteria for evaluating sustainability performance and are often adapted or localised to reflect regional environmental conditions and regulatory contexts (Hwang et al., 2017).

However, the adoption of Green building certification and technologies is not as evident as it should have been (Chan et al., 2016). Though Ghana has introduced a Green building rating system, the certification rate remains low (Agyekum et al., 2020). The Malaysian construction industry experienced a similar situation with respect to the adoption of Green practices, with less than 5% of buildings having achieved Green certification (Masyhur et al., 2024). In Sri Lanka, only 55% of the registered buildings are recognised as Green certified buildings under the LEED certification system (United States Green Building Council [USGBC], 2026). Moreover, only 3.6% of projects registered with the Urban Development Authority (UDA) have attained certification, indicating significant gaps between policy intentions and practical implementation (Urban Development Authority [UDA], 2020).

High certification costs, limited awareness, technical complexities, and insufficient professional capacity have hindered the widespread adoption of Green certification globally (Akadiri, 2015; Zhao et al., 2022). Further, the main challenges include high costs, limited knowledge, and low awareness among stakeholders (Masyhur et al., 2024). It is reported in Sri Lanka that lack of awareness and professional knowledge regarding rating systems, lack of skilled labourers to implement Green requirements, required funds, poor planning during designs, and stakeholder management are the key barriers for green certification (Illeperuma & Abeynayake, 2022). Moreover, Mahagamage and Perera (2024) highlighted that the lack of knowledge and awareness among stakeholders about Green practices and strategies is a considerable barrier to obtaining the Green certification. The foregoing highlights that the lack of knowledge and awareness about rating systems and the requirements hindered Green adoption. To this end, the present study aims to examine the architectural design features that supported green achievements in Green Building Council of Sri Lanka (GREENSL) awarded buildings in Sri Lanka. The paper identifies the criteria under the rating system and examines the design strategies incorporated to obtain points under each criteria.

## 2. LITERATURE REVIEW

Initially, a document as well as an internet-based survey was carried out to examine the status of Green certification obtained by the local buildings in terms of locally used rating systems. Table 1 presents the profile of Green certified buildings in Sri Lanka.

*Table 1: Green awarded buildings in Sri Lanka*

| Description | | Proportion | | |
|---|---|---|---|---|
| Year of commencement of operation | LEED | 2009 | | |
| | GREENSL | 2014 | | |
| | UDA | 2017 | | |
| No. of certified buildings (Up to 2023) | | Awarded | Registered | % |
| | LEED | 68 | 116 | 55% |
| | GREENSL | 54 | NA | NA |
| | UDA BG | 03 | 100 | 3% |
| | Total | 125 | | |
| No. of certified buildings | Gold | 73 | | 58% |
| | Platinum | 30 | | 24% |
| | Silver | 20 | | 16% |
| | Certificate | 02 | | 2% |
| | Total | 125 | | |
| Function of certified buildings | Commercial | 53 | | 42% |
| | Industrial | 41 | | 33% |
| | Residential | 07 | | 6% |
| | Educational | 10 | | 8% |
| | Hotel | 14 | | 11% |
| | Total | 125 | | |

*Source: (USGBC, 2026; Green Building Counsil Sri Lanka [GBCSL], 2025)*

Though three main Green rating systems are in use, only a limited number of buildings are being Green awarded since their commencement as per the certification in 2023. As seen from the table, the LEED rating system, introduced in Sri Lanka in 2009, precedes both GREENSL and the UDA Blue Green (BG) in terms of certification (Weerasinghe et al., 2022). Its early commencement is attributed to having an increased number of registered and certified buildings under the rating system. In contrast, although the UDA BG was introduced as a compulsory certification for public buildings and has registered around 100 buildings since its inception, only three buildings have completed certification (UDA, 2025). Although platinum is the highest certification level, according to the data available, most buildings under both the LEED and GREENSL ratings have been gold rated. This reflects that while platinum is an aspirational goal for sustainability, gold certification seems more practical. Building projects aiming for platinum certification typically need to meet more stringent sustainability criteria, which can involve implementing advanced technologies, materials, and design features that may come with higher upfront costs (Uğur & Leblebici, 2017). In contrast, achieving gold certification aligns better with the sustainability goals and budget constraints of many building developers and owners (Sandoval & Prakash, 2016). Gold certification still represents a significant commitment to sustainability and offers substantial environmental benefits while being more financially feasible and practical for a broader range of projects. This might be attributed to the high number of gold-rating achievements. Further, concerning the breakdown, a higher number of commercial buildings have been awarded under the GREENSL rating system, and among the certified buildings in all, three rating system 74% of the buildings have been awarded in gold.

## 2.1 SIGNIFICANT GREEN FEATURES: COMPARISON OF RATING SYSTEMS USED IN SRI LANKA

Although the allocation of points and credit requirements vary across rating systems, the core assessment domains: Sustainable Site Development (SS), Energy and Atmosphere Performance (EA), Water Efficiency (WE), Indoor Environmental Quality Management (IEQ), and Material Management and Waste Management remain fundamentally consistent across the rating systems. Table 2 outlines the point distribution of Green rating system of GREENSL new rating system.

*Table 2: Significant criteria - GREENSL rating systems*

| Code | Sub-criteria | Scores |
|---|---|---|
| ***Sustainable Sites (SS) - 25*** | | |
| SS1 | Heat Island Reduction: Non-roof | 1 |
| SS2 | Heat Island Reduction: Roof | 1 |
| SS3 | Light Pollution Reduction | 1 |
| SS4 | Reduced Site Disturbance | 6 |
| SS5 | Development Density and Community coordination /management /involvement | 2 |
| SS6 | Storm Water Design – Quantity & Quality Control | 3 |
| SS7 | Site Selection | 4 |
| SS8 | Reuse of Previously Developed sites and Allowance for Connectivity of Green Lands | 2 |
| SS9 | Site Assessment and development | 2 |
| SS10 | Alternative Transportation | 3 |
| ***Energy and Atmosphere (EA) -22*** | | |
| EA1 | On-Site Renewable Energy | 1-5 |
| EA2 | Off-Site Renewable Energy | 1 |
| EA3 | Optimise energy performance | 1-10 |
| EA4 | Refrigerant Management | 1 |
| EA5 | Greenhouse Gas Emissions Management | 1 |
| EA6 | Certified Energy Auditor | 1 |
| EA7 | Enhanced Commissioning | 1 |
| EA8 | Measurement & Verification | 1-2 |
| ***Water Efficiency (WE) (14)*** | | |
| WE1 | Cooling tower Water Efficiency in air – conditioning system | 1 |
| WE2 | Water Sub Metering | 1 |
| WE3 | Water Efficient Construction | 1 |
| WE4 | Indoor Water Use Reduction | 1-5 |
| WE5 | Reduce Potable Water Use | 1 |
| WE6 | Reduce Potable Water Use or Treat Wastewater | 1 |
| WE7 | Harvested rainwater | 2 |
| WE8 | Aquifer Recharge | 1 |
| WE 9 | Innovative Water Transmission | 1 |

| Code | Sub-criteria | Scores |
|---|---|---|
| ***Indoor Environment Quality (IEQ) (13)*** | | |
| IEQ1 | Outdoor air delivering Monitoring | 1 |
| IEQ2 | Increased Ventilation | 1 |
| IEQ3 | Construction IAQ Management Plan | 1 |
| IEQ4 | Low- Emitting Materials | 3 |
| IEQ5 | Indoor Chemical & Pollutant Source Control | 1 |
| IEQ6 | Lighting and Comfort Controls | 2 |
| IEQ7 | Thermal comfort, design and Verification | 1 |
| IEQ8 | Air Purification and Disinfection | 1 |
| IEQ9 | Daylight & Views | 2 |
| *Materials, Resources and Waste Management (MR & W) (14)* | | |
| MR & WM1 | Local/ Regional Materials | 1 |
| MR & WM2 | Rapidly Renewable materials | 1 |
| MR & WM3 | Upfront Carbon Emissions | 1 |
| MR & WM4 | Building Reuse | 1-2 |
| MR & WM5 | Certified wood | 1 |
| MR & WM6 | Green Labelled Products | 1 |
| MR & WM7 | Reused and recycled Materials/products | 1-2 |
| MR & WM8 | Sustainable Building Systems | 1-2 |
| MR & WM9 | Construction and Demolition Waste Management | 1 |
| MR & WM10 | Waste materials to construction materials | 1 |
| MR & WM11 | Storage, Collection and safe disposal of hazardous wastes | 1 |

*Source: (GBCSL, 2022)*

According to Table 2, the largest proportion of points is allocated to the sustainable sites' category, accounting for 25% of the total score. Within this category, "reducing site disturbance" receives the highest allocation, followed by "site selection," "alternative transportation," and "stormwater design." Although the remaining sub-criteria carry comparatively lower weightings, their achievement remains important for maximising the overall score. The next most significant category is energy and atmosphere. Within this category, "optimise energy performance" is assigned the highest number of points, followed by "on-site renewable energy." While the other sub-criteria have relatively lower point allocations, addressing them can still contribute to improving the overall rating. The remaining categories, including water efficiency, indoor environmental quality, and materials and resources/waste management, receive approximately similar weightings. These categories comprise a broader range of sub-criteria, each with a relatively smaller proportion of points. Nevertheless, collectively addressing these sub-criteria is essential for achieving a higher overall performance (GBCSL, 2022).

## 3. RESEARCH METHODOLOGY

This study adopted a qualitative research approach where a case study strategy was employed to explore the green features and strategies embedded within the selected Green certified buildings in Sri Lanka. Three buildings awarded under the GREENSL rating system for new buildings were selected based on accessibility, relevance, and data

availability. The selection of three cases ensured sufficient diversity in Green technologies and allowed for comparative analysis within the cases. Further, comparative study is adopted to understand the impact of different features on the points achieved to identify the best techniques to be incorporated to achieve the maximum points. Moreover, different building types were selected to examine the strategies that can be implemented in each type to achieve points under the respective green certification criteria. Data collection was carried out through review of the final documents submitted to achieve the green rating under the GREENSL rating system, and semi-structured interviews. Primarily, a review was conducted into project documents, including user manuals, and supplier invoices submitted for certification purposes. Further, to validate and contextualise these findings, semi-structured interviews were conducted with Architects who were in charge of the design of the respective cases. Table 3 provides a summary profile of the selected three cases.

*Table 3: Profile of selected cases*

| Criteria | Case A | Case B | Case C |
|---|---|---|---|
| **Function** | Office | Educational* | Commercial |
| **Location** | Malabe | Sabaragamuwa | Colombo |
| **Award** | Platinum | Platinum | Gold |
| **Green certification** | 2020 | 2022 | 2014 |
| **Construction commencement** | 2018 | 2020 | 2012 |
| **Gross floor Area** | 21,284 m2 | * | 10,730m2 |
| **Number of Floors** | 10 floors (G+9 with one mezzanine and two basements) | ** | 11 floors, including 2 basements |
| **Building Orientation** | East-west oriented | *** | East-west oriented linear shape |
| **Structural Composition** | Reinforce Concrete (RCC) Block wall | RCC/Block walls | RCC/Block walls |
| **Façade Curtain** | Glass and Blockwork (plastered and painted) | Green Walls, | Eastern façade -glazed with PLINKTON Low-E glass and green wall |

*Note: * Exact floor area cannot be provided since the case consists of a cluster of buildings*

*** Case B is a building complex, and it consists of several medium and low-rise buildings.*

**** Since Case B is a building complex, different buildings have different orientations.*

Although Case B is part of a larger educational development comprising multiple buildings, the selected buildings within the project function as independent, standalone commercial-type facilities. Therefore, the comparison remains relevant, as the analysis focuses on building-level design strategies and green features rather than the overall campus scale. The inclusion of Case B was intended to broaden the study by incorporating

a project consisting of integrated yet independently functioning buildings while maintaining comparability with Cases A and C.

# 4. FINDINGS AND DISCUSSION

## 4.1 STATUS OF GREEN ACHIEVEMENT IN THE SELECTED GREEN CERTIFIED BUILDINGS

To assess the level of Green achievement of the selected buildings in terms of main criteria, points achieved by the selected buildings were compared with allocated points for the same main criteria as per the considered rating system. Table 4 presents the points achievement of the selected cases.

*Table 4: Level of green achievement*

| Main criteria | Allocated points | Level of significance (MS, S, LS) | Achieved points | | |
|---|---|---|---|---|---|
| | | | Case A | Case B | Case C |
| Sustainable Site (SS) | 25 | MS | 92% | 92% | 60% |
| Energy and Atmosphere (EA) | 22 | MS | 73% | 91% | 73% |
| Water Efficiency (WE) | 14 | S | 57% | 57% | 43% |
| Material, Resource and Waste Management (MR & WM) | 14 | S | 64% | 64% | 43% |
| Indoor Environment Quality (IEQ) | 13 | S | 100% | 100% | 100% |
| Innovation and Design Process (IDP) | 4 | LS | 100% | 100% | 100% |
| Social and Cultural Awareness (SCA) | 4 | LS | 100% | 100% | 100% |
| Management (M) | 4 | LS | 100% | 100% | 100% |
| Marking Criteria | | | 70-100 | 70-100 | 60-69 |
| Overall achieved points | 100 | | 81 | 85 | 68 |
| Overall achieved points (%) | 100 | | 81 | 85 | 68 |

*MS – Most Significant, S – Significant, LS – Least Significant*

As per the rating system, 50% of the total points are allocated to SS and EA features while another 40% is equally shared by the features of WE, IEQ and MR & WM. This allocation of points indicates the relative significance of the features within the system. In terms of the Most Significant (MS) features, the selected buildings have achieved over 70% for the EA irrespective of the rating level achieved. This indicates that developers/designers have paid more attention to the feature in achieving Green ratings. However, in terms of SS, platinum-rated buildings have scored high compared to gold rated. This could be due to the increased requirement for the given rating.

In terms of the Significant (S) features, the buildings have achieved an average level of points for WE and MR&WM, while 100% achievement is obtained for IEQ. This shows that the IEQ feature has received priority over the other two features of WE and MR&WM. However, in terms of the Less Significant (LS) features, all selected buildings

have achieved 100% of the required scores. This could be due to the lower score required to achieve the features.

## 4.2 DESIGN FEATURES CONTRIBUTED TO THE GREEN RATING OF THE SELECTED BUILDINGS

According to the rating systems, compliance with green building requirements is achieved through the incorporation of appropriate design features. Therefore, the design features implemented in the selected green awarded buildings, for the major criteria stipulated in the green rating system, are examined and summarised in Table 5.

*Table 5: Design features of selected buildings*

| Criteria | | Design Features | | |
|---|---|---|---|---|
| | | **Case A** | **Case B** | **Case C** |
| SS1 | Parking | Covered parking | Covered parking | Covered parking |
| SS4 | Minimum Site Disturbance | Sloping land to minimise excavation and natural contours for ramps and roadways.<br>Properly marked construction boundaries and dust control during the construction | Conservation of vegetation except building footprint, and natural vistas. | Terminalia catappa for landscaping, preservation of trees, and native drought-resistant plants |
| SS3/EA3 | Light Pollution Reduction | Full-height glass façade.<br>Minimum use of non- emergency lights and exterior lights | Vertical green wall, canteen bridge. | PLINKTON low-e glass, green wall.<br>Automatic control for interior lights, energy-efficient façade lighting, and no lights directed towards the sky. |
| SS8 | Building Design | Focus on existing trees for building roads and ramps. | Placement for panoramic views. | Open glazed façade for panoramic views |
| SS8 | Aesthetic | Plant troughs, medium-height trees in public areas | Large garden, open landscape, pathways | Open landscape, glazed façade for a panoramic view. |
| SS2/ EA3 | Services Installation | Service areas in the east-west direction to avoid direct sunlight.<br>Use of CFC-free HVAC Systems. | Use of CFC-free HVAC Systems. | The roof terrace is covered with solar panels.<br>Use of CFC-free HVAC Systems. |
| EA3, IEQ2 | Ventilation | Large pond and cooling tower effect in atrium, high ceiling office, max window coverage with protection. | Plants, medium-height trees, triple-height lobby with cement louvres. | Windows and fixed glass on all 4 sides, wind tunnel formation.<br>Microclimate Treatment |

| Criteria | | Design Features | | |
|---|---|---|---|---|
| | | **Case A** | **Case B** | **Case C** |
| | | Installation of a glass façade for all the occupied spaces. | Introduction of the window canopies a hybrid of vertical fins and sunshades. Internal spaces are designed to match the control of glare intake. | |
| EA1 | Facilities | Solar power systems | Solar power systems | Solar power systems |
| EA3 | | | Use of VRF system as HVAC technology and multi-V system for distribution, use specially designed heat exchangers, and inverter technology. | Use of specially designed MVAC. |
| EA3/ IEQ2, IEQ 9 | Lighting | Building orientation avoids direct sunlight, high ceilings, sunshades, window canopies, and trees to reduce glare. | Max window coverage with protection, contoured building orientation. Lighting system controllability for all shared multi-occupant spaces, and individual controls for fully partitioned areas. Introduce switches in possible areas. | Windows on all 4 sides, east-west oriented linear shape, and internal design to control glare. |
| EA3 | Optimise Energy Performance | Whole Building Energy Simulation, Comply with the final version of the Code of Practice on Energy Efficient Buildings. | Whole Building Energy Simulation. Comply with the final version of the Code of Practice on Energy Efficient Buildings, Placement of rainwater harvesting tanks in upper areas | all non-emergency fixtures are equipped with automatic control and comply with the final version of the Code of Practice on Energy Efficient Buildings. |
| IEQ5 | Indoor Chemical & Pollutant Source Control | Use of an automatic sensor doors, All the chemicals and materials are stored separately. | All the chemicals and materials are stored in a separate storeroom | All the chemicals and materials are stored in a separate storeroom |

| Criteria | | Design Features | | |
|---|---|---|---|---|
| | | Case A | Case B | Case C |
| IEQ1 | Outdoor air delivering Monitoring | The design occupant density is 10 people per 100m$^2$. Provision of $CO_2$ monitoring | The design occupant density is 10 people per 100m2. Provision of CO2 monitoring | Provision of $CO_2$ monitoring |
| WE3 | Water Efficiency | Use of water-efficient fixtures, fittings, and appliances. Use condensate water for irrigation. Installation of water faucet with Movable Heads and Flow Aerators. | Use of water-efficient fixtures. Introduce the VRF AC system. Use condensate water for irrigation. Introduce separate water meters in buildings | Use of water-efficient fixtures, fittings, and appliances |
| WE7 | Rainwater Harvesting System | Harvest rainwater for irrigation. | Harvest rainwater for irrigation. | Harvest rainwater for irrigation. |
| MR & WM9/ MR & WM11 | Recycling construction waste | Recycle the construction waste, Initiation waste management and Categorisation waste | Recycle the construction waste, Initiation waste management and Categorisation waste | Allocate a separate place to store waste, and remove the disposal waste every week. |
| MR & WM1 | Local/ Regional Materials | Purchasing locally manufactured materials, use of composite roofing system, ceiling material, floor and wall tiles and glass façade. | | Purchase materials only from suppliers and vendors who have sustainable certification, selecting sustainable maintenance and solution providers |

According to Table 5, it is clear that the buildings have concentrated on the most significant (SS & EA) as well as significant (WE, IEQ & MR & WM) criteria. The identified features were validated, and further explanations were obtained from the interviewees for each case. Further, each building demonstrates a clear commitment to enhancing natural ventilation and lighting efficiency. Moreover, major significance is given to sustainable site selection. Though case C has obtained only 68% of the total points allocated for site selection, they have incorporated new design features to achieve the points.

## 5. DISCUSSION

The comparative analysis of the three case studies demonstrates that the achievement of green building credits under the GREENSL rating system is strongly influenced by the

integration of context-responsive design strategies. The study analyses the various design features and strategies adopted in each case to achieve green certification. The findings provide valuable insights for future stakeholders, enabling them to adopt similar approaches and more effectively meet certification requirements. Each case adopted a distinct architectural approach. However, all three projects incorporated passive design principles and environmentally responsive planning to enhance sustainability performance.

Case A was conceptualised with a 10-level central atrium functioning as a "Green lung," facilitating cross-ventilation and daylight penetration through public areas of the buildings through open to sky atrium. This was complemented by open-plan lobbies and mezzanine levels to foster spatial flexibility and user customisation. Further, a solar power system is installed in these buildings to ensure the utilisation of natural resources. Case B integrates both biological and engineering elements harmoniously, emphasising a balance between active and passive design strategies. The development retained much of the site's native vegetation and adapted the building layout to the existing topography. The building orientation and positioning foster natural ventilation and internal connectivity, also aligning with both international and local sustainability codes.

In contrast, Case C has come into life with the concept of “Melting Ice Burg”. This land has two close water bodies, a sea from the west and a lake from the East. Therefore, a wind tunnel has been formed to allow the natural sea breeze path to pass through the building without an obstacle, which reduces the heat island effect. The use of low-e glazing not only maximised visual connectivity to the surroundings yet minimised solar heat gain, improving thermal comfort and energy performance.

It is necessary to understand the different design features they have incorporated to achieve points in different criteria. Accordingly, natural landscaping and passive design strategies will easily score more points in site selection criteria. As shown, Sustainable Sites (SS) consistently yielded the highest point scores in Cases A and B due to well-planned site layouts, minimal ecological disturbance, and preservation of native vegetation. In Case B, a deliberate focus on preserving existing trees during the construction phase facilitated the attainment of credits for Light Pollution Reduction (SS3). Additionally, the incorporation of expansive gardens and open landscaped areas played a significant role in satisfying the criteria for Site Assessment and Development (SS9). These landscape-driven approaches not only reinforced ecological integrity but also enhanced the aesthetic and recreational value of the built environment. Moreover, land development was executed with minimal ecological disruption across all cases. For example, in Case A, roads and structures were adjusted to avoid cutting down existing trees, and basement parking was preferred over altering the natural terrain. Furthermore, all three cases adopted key sustainable technologies and strategies, including passive solar design, green facades, native landscaping, and renewable energy systems.

In contrast, Case C, while achieving commendable outcomes, scored lower across SS, WE, and MW categories, indicating areas where design integration could have been strengthened. Further, Case C couldn’t achieve higher points in the reuse of previously developed sites and allowance for connectivity of green lands since it was built in the centre of the main city. The use of marked construction boundaries and noise and dust control is also visible in cases A and B to Reduce Site Disturbance, whereas Case C does

not reveal such practice. It is recommended to use those mechanisms to gather more points while enhancing the environment's friendliness.

A comprehensive case analysis reveals that all three buildings prioritised energy efficiency through strategic orientation, controlled glare, and ventilation systems. Further, Case B has obtained higher points in energy and atmosphere criteria than the other two buildings. The use of a VRF system as HVAC technology, the use of a multi-V system for distribution instead of using large distribution ducts, and the use of optimised scroll compressors are such advanced techniques utilised by Case B. Though case C has obtained only 68% of the total points allocated for site selection, they have incorporated new design features to achieve the points. It is noticed that energy efficiency will not gain points under energy efficiency criteria, yet adds points to other criteria, including sustainable sites, water efficiency, indoor environment quality, and energy and atmosphere. Moreover, by changing the building orientation and by emphasising energy efficiency, the points for energy and atmosphere can be easily achieved.

Further, several strategic design considerations also contributed to the achievement of key sustainability credits. Specifically, Cases A and C earned points under the category of Occupant Comfort: Daylight and Views (IEQ9) by integrating features including the strategic placement of plants and medium-height trees, along with building orientations that minimise direct solar exposure. In Case A, automatic sensor doors are built, and the chemicals and materials are stored in a separate room in all cases to achieve points under indoor chemical and pollutant source control (IEQ5) criteria. Moreover, provision is given for $CO_2$ monitoring in all three buildings. These collectively demonstrate a deep integration of sustainability principles into architectural practice, contributing to energy efficiency, occupant comfort, and ecological preservation. These passive design interventions enhanced indoor environmental quality and visual comfort for occupants.

Moreover, under water efficiency criteria, installation of a rainwater harvesting system will provide 2 points, and incorporation of water-efficient fixtures will reduce the water consumption and add more points. Further, the scores for water efficiency are similar in all cases, and the points achievement is low compared to other criteria. Though they have installed a rainwater harvesting system, water efficient fixtures, reuse the water for irrigation, the scores are low due to insufficient achievement of scores in the main criteria. Therefore, more design features and technologies should be utilised to achieve maximum points under the water efficiency criteria.

Finally, to achieve points under the MR & WM criteria, construction waste was recycled in Case A and Case B. In addition, the waste during the operation period is managed properly by categorising and disposing of it weekly in all three buildings. In addition, to achieve points under sub-criteria MR & WM 1 (local/regional materials), locally manufactured materials are utilised in Case A and Case C. Moreover, all three buildings have obtained full marks for the least significant criteria.

An in-depth analysis of the three case studies confirms that many of the green building technologies have been adopted in Sri Lanka to varying extents. However, it is important to note the absence of several advanced technological interventions in the local context. These include but are not limited to colour-changing concrete paving, cement-stabilised earth construction, permeable surface technology, double/triple glazing smart windows, self-regulating building systems, key card access systems, advanced energy management systems, air filtration media, and smart grid technologies.

Critically, the study demonstrates that Green achievement under the GREENSL framework is heavily dependent on thoughtful architectural planning, contextual responsiveness along with technologically intensive solutions. The widespread reliance on passive design strategies indicates a pragmatic adaptation to local climatic, economic, and regulatory conditions. Nevertheless, the limited adoption of innovative technologies suggests that future improvements in green building performance will require stronger integration of advanced sustainable systems, particularly in water management, energy optimisation, and smart building operations. Overall, the findings confirm that while Sri Lanka has made notable progress in incorporating sustainable building principles, there remains significant potential to strengthen environmental performance through a balanced integration of passive design and emerging green technologies.

The collective findings underscore a broader trend in Sri Lankan green building practice including the integration of sustainable design principles is predominantly achieved through design-oriented strategies rather than through the application of high-end technological solutions. This approach not only aligns with the local context and regulatory frameworks yet illustrates a pragmatic application of sustainable principles in building design and site development. The findings summarise the strategies incorporated in each case study to achieve the green certificate.

## 6. CONCLUSIONS

This study critically examined the design features that contributed to significant Green achievement in GREENSL-certified buildings in Sri Lanka. Findings from the three case studies demonstrated that early-stage design interventions such as passive ventilation, optimised building orientation, preservation of existing vegetation, integration of shading devices, and façade installations are key enablers of higher Green ratings. Moreover, achieving full compliance with minor criteria, despite their lower individual weighting, together with the integration of significant design features in major areas, can result in a higher overall score. Furthermore, it is evident that alignment of design concepts with the rating system criteria from project inception leads to performance improvements and point maximisation across multiple environmental indicators.

The research affirms that technically grounded, performance-oriented design decisions, when implemented at the conceptual design stage, serve as critical determinants of Green point achievement. To advance the efficacy and integrity of green certification in Sri Lanka, the study recommends a twofold strategy: (1) the formal integration of minimum design performance standards into national rating frameworks to ensure baseline compliance with environmental objectives; and (2) targeted capacity-building initiatives for design and construction professionals to promote early-stage incorporation of verifiable sustainability metrics in project planning and execution. Further, from the study it is observed that a lack of knowledge regarding GB construction and GB technologies is one of the major barriers in Sri Lanka. Therefore, it is recommended to acknowledge society by conducting workshops and to provide the basic knowledge about the GBs from the school education to the future generation. These measures are pivotal for transitioning from policy intent to measurable environmental performance across the built environment.

# 7. REFERENCES

Agyekum, K., Adinyira, E., & Ampratwum, G. (2020). Factors driving the adoption of green certification of buildings in Ghana. *Smart and Sustainable Built Environment*, *9*(4), 595–613. https://doi.org/10.1108/sasbe-02-2019-0017

Akadiri, P. O. (2015). Understanding barriers affecting the selection of sustainable materials in building projects. *Journal of Building Engineering*, *4*, 86–93. https://doi.org/10.1016/J.JOBE.2015.08.006

Chan, A. P. C., Darko, A., Ameyaw, E. E., & Owusu-Manu, D. (2016). Barriers affecting the adoption of green building technologies. *Journal of Management in Engineering*, *33*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000507

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment*, *123*, 243–260. https://doi.org/10.1016/j.buildenv.2017.07.007

Green Building Counsil Sri Lanka [GBCSL]. (2022). *GREENSL® Rating system for new constructions.* https://www.srilankagbc.org/wp-content/uploads/2022/08/Green-Building-Rating-System-Version-2.1-FINAL-25-02-2022-1.pdf

Green Building Counsil Sri Lanka [GBCSL]. (2025, December). *Green Rating System for Built Environment*. Green Building Council of Sri Lanka. Retrieved January 31, 2026, from https://www.srilankagbc.org/green-rating-system-for-built-environment/

Hwang, B.G., Zhu, L., & Ming, J. T. T. (2017). Factors affecting productivity in green building construction projects: The case of Singapore. *Journal of Management in Engineering*, *33*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000499

Illeperuma, I.E. and Abeynayake, M.D.T.E., (2022). Drivers and barriers to implement green building practices in higher education institutes in Sri Lanka. In: Y.G. Sandanayake, S. Gunatilake, & K.G.A.S. Waidyasekara, (Eds.), *Proceedings of the 10th World Construction Symposium* (pp. 365-378). Ceylon Institute of Builders, Sri Lanka. https://doi.org/10.31705/WCS.2022.30

Mahagamage, V.C. and Perera, J.L.S.R., (2024). Barriers to adopting and implementing green practices: A Study of Small and Medium-Sized Enterprises (SMEs) in Sri Lanka. In H. Hansson, P. Wickremasinghe, S. Gayanika & T. Hettiarachchi (Eds.), *7th International Conference on Business Innovation*, (pp. 365-378). NIBM Green University, Colombo.

Masyhur, R. T., Alias, A. H., Haron, N. A., & Zulkafli, Z. (2024). A systematic review on green practices in the Malaysian construction industry: Status, challenges, key motivations, rating systems and technology evolution. *Energy and Buildings*, *320*, 114550. https://doi.org/10.1016/j.enbuild.2024.114550

Periyannan, E., Ramachandra, T., & Geekiyanage, D. (2023). Assessment of costs and benefits of green retrofit technologies: Case study of hotel buildings in Sri Lanka. *Journal of Building Engineering*, *78*, 107631. https://doi.org/10.1016/j.jobe.2023.107631

Sachchithananthan, M., & Thayaparan, M. (2024). A framework to select suitable sustainable materials for high-rise buildings in Sri Lanka. *International Journal of Construction Management*. *25*(9), 1072-1086. https://doi.org/10.1080/15623599.2024.2397285

Sachchithananthan, M., Ramachandra, T., Thayananth, M., & Rotimi, J. O. B. (2024). Benchmarking green technologies: a survey of non-domestic buildings in Sri Lanka. *Journal of Building Design and Environment*. https://doi.org/10.70401/jbde.2024.0004

Sandoval, P., & Prakash, A. (2016). The gold rush: The popularity of the gold tier in LEED certification. *Environmental Policy and Governance*, *26*(6), 543–555. https://doi.org/10.1002/eet.1724

Urban Development Authority [UDA]. (2020). *Building applications*. Retrieved January 31, 2026, from https://osu.uda.lk/Download_Documents/Building%20Application%20-%20OSU.zip

Urban Development Authority [UDA]. (2025). *Instructions and guidelines - National green building certification.* Retrieved January 31, 2026, from https://www.uda.gov.lk/attachments/green_building/2025/green_instructions_2025.pdf

Uğur, L. O., & Leblebici, N. (2017). An examination of the LEED green building certification system in terms of construction costs. *Renewable and Sustainable Energy Reviews*, *81*, 1476–1483. https://doi.org/10.1016/j.rser.2017.05.210

United Nations Environmental Programme [UNEP]. (2025). *Global status report for buildings and construction 2024/2025.* https://wedocs.unep.org/bitstreams/d0d91b5a-01c6-4be2-a390-fdd11e8b14c6/download

United States Green Building Council. (2019). *LEED V4 for building design and construction.* https://www.usgbc.org/sites/default/files/LEED%20v4%20BDC_07.25.19_current.pdf

United States Green Building Council [USGBC]. (2026, April 23). *LEED Project Directory, USGBC.* Retrieved July 2, 2026, from https://www.usgbc.org/projects?Country=%5B%22Sri%20Lanka%22%5D

Weerasinghe, S., Ramachandra, T., & Madushika, U. (2022, September 1). *Contribution of green buildings towards achieving sustainability: A perspective of LEED-certified buildings in Sri Lanka*. In *15th International Research Conference, KDU* (pp. 316-325). General Sir John Kotelawala Defence University, Sri Lanka. http://ir.kdu.ac.lk/handle/345/6468

Zhao, C., Liu, M., & Wang, K. (2022). Monetary valuation of the environmental benefits of green building: A case study of China. *Journal of Cleaner Production*, *365*, 132704. https://doi.org/10.1016/j.jclepro.2022.132704

Umar, T., Chun, K. and Smith, J., 2026. Enhancing High-Performance Computing adoption in the built environment: A user-centred approach to inclusive digital innovation. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 672-685. DOI: https://doi.org/10.31705/WCS.2026.50. Available from: https://ciobwcs.com/papers/

# ENHANCING HIGH-PERFORMANCE COMPUTING ADOPTION IN THE BUILT ENVIRONMENT: A USER-CENTRED APPROACH TO INCLUSIVE DIGITAL INNOVATION

**Tariq Umar[1], Kwok Chun[2] and Jim Smith[3]**

## *ABSTRACT*

*High-Performance Computing (HPC) is increasingly recognised as a critical enabler of advanced modelling, simulation, and data-intensive research. However, its adoption within the built environment remains limited compared to more established computational domains. This paper presents a user-centred investigation into the barriers and opportunities associated with HPC adoption in the built environment, drawing on qualitative data from a stakeholder workshop involving 20 participants, supported by Mentimeter-based interactive polling and analysis of workshop discussions. The findings reveal a persistent gap between the perceived relevance and practical use of HPC. While participants recognised its potential for applications such as digital twins, infrastructure simulation, and data-driven design, adoption was constrained by complex access processes, limited training, and poor interoperability with tools such as Building Information Modelling (BIM), Geographic Information Systems (GIS), and Computer-Aided Design (CAD). Additional barriers included data governance challenges, intellectual property concerns, and limited trust in shared computational environments. The findings demonstrate that HPC adoption is not solely a technical issue, but a socio-technical challenge shaped by organisational practices, institutional structures, and user capabilities. In response, the paper proposes a user-centred roadmap for inclusive HPC adoption in the built environment. Key priorities include simplifying access pathways, developing domain-specific training, improving interoperability, and strengthening governance frameworks. The study contributes practical insights to support more accessible and inclusive digital research infrastructure and informs the development of the National Federated Compute Services (NFCS) roadmap for interoperable HPC adoption within the built environment sector.*

***Keywords:*** *Built Environment; Digital Infrastructure; Digital Transformation; High-Performance Computing (HPC); User-Centred Design.*

[1] Senior Lecturer, School of Architecture and Environment University of the West of England, UK, tariq.umar@uwe.ac.uk
[2] Senior Lecturer, School of Architecture and Environment University of the West of England, UK, Kwok.Chun@uwe.ac.uk
[3] Professor, School of Computing and Creative Technologies, University of the West of England, UK, James.Smith@uwe.ac.uk

# 1. INTRODUCTION

HPC is widely recognised as a critical enabler of digital transformation, supporting large-scale simulation, artificial intelligence, and data-intensive research across diverse disciplines (Dongarra et al., 2020). HPC has played a central role in advancing scientific discovery in areas such as climate modelling, genomics, and physics, where computational demands exceed the capabilities of conventional desktop systems (Yousaf & Khan, 2022). As analytical complexity and data volumes continue to increase, HPC is increasingly positioned as essential digital research infrastructure within national and international research ecosystems (Asch et al., 2018).

In the United Kingdom, this strategic importance is reflected in initiatives such as the National Federated Compute Services (NFCS) NetworkPlus programme, which aims to develop a coordinated and federated approach to digital research infrastructure. The programme focuses on community, technology, and governance to support a more accessible, interoperable, and inclusive HPC ecosystem. A key ambition is to broaden participation beyond traditional computational domains and address persistent inequalities in HPC access and use. Despite these developments, HPC adoption remains uneven across sectors (Kumar et al., 2025). While computationally intensive disciplines have long integrated HPC into their workflows, many applied and interdisciplinary sectors, including the built environment, have yet to fully realise its potential (Aghimien et al., 2021). This disparity highlights a critical challenge: the availability of advanced computational infrastructure does not automatically translate into widespread or equitable adoption.

The built environment sector, encompassing architecture, engineering, construction, and urban planning, is undergoing rapid digital transformation through technologies such as Building Information Modelling (BIM), digital twins, and sensor-based monitoring systems (Bolton et al., 2018; Succar & Kassem, 2015; Hosseini et al., 2026). These technologies generate increasingly large and complex datasets and create opportunities for HPC-enabled applications including infrastructure simulation, climate resilience modelling, materials analysis, and real-time decision-making. However, HPC adoption within the sector remains limited and fragmented (Usman et al., 2019). Existing workflows continue to rely heavily on desktop-based environments, while many commonly used tools are not readily compatible with HPC systems (Piane et al., 2024). Consequently, a disconnect persists between the computational potential of HPC and the practical realities of built environment workflows.

Emerging evidence suggests that this disconnect is not solely technical. Users frequently encounter barriers related to access procedures, limited awareness, insufficient training, inconsistent software environments, and concerns regarding data governance and security (Gamblin & Katz, 2023). These challenges are particularly significant in the built environment, where workflows are often time-sensitive, collaborative, and dependent on domain-specific data ecosystems. Data governance represents an additional challenge because built environment data is frequently proprietary, commercially sensitive, and distributed across multiple organisations (Berlato et al., 2025). This limits data sharing and collaboration while raising concerns regarding trust, privacy, and regulatory compliance.

Socio-technical perspectives provide an important framework for understanding these challenges. Socio-technical systems theory emphasises that successful technology

adoption depends on alignment between technological systems, organisational structures, and user practices (Baxter & Sommerville, 2011). Similarly, sociomaterial perspectives highlight that technologies are shaped through dynamic interactions between users, tools, and institutional contexts (Orlikowski, 2007). From this perspective, HPC adoption cannot be understood solely in terms of computational capability, but also in relation to usability, accessibility, workflow integration, and governance.

Additional barriers arise from the structural characteristics of the built environment sector, including fragmented supply chains, conservative practices, and resistance to technological change (Oesterreich & Teuteberg, 2016). Unlike BIM adoption, which benefited from policy mandates and coordinated implementation strategies, HPC adoption currently lacks equivalent institutional or regulatory drivers. As a result, uptake remains dependent on individual initiative rather than system-level support. Against this background, there is a clear need for research that bridges the gap between HPC infrastructure and built environment practice. Although previous studies have examined digital transformation in construction and the technical development of HPC systems, there remains limited empirical research exploring HPC adoption from a user-centred perspective within the built environment. This paper addresses this gap using qualitative data collected through a UKRI-funded project under the NFCS NetworkPlus programme. Drawing on stakeholder workshop discussions and interactive engagement methods, the study investigates barriers and enablers influencing HPC adoption across the user journey. Accordingly, this study aims to investigate the barriers and enablers influencing HPC adoption within the built environment from a user-centred and socio-technical perspective. The specific objectives are to: (1) examine stakeholder awareness and perceptions of HPC; (2) identify barriers related to access, workflows, governance, and skills; (3) explore how organisational and institutional contexts influence adoption; and (4) propose a user-centred roadmap to support more inclusive and accessible HPC adoption.

# 2. LITERATURE REVIEW

## 2.1 HPC AND DIGITAL TRANSFORMATION IN THE BUILT ENVIRONMENT

HPC has become a key component of digital research infrastructure, supporting large-scale simulation, advanced modelling, and data-intensive analysis across diverse disciplines (Dongarra et al., 2020). Traditionally associated with computationally intensive fields such as climate science and physics, HPC is increasingly relevant to interdisciplinary and applied domains due to the growing importance of data-driven research (Hey et al., 2009; Yin & Shi, 2022). However, existing HPC systems have historically been designed around specialist computational users and prioritised performance, scalability, and efficiency over usability and accessibility (Carver et al., 2019). Consequently, many non-expert users face barriers related to complex software environments, command-line interfaces, and limited workflow integration (Adimora et al., 2025). While recent policy initiatives increasingly emphasise inclusive and accessible digital research infrastructure (Gadam, 2025), there remains limited empirical research examining how these objectives can be achieved in applied sectors such as the built environment.

The built environment sector has undergone rapid digital transformation through technologies such as BIM, digital twins, and Internet of Things (IoT) systems (Succar &

Kassem, 2015; Bolton et al., 2018). These technologies generate large and complex datasets, creating opportunities for HPC-enabled applications including infrastructure simulation, climate resilience modelling, and real-time decision-making. However, adoption remains constrained by interoperability challenges, organisational readiness, fragmented supply chains, and reliance on established desktop-based workflows (Oesterreich & Teuteberg, 2016; Tran & Nguyen, 2024). Although digital twins align closely with HPC capabilities, implementation remains limited due to difficulties related to data integration, interoperability, and computational infrastructure (Boyes & Watson, 2022). This suggests that digital transformation challenges in the built environment are not solely technical but also organisational and socio-technical in nature.

## 2.2 DATA, GOVERNANCE, AND INTEROPERABILITY

Data management and interoperability represent major challenges for HPC adoption in the built environment. The increasing availability of data from sensors, monitoring systems, and digital models has expanded opportunities for data-driven analysis yet introduced significant governance and integration challenges (Kosicki et al., 2021). The FAIR principles Findable, Accessible, Interoperable, and Reusable—provide an important framework for improving data practices (Wilkinson et al., 2016), yet implementation remains uneven due to fragmented and proprietary data ecosystems (Jacobsen et al., 2020). Interoperability extends beyond technical compatibility to include semantic and organisational dimensions (Mistry et al., 2022; Pauwels & McGlinn, 2022). While HPC systems may provide significant computational capability, the effort required to prepare, integrate, and manage heterogeneous datasets can limit practical adoption (Reuther et al., 2024). Governance and trust further complicate implementation, particularly where concerns regarding intellectual property, commercial sensitivity, and regulatory compliance restrict data sharing and collaboration (Roski et al., 2021). Existing governance approaches are often designed for academic rather than industry-oriented environments and may not adequately address these concerns (Besednjak Valič et al., 2023). These challenges are intensified by the long lifecycle of built assets, which creates additional requirements for long-term data continuity and accessibility (Hernández-Moral et al., 2021).

## 2.3 SOCIO-TECHNICAL PERSPECTIVES ON HPC ADOPTION

Socio-technical systems theory provides a useful framework for understanding HPC adoption in the built environment (Brackley et al., 2024). Rather than viewing technology as an isolated artefact, socio-technical perspectives emphasise the interaction between technical systems, organisational practices, and institutional structures (Baxter & Sommerville, 2011). Successful adoption therefore depends on alignment between technological capability and user needs (Lukyamuzi et al., 2026). Orlikowski's (2007) concept of sociomateriality further suggests that technologies are shaped through ongoing interaction between users and systems rather than through straightforward implementation processes. These perspectives highlight the importance of user-centred design in digital infrastructure development (Peltonen & Nieminen, 2025). Traditional HPC systems often prioritise computational performance at the expense of usability, creating barriers for non-specialist users. In contrast, user-centred approaches focus on accessibility, workflow integration, and alignment with real-world practices. This is particularly important within the built environment, where diverse stakeholders,

fragmented workflows, and project-based delivery structures complicate technology adoption.

### 2.4 SYNTHESIS AND RESEARCH GAP

The literature demonstrates that HPC has significant potential to support data-intensive and interdisciplinary applications within the built environment. However, adoption remains constrained by interoperability challenges, governance concerns, skills gaps, and organisational barriers. Existing HPC research predominantly focuses on computational performance and technical architecture, while built environment research largely concentrates on digital tools such as BIM and digital twins. Consequently, there is limited integration between these domains and relatively few empirical studies examining HPC adoption from a user-centred perspective within the built environment.

This paper addresses this gap by applying a socio-technical framework to empirical data collected through a UK Research and Innovation (UKRI)-funded project under the NFCS NetworkPlus programme. By focusing on user experiences, workflow integration, governance, and institutional challenges, the study contributes to a more nuanced understanding of how HPC can be made accessible, inclusive, and aligned with real-world built environment practices.

## 3. RESEARCH METHODOLOGY

### 3.1 RESEARCH DESIGN

This study adopted a qualitative, user-centred research design to investigate barriers and enablers influencing HPC adoption within the built environment. The approach reflects the socio-technical nature of HPC adoption, recognising that engagement with digital infrastructure is shaped by interactions between technological systems, organisational practices, and user capabilities (Raybourn & Muollo, 2023; Frericks et al., 2018). Rather than focusing solely on technical performance, the study explored the broader user journey, including awareness, access, practical use, and long-term engagement with HPC systems. A qualitative approach was selected to capture context-specific insights into user experiences, workflow constraints, governance concerns, and organisational practices that are difficult to examine using quantitative methods alone. The methodology combined a stakeholder workshop with interactive polling using Mentimeter, enabling collection of both in-depth qualitative insights and broader patterns of participant responses. This approach aligns with broader calls for more inclusive and accessible digital research infrastructure and the objectives of the wider NFCS NetworkPlus project (Almusaed et al., 2025).

### 3.2 ETHICAL CONSIDERATIONS

Ethical approval was obtained from the University of the West of England (UWE) Research Ethics Committee. Participants received information regarding the purpose of the study, the voluntary nature of participation, and the intended use of data. Informed consent was obtained prior to participation, and all data were anonymised before analysis. Data were stored securely in accordance with institutional data management procedures and relevant data protection regulations. Attention was given to confidentiality where participants discussed commercially sensitive practices and organisational challenges.

### 3.3 WORKSHOP DESIGN AND PARTICIPANT RECRUITMENT

A stakeholder workshop was used as the primary data collection method. Participants were recruited through an Expression of Interest (EOI) process circulated through professional networks, email invitations, and NFCS NetworkPlus events. More than 50 responses were received, from which 30 participants were selected to ensure diversity in professional background, sector representation, and experience with digital and data-driven practices. Ultimately, 20 participants attended the workshop. Although participant attrition may have influenced the breadth of perspectives represented, non-attendance was not concentrated within a specific professional group. As recruitment was voluntary, the sample may have been biased towards participants with greater interest in HPC and digital infrastructure. The findings should therefore be interpreted as indicative rather than statistically representative. The workshop included researchers, industry practitioners, and technical specialists from the built environment sector. Activities included expert presentations, facilitated breakout discussions, plenary sessions, and interactive polling. Discussions focused on three themes: (1) barriers to HPC adoption, including workflow and infrastructure challenges; (2) trust, governance, and data-related concerns; and (3) future priorities for more inclusive HPC adoption and roadmap development.

### 3.4 MENTIMETER INTEGRATION

Mentimeter was used during the workshop to capture real-time and anonymised participant responses. Interactive polling tools such as Mentimeter are increasingly used in participatory research to support engagement and rapid collection of stakeholder perspectives (Khan, 2026). The integration of Mentimeter enabled broader participation, including from individuals less comfortable contributing during group discussions, while also reducing participation bias. The polling questions aligned with the workshop themes and explored issues including access barriers, workflow integration, governance concerns, and skills gaps. Combining polling outputs with facilitated discussion enabled corroboration of findings across multiple forms of participant engagement.

### 3.5 DATA ANALYSIS

Data analysis was conducted using qualitative thematic analysis supported by descriptive interpretation of Mentimeter responses. Thematic analysis was selected because it enables systematic identification of patterns within qualitative datasets while remaining sufficiently flexible to capture context-specific insights (Ahmed et al., 2025). Workshop notes, transcripts, and Mentimeter outputs were first reviewed to achieve familiarity with the data. Initial codes were then generated and grouped into broader themes relating to HPC adoption, including access barriers, workflow integration, governance concerns, and skills gaps. Themes were refined through iterative comparison across data sources to improve consistency and depth of interpretation. To enhance analytical rigour, preliminary themes were revisited multiple times and informally discussed among members of the research team to challenge interpretations and reduce researcher bias. Although formal inter-coder reliability testing and member-checking were not undertaken due to the exploratory nature of the study, efforts were made to maintain transparency and consistency throughout the analytical process. The combination of workshop discussions and Mentimeter responses supported convergent validation of findings.

Several limitations should be acknowledged. The workshop sample was relatively small and based on voluntary participation, which may have resulted in greater representation

from participants already interested in HPC-related topics. Consequently, the findings may not fully represent the diversity of perspectives within the wider built environment sector. Nevertheless, the participatory and user-centred design enabled the collection of rich qualitative insights into real-world barriers and opportunities associated with HPC adoption.

# 4. DATA ANALYSIS AND RESULTS

## 4.1 OVERVIEW OF FINDINGS

The findings are based on qualitative data collected through a stakeholder workshop involving 20 participants from academia, industry, and technical domains within the built environment sector, supported by Mentimeter polling. The analysis identified a series of interconnected barriers influencing HPC adoption, including limited awareness, access difficulties, workflow incompatibility, governance concerns, skills gaps, and institutional constraints.

## 4.2 AWARENESS, USE, AND ACCESS BARRIERS

Participants generally recognised the potential relevance of HPC for applications such as digital twins, infrastructure simulation, climate modelling, and data-intensive analysis. However, HPC was frequently perceived as a specialised resource rather than a practical tool for routine use. One participant noted that "HPC still feels like something designed for computer scientists rather than built environment professionals." Mentimeter responses indicated that approximately 70% of participants considered HPC highly relevant to future built environment applications, while fewer than 30% reported confidence in independently accessing or using HPC systems. Despite recognising potential benefits, participants reported limited practical engagement with HPC and continued reliance on local computing resources or simplified models. This suggests a clear gap between perceived value and practical adoption. Access and onboarding barriers were identified as major challenges, particularly within time-sensitive project environments. Participants highlighted difficulties in identifying suitable HPC resources, navigating access procedures, and obtaining timely system access. One participant explained that "the process of identifying the right HPC resource and obtaining access can take longer than the project timeline itself." More than half of participants identified onboarding complexity and access procedures as significant barriers to adoption.

## 4.3 WORKFLOW, GOVERNANCE, AND TRUST CHALLENGES

Workflow incompatibility emerged as a major obstacle to adoption. Participants relied heavily on domain-specific tools such as BIM, GIS, CAD, and statistical software, many of which are designed for desktop-based environments and are not easily integrated into HPC systems. Participants reported difficulties related to software compatibility, licensing, and workflow adaptation. As one participant observed, "most of our existing workflows are built around BIM and desktop-based tools, and moving these into HPC environments requires significant adaptation." These findings indicate that HPC systems often prioritise computational performance over usability and workflow compatibility. Data governance and trust-related concerns were also consistently identified. Participants raised issues relating to intellectual property, commercial sensitivity, data ownership, and confidentiality, particularly within industry–academia collaborations. One participant

stated that "sharing data across external computational environments raises concerns about intellectual property and client confidentiality." Participants expressed concerns regarding transparency, reliability, and accountability in high-stakes applications such as infrastructure design and safety analysis. These findings highlight the importance of governance frameworks capable of supporting secure and trusted collaboration.

### 4.4 SKILLS, TRAINING, AND INSTITUTIONAL FACTORS

Limited skills, training, and technical support were identified as additional barriers to HPC adoption. Participants reported low confidence in using HPC systems and highlighted the lack of accessible, application-focused training opportunities. Mentimeter responses indicated that many participants had received little or no formal HPC training. One participant explained that "there is a lack of practical guidance showing how HPC can actually support day-to-day built environment tasks." Participants emphasised the importance of ongoing technical support and guidance to facilitate workflow integration and experimentation with HPC platforms. Beyond technical barriers, participants identified broader institutional and cultural challenges. Resistance to change, fragmented supply chains, risk-averse decision-making, and the absence of strong policy drivers were all perceived as limiting adoption. Unlike BIM, which benefited from regulatory mandates, HPC adoption remains largely voluntary and lacks coordinated implementation strategies.

### 4.5 SYNTHESIS OF FINDINGS

The findings reveal a consistent pattern of interconnected socio-technical barriers affecting HPC adoption within the built environment. Although there is clear demand for advanced computational capabilities, adoption is constrained by challenges relating to access, workflow integration, governance, skills, and institutional practices. These barriers are mutually reinforcing; for example, limited training reduces the ability to adapt workflows, while governance concerns restrict collaboration and data sharing. Overall, the results demonstrate that improving HPC adoption requires more than technological advancement alone. Effective implementation depends on aligning infrastructure, governance, workflows, and user practices to ensure that HPC systems are accessible, usable, and relevant within real-world built environment contexts.

## 5. DICUSSION

The findings of this study demonstrate that the adoption of HPC in the built environment is fundamentally a socio-technical challenge rather than a purely technical one. Consistent with socio-technical systems theory (Baxter & Sommerville, 2011), successful adoption depends on alignment between technological capabilities, user practices, and institutional contexts. While HPC infrastructure is increasingly available, its integration into built environment workflows remains constrained by a combination of access barriers, workflow misalignment, governance challenges, and skills gaps.

A key insight is the persistence of an awareness–adoption gap. Although stakeholders recognise the potential relevance of HPC, this awareness does not translate into routine use. This finding aligns with broader research on digital infrastructure adoption, which highlights that awareness alone is insufficient without improvements in accessibility and usability (Hey et al., 2009). In the built environment, HPC is often perceived as a specialised or peripheral resource rather than an integral component of everyday practice.

This perception is reinforced by limited visibility within organisational workflows and the absence of clear entry points for engagement.

The findings reveal a significant mismatch between HPC systems and established built environment workflows. Practitioners rely heavily on domain-specific tools such as BIM, GIS, and simulation software, which are typically designed for desktop environments. The difficulty of integrating these tools with HPC systems creates a substantial barrier to adoption. This reflects observations from BIM adoption literature, where interoperability challenges and workflow disruption hinder digital transformation (Succar & Kassem, 2015). These findings suggest that efforts to promote HPC adoption should prioritise integration rather than replacement. Expecting users to abandon established tools is unlikely to be effective in a sector characterised by complex, collaborative, and time-sensitive practices. Instead, HPC systems must support and extend existing workflows, reflecting a shift from technology-driven approaches to user-centred design focused on compatibility and usability.

Access and onboarding processes represent another critical barrier. Although HPC resources may be technically available, they are not easily accessible in practice. Complex procedures, unclear pathways, and delays reduce usability, particularly in time-constrained environments such as consultancy and project delivery. These findings align with broader critiques of digital research infrastructure, which emphasise the need for more user-friendly and responsive access models (UKRI, 2022). Without streamlined access, HPC remains impractical despite its potential benefits. The concept of "right-sized computing" provides a useful framework for addressing these challenges. Rather than assuming universal reliance on large-scale HPC systems, the findings suggest that many applications in the built environment would benefit from flexible and scalable solutions. This includes hybrid models combining local, cloud, and HPC resources, allowing users to select appropriate computational capacity based on project needs. Such approaches align with federated infrastructure models, including those promoted by the NFCS NetworkPlus programme, which aim to provide more adaptable and user-oriented access to computational resources.

Data governance and trust emerge as particularly significant challenges. Built environment data is often proprietary, commercially sensitive, and distributed across multiple stakeholders, creating barriers to sharing and collaboration. Effective HPC use requires balancing openness with control, highlighting the need for governance frameworks that address intellectual property, security, and regulatory concerns. The findings also show that trust extends beyond data to include confidence in computational outputs, particularly in high-stakes applications such as infrastructure design and safety analysis. This underscores the importance of governance models that not only protect data but also build user confidence.

Skills and training represent another critical dimension of the socio-technical challenge. Many users lack the knowledge and confidence required to engage with HPC, and existing training provision is often insufficient or poorly aligned with domain-specific needs (Carver et al., 2019). The findings emphasise the importance of practical, application-focused training that supports integration into existing workflows. In this context, support structures such as Research Software Engineers (RSEs) play a key role by bridging the gap between domain expertise and computational infrastructure.

However, access to such support remains uneven, particularly outside research-intensive institutions.

Beyond technical and operational barriers, cultural and institutional factors significantly influence adoption. The built environment sector is characterised by fragmented supply chains, project-based organisation, and risk-averse practices, all of which can inhibit the uptake of new technologies. The absence of strong policy drivers further limits adoption. Unlike BIM, which has been widely adopted following regulatory mandates, HPC remains largely voluntary and lacks systemic incentives. This suggests that policy interventions may be necessary to encourage adoption, particularly where HPC can contribute to broader goals such as sustainability and digital transformation.

Taken together, these findings highlight the need for a holistic, user-centred approach to HPC development. Improving adoption requires coordinated interventions across multiple dimensions. Simplifying access pathways is essential to reduce barriers to entry, while domain-specific training can improve user capability and confidence. Enhancing interoperability with commonly used tools is critical for workflow integration, and the development of communities of practice can support knowledge sharing and peer learning. Finally, robust governance frameworks are needed to address issues of trust, data ownership, and security.

Based on the identified barriers and enabling factors, Figure 1 presents a proposed user-centred roadmap for improving HPC adoption within the built environment sector.

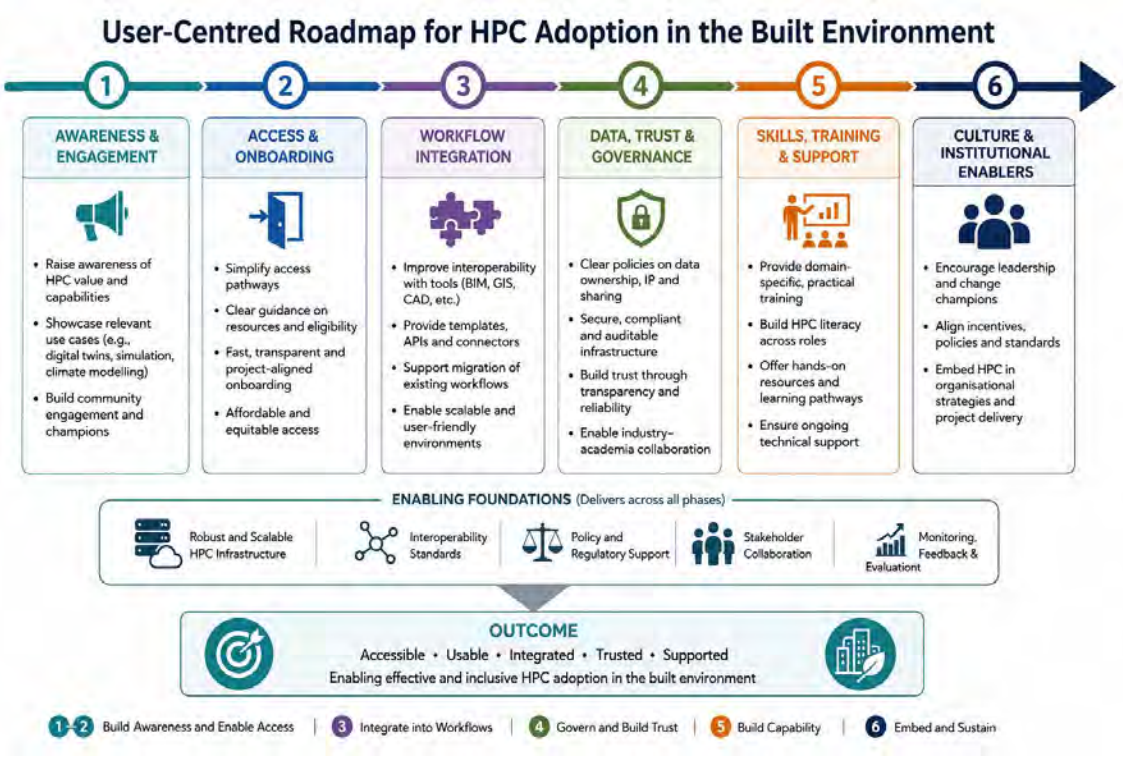



*Figure 1: User-Centred roadmap for HPC adoption in the built environment*

The roadmap highlights the interconnected technical, organisational, and institutional interventions required to support accessible, trusted, and workflow-integrated HPC adoption across the built environment.

## 6. CONCLUSIONS

This study investigated the barriers and enablers influencing HPC adoption within the built environment through a user-centred and socio-technical lens. Drawing on stakeholder workshop discussions and interactive engagement activities, the findings reveal a persistent gap between awareness of HPC potential and its practical adoption. The study makes three principal contributions. First, it provides empirical evidence on HPC adoption within the built environment, a domain that has received limited attention in existing research. Second, it demonstrates how socio-technical factors—including access, workflow integration, governance, skills, and institutional contexts—collectively shape adoption outcomes. Third, it proposes a user-centred roadmap to support more inclusive, accessible, and interoperable HPC adoption aligned with the objectives of the NFCS NetworkPlus programme. Collectively, these contributions advance understanding of how advanced computational infrastructure can be better aligned with the needs and practices of built environment stakeholders. From a practical perspective, the findings support the development of inclusive and flexible HPC ecosystems, such as those envisioned by the NFCS NetworkPlus programme. The concept of "right-sized computing" offers a pathway for making advanced computational resources more accessible by enabling users to engage with local, cloud, and HPC resources according to project requirements and organisational capabilities. The proposed roadmap provides actionable priorities for infrastructure providers, policymakers, researchers, and industry stakeholders seeking to broaden participation in HPC-enabled innovation. Several limitations should be acknowledged. The study was based on a relatively small workshop sample and focused primarily on UK-based stakeholders. As participation was voluntary, the findings may over-represent individuals already interested in digital innovation and HPC-related technologies. Future research could expand the evidence base through larger-scale surveys, longitudinal studies, and comparative investigations across different sectors and national contexts. Additional research is needed to evaluate the effectiveness of specific interventions, including training programmes, governance models, interoperability solutions, and federated computing approaches. In conclusion, unlocking the potential of HPC in the built environment requires a shift from a technology-centric to a user-centred approach. By prioritising usability, accessibility, trust, and integration with existing practices, HPC can evolve from a specialist resource into a practical enabler of innovation, sustainability, resilience, and data-driven decision-making. Such a transformation is essential if advanced computational capabilities are to be effectively and inclusively leveraged across the built environment sector.

## 7. REFERENCES

Adimora, K., Gundla, S. R., & Sun, H. (2025). Machine learning approaches for optimizing high-performance computing scheduling: A comprehensive survey and analysis. *Cluster Computing, 28*(13), 831. https://doi.org/10.1007/s10586-025-05521-8

Aghimien, E. I., Aghimien, L. M., Petinrin, O. O., & Aghimien, D. O. (2021). High-performance computing for computational modelling in built environment-related studies: A scientometric review. *Journal of Engineering, Design and Technology, 19*(5), 1138–1157. https://doi.org/10.1108/JEDT-07-2020-0294

Ahmed, S. K., Mohammed, R. A., Nashwan, A. J., Ibrahim, R. H., Abdalla, A. Q., Ameen, B. M. M., & Khdhir, R. M. (2025). Using thematic analysis in qualitative research. *Journal of Medicine, Surgery, and Public Health, 6*, 100198. https://doi.org/10.1016/j.glmedi.2025.100198

Almusaed, A., Almssad, A., & Yitmen, I. (2025). Introduction to research methodology. In *Practice of research methodology in civil engineering and architecture: A comprehensive guide* (pp. 5–33). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-97393-2_1

Asch, M., Moore, T., Badia, R., Beck, M., Beckman, P., Bidot, T., ... Zacharov, I. (2018). Big data and extreme-scale computing: Pathways to convergence toward a shaping strategy for a future software and data ecosystem for scientific inquiry. *The International Journal of High Performance Computing Applications, 32*(4), 435–479. https://doi.org/10.1177/1094342018778123

Baxter, G., & Sommerville, I. (2011). Socio-technical systems: From design methods to systems engineering. *Interacting with Computers, 23*(1), 4–17. https://ieeexplore.ieee.org/abstract/document/8147295

Berlato, M., Binni, L., Durmus, D., Gatto, C., Giusti, L., Massari, A., ... Mirarchi, C. (2025). Digital platforms for the built environment: A systematic review across sectors and scales. *Buildings, 15*(14), 2432. https://doi.org/10.3390/buildings15142432

Besednjak Valič, T., Kolar, J., Lamut, U., & Pandiloska Jurak, A. (2023). Key policy mechanisms supporting university–industry collaboration in the Danube region: Case study of academic HPC centres and SMEs. *European Journal of Management and Business Economics, 32*(5), 509–524. https://doi.org/10.1108/EJMBE-09-2022-0283

Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., ... Pawsey, N. (2018). *The Gemini principles: Guiding values for the national digital twin and information management framework*. Centre for Digital Built Britain. https://www.repository.cam.ac.uk/items/589a0fb1-b350-462f-abda-ace640cb0654

Boyes, H., & Watson, T. (2022). Digital twins: An analysis framework and open issues. *Computers in Industry, 143*, 103763. https://doi.org/10.1016/j.compind.2022.103763

Brackley, C., Ouf, M. M., & O'Brien, W. (2024). Bridging the gap between theory and adoption: A critical review of socio-technical and human-computer interaction studies of fault detection and diagnosis in commercial buildings. *Science and Technology for the Built Environment, 30*(8), 918–931. https://doi.org/10.1080/23744731.2024.2378674

Carver, J. C., Kendall, R. P., Squires, S. E., & Post, D. E. (2019). Software engineering for science. *Computing in Science & Engineering, 9*(4), 44–52. https://ecommons.luc.edu/cgi/viewcontent.cgi?article=1127&context=cs_facpubs

Dongarra, J., et al. (2020). The International Exascale Software Project roadmap. *International Journal of High Performance Computing Applications, 25*(1), 3–60. https://doi.org/10.1177/1094342010391989

Frericks, P., Höppner, J., & Och, R. (2018). The difficulty of measuring institutions: A methodological approach to the comparative analysis of institutions. *Social Indicators Research, 137*(3), 847–865. https://doi.org/10.1007/s11205-017-1638-9

Gadam, S. (2025). Enhancing usability and accessibility: Innovations in human–computer interaction for modern systems. *Economic Sciences, 21*(1), 373–384. https://elibrary.ru/item.asp?id=82214762

Gamblin, T., & Katz, D. S. (2023). Overcoming challenges to continuous integration in HPC. *Computing in Science & Engineering, 24*(6), 54–59. https://doi.org/10.1109/MCSE.2023.3263458

Hernández-Moral, G., Mulero-Palencia, S., Serna-González, V. I., Rodríguez-Alonso, C., Sanz-Jimeno, R., Marinakis, V., ... Doukas, H. (2021). Big data value chain: Multiple perspectives for the built environment. *Energies, 14*(15), 4624. https://doi.org/10.3390/en14154624

Hey, T., Tansley, S., & Tolle, K. (2009). *The fourth paradigm: Data-intensive scientific discovery*. Microsoft Research.

Hosseini, M. R., Najafi, M., & Rahimian, F. (2026). Digital transformation and smart technologies for sustainable built environment: Innovations, applications and future pathways. *Smart and Sustainable Built Environment, 15*(1), 1–8. https://doi.org/10.1108/SASBE-02-2026-689

Jacobsen, A., de Miranda Azevedo, R., Juty, N., Batista, D., Coles, S., Cornet, R., ... Schultes, E. (2020). FAIR principles: Interpretations and implementation considerations. *Data Intelligence, 2*(1–2), 10–29. https://doi.org/10.1162/dint_r_00024

Khan, M. A. (2026). Mentimeter tool for enhancing student engagement and active learning: A literature review. *International Journal of Changes in Education, 3*(1), 1–10. https://doi.org/10.47852/bonviewIJCE52023801

Kosicki, M., Tsiliakos, M., ElAshry, K., & Tsigkari, M. (2021). Big data and cloud computing for the built environment. In *Industry 4.0 for the built environment: Methodologies, technologies and skills* (pp. 131–155). Springer International Publishing. https://doi.org/10.1007/978-3-030-82430-3_6

Kumar, M., Kaur, G., & Rana, P. S. (2025). Performance, portability, productivity, and security in HPC cloud: A systematic literature review. *The Journal of Supercomputing, 81*(11), 1197. https://doi.org/10.1007/s11227-025-07685-x

Le Piane, F., Vozza, M., Baldoni, M., & Mercuri, F. (2024). Integrating high-performance computing, machine learning, data management workflows, and infrastructures for multiscale simulations and nanomaterials technologies. *Beilstein Journal of Nanotechnology, 15*(1), 1498–1521. https://doi.org/10.3762/bjnano.15.119

Lim, W. M. (2025). What is qualitative research? An overview and guidelines. *Australasian Marketing Journal, 33*(2), 199–229. https://doi.org/10.1177/14413582241264619

Lukyamuzi, E., Kimbowa Wamala, T., Ssekagiri, A., Galiwango, R., Kebirungi, G., Mugume, A., ... Kayondo, J. (2026). A scalable HPC framework for bioinformatics in resource-limited settings: Design principles, implementation, and sustainability from the UVRI experience. *Bioinformatics*, btag149. https://doi.org/10.1093/bioinformatics/btag149

Mensa, S., Sahin, E., Williamson, G., & Allan, R. J. (2023). An educational and training perspective on integrating hybrid technologies with HPC systems for solving real-world commercial problems. *Journal of Computational Science, 14*(1). https://jocse.org/downloads/jocse-14-1-6.pdf

Mistry, P., Maguire, D., Chikwira, L., & Lindsay, T. (2022). Interoperability is more than technology. *Human Factors and Ergonomics in Manufacturing & Service Industries, 32*(5), 406–418. https://assets.kingsfund.org.uk/f/256914/x/c48bd5a1a2/interoperability_more_than_technology_2022.pdf

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation in the construction industry. *Computers in Industry, 83*, 121–139. https://doi.org/10.1016/j.compind.2016.09.006

Orlikowski, W. J. (2007). Sociomaterial practices: Exploring technology at work. *Organization Studies, 28*(9), 1435–1448. https://doi.org/10.1177/0170840607081138

Pauwels, P., & McGlinn, K. (Eds.). (2022). *Buildings and semantics: Data models and web technologies for the built environment*. CRC Press. https://research.tue.nl/en/publications/buildings-and-semantics-data-models-and-web-technologies-for-the-/

Peltonen, R., & Nieminen, M. (2025, September). Human-centred design for digital ecosystems: Actors, roles and responsibilities. In *Linking theory and practice of digital libraries: 29th International Conference on Theory and Practice of Digital Libraries, TPDL 2025, Tampere, Finland, September 23–26, 2025, Proceedings* (p. 287). Springer Nature. https://doi.org/10.1007/978-3-032-05409-8_17

Piras, G., Agostinelli, S., & Muzi, F. (2024). Digital twin framework for the built environment: A review of key enablers. *Energies, 17*(2), 436. https://doi.org/10.3390/en17020436

Raybourn, E. M., & Muollo, K. (2023, July). Guidelines for practicing responsible innovation in HPC: A sociotechnical approach. In *International Conference on Human-Computer Interaction* (pp. 105–118). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-34668-2_8

Reuther, A., Brown, N., Arndt, W., Blaschke, J., Boehme, C., Chazapis, A., ... Martinasso, M. (2024). Interactive and urgent HPC: Challenges and opportunities. *arXiv*. https://arxiv.org/abs/2401.14550

Roski, J., Maier, E. J., Vigilante, K., Kane, E. A., & Matheny, M. E. (2021). Enhancing trust in AI through industry self-governance. *Journal of the American Medical Informatics Association, 28*(7), 1582–1590. https://doi.org/10.1093/jamia/ocab065

Singh, V. (2025). Digitalization, BIM ecosystem, and the future of the built environment: How widely are we exploring the different possibilities? *Engineering, Construction and Architectural Management, 32*(7), 4900–4917. https://doi.org/10.1108/ECAM-01-2018-0004

Succar, B., & Kassem, M. (2015). Macro-BIM adoption: Conceptual structures. *Automation in Construction, 57*, 64–79. https://doi.org/10.1016/j.autcon.2015.04.018

Tran, H. V. V., & Nguyen, T. A. (2024). A review of challenges and opportunities in BIM adoption for construction project management. *Engineering Journal, 28*(8), 79–98. https://doi.org/10.4186/ej.2024.28.8.79

UK Research and Innovation. (2022). *UK digital research infrastructure strategy*. https://www.ukri.org/publications/ukri-strategy-2022-to-2027/

Usman, S., Mehmood, R., & Katib, I. (2019). Big data and HPC convergence for smart infrastructures: A review and proposed architecture. In *Smart infrastructure and applications: Foundations for smarter cities and societies* (pp. 561–586). https://doi.org/10.1007/978-3-030-13705-2_23

Wilkinson, M. D., et al. (2016). The FAIR guiding principles for scientific data management and stewardship. *Scientific Data, 3*, 160018. https://doi.org/10.1038/sdata.2016.18

Yin, F., & Shi, F. (2022). A comparative survey of big data computing and HPC: From a parallel programming model to a cluster architecture. *International Journal of Parallel Programming, 50*(1), 27–64. https://doi.org/10.1007/s10766-021-00717-y

Yousaf, F., & Khan, A. (2022). Accelerating scientific discovery with high-performance advanced computing systems. *Journal of Advanced Computing Systems, 2*(8), 1–8. https://scipublication.com/index.php/JACS/article/view/49

Kasthuriarachchi, T.A., Mapa, M.M.I.S. and Chandani, G.G.N., 2026. Ergonomic performance indicators for evaluating office workstation arrangements. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 686-701. DOI: https://doi.org/10.31705/WCS.2026.51. Available from: https://ciobwcs.com/papers/

# ERGONOMIC PERFORMANCE INDICATORS FOR EVALUATING OFFICE WORKSTATION ARRANGEMENTS

**T.A. Kasthuriarachchi[1], M.M.I.S. Mapa[2] and G.G.N. Chandani[3]**

## *ABSTRACT*

*Ergonomics is the scientific field involved in the process of optimising the relationship between human beings and the working environment to improve human well-being and system performance. In the modern office environment, where knowledge-intensive activity and heavy computer usage are common, workstation design and layout have become a critical factor in determining the comfort, health and output of employees. Office workers spend between six and twelve hours in sedentary workstations. Hence, a suitable computer workstation setup is a requirement to preserve the performance and physical health of the office worker. There are ergonomic risk assessment tools, such as ROSA, RULA, and REBA, but these are mostly designed to measure ergonomic risk factors that contribute to musculoskeletal disorders (MSDs). However, these tools do not systematically assess the overall arrangement of computer office workstations or determine whether workstations are ergonomically compliant. Therefore, a structured and consistent set of ergonomic performance indicators must be identified, which can be used to assess the workstation arrangement. The purpose of this paper is to determine and validate a list of ergonomic performance indicators across six main areas: the office chair, work surface, monitor, keyboard, mouse and workstation accessories. A literature review of the existing ergonomic standards/guidelines and previous research articles was initially conducted to determine the performance indicators. These scattered indicators were then systematically consolidated. A structured expert interviews were conducted with eleven experienced ergonomic and occupational health specialists. The results created a finalised, expert-validated ergonomic performance indicators, which allows for recognition of workstation deficiencies, prioritising ergonomic interventions and workstation adjustments. This approach is unlike current ergonomic assessment tools, as it focuses on structured, component-wise performance indicators rather than posture-based risk scoring systems.*

***Keywords:*** *Ergonomics; Ergonomic Performance Indicators; Office Workstation; Workstation Ergonomics.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, thimnaasheni@gmail.com

[2] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, isuru.mapa@uom.lk

[3] Lecturer (Temporary), Department of Facilities Management, University of Moratuwa, Sri Lanka, navodag@uom.lk

# 1. INTRODUCTION

Companies are currently encountering various challenges in sustaining employee health and performance while incorporating new technologies and accommodating a variety of work styles (Chandwani et al., 2019). The contemporary workplace is rapidly becoming a critical factor in employee health and performance, as well as long-term health outcomes. As jobs shift to be knowledge-based and more screen-intensive in office environments, workstation design and arrangement have become a primary subject of discussion in occupational health and safety (Ankamah-Lomotey, 2025). With the evolution of information technology and changing work trends, the use of computers in offices is growing at a significant rate (Mohammadian et al., 2025). Computer workers in offices spend on average 6-12 hours per day in a sedentary working position (Chandwani et al., 2019).

The arrangement of the workstation is central to the ergonomic quality of the office working environment. According to Berner and Jacobs (2002), more than 60% of computer users had received information regarding workstation ergonomics, but less than 10% had managed to apply that information to daily work activities. This suggests that the issue is not simply about awareness but due to a lack of structured, accessible assessment methods. A significant number of ergonomic risk assessment tools are designed to assess the ergonomic risk, including the Rapid Office Strain Assessment (ROSA) (Sonne et al., 2012), Rapid Upper Limb Assessment (RULA) (McAtamney & Corlett, 1993) and Rapid Entire Body Assessment (REBA), etc. These tools primarily determine ergonomic risks related to MSDs and postural deviations, but do not comprehensively evaluate computer office workstations based on ergonomic performance indicators in a component-wise manner. Furthermore, no single study consolidates ergonomic guidelines/standards and previous research to identify such indicators. Therefore, there is a clear need for a unified set of ergonomic performance indicators for a comprehensive evaluation of workstations.

To achieve the research aim, this paper establishes three objectives. The first goal is to determine the ergonomic performance indicators of each of the six main workstation components by reviewing the existing ergonomic guidelines/standards and literature. Second, the study validates the identified ergonomic performance indicators by the expert judgment of specialists who are experienced in ergonomics and occupational health. The consensus of experts regarding the relevance and applicability of the identified ergonomic indicators in the field were done in two rounds. Finally, the study contributes a consolidated summary of expert-validated ergonomic performance indicators for office workstation arrangement. This acts as a structured, evidence-based instrument to identify workstation deficiencies and recommend ergonomic modifications.

# 2. LITERATURE REVIEW

## 2.1 ERGONOMICS IN OFFICE WORK ENVIRONMENTS

The word ergonomics is derived from the Greek word “Ergon” meaning work, and “Nomos” meaning laws, which means "science of work" (International Ergonomics Association and Human Factor Association [IEA]). It is the scientific field that studies how people interact with system elements to maximize both human well-being and system performance (Mishra & Narendra, 2020). Ergonomics focuses on adjusting work

to human limitations and capacities rather than making people adapt to uncomfortable situations (Mishra & Narendra, 2020).

There are three domains. Physical ergonomics deals with human anatomical, anthropometric, physiological and biomechanical features considering the relation to body movement. Cognitive ergonomics addresses mental workload and human-computer interaction. Organizational ergonomics is concerned with the optimization of sociotechnical systems (IEA, n.d.). Physical ergonomics is essential in the workplace since they are characterized by sedentary work and prolonged standing postures that cause WMSDs (Berenyi et al., 2015).

Employee productivity has emerged as one of the most important elements of organizational performance and sustainability in the contemporary organizational setting. As computer-based and sedentary work-related occupations have become more prevalent, workplace ergonomics has become of critical importance in terms of employee health, comfort, and productivity (Suchitra et al., 2025). Low comfort level of ergonomics or organization at the workplace has serious economic consequences to the organizations due to dissatisfaction of the employees, reduced productivity and reduced emotional and physical well-being of the employees (Makhbul, 2013).

Poorly ergonomically designed workstations result in WMSD, which causes low productivity and worker performance degradation (Khan & Pope-Ford, 2015). Moreover, the scientific literature has proposed that computer users are more likely to develop upper extremity MSDs (Gerr et al., 2004).

## 2.2 ERGONOMIC RISK FACTORS IN OFFICE WORKSTATIONS

The frequent work with the computer in the office results in numerous risk factors associated with WMSD, including long sitting postures and awkward positioning of the head, neck and upper limbs, contributing to higher muscle activity in the cervical spine and shoulders (Matos & Arezes, 2015). According to Mohammadian et al. (2025), the most significant ergonomic risks in office settings include prolonged awkward postures, repetitive motion, static activity and lack of ergonomics of workstations. Further evidence supports that the design of a workstation, improper postures and use of non-ergonomic office equipment are among the most significant occupational risk factors towards MSDs (Daneshmandi et al., 2017).

## 2.3 OFFICE WORKSTATION ARRANGEMENTS AND KEY ERGONOMIC INDICATORS COMPONENTS

The evolution of office workstations has been driven by technological progress in the late 1980s, and one of the transformations is the shift from typewriters to computer interfaces (Carlson et al., 2019). An office workstation is a whole system of physical equipment such as chairs, desks, monitors, keyboards and input devices that constitute the place in which a worker works (Woo et al., 2016). The quality of an office workstation is eventually defined by the interaction between the human user and the physical components within the space, especially furniture and the computing equipment (Shahwan et al., 2022). The alignment and compatibility between the workstation components and the user must be done properly to facilitate neutral working positions and reduce the physical load. Working postures are directly related to the workstation and prolonged sitting, which results in musculoskeletal overload, pain and discomfort in

office workers (Lee et al., 2020). Workstation adjustments based on ergonomic guidelines are recommended to avoid such problems (Lee et al., 2020). A well-configured workstation based on ergonomic principles minimizes the risk of poor postures and promotes postural changes in the workplace (Kar & Hedge, 2021).

### 2.3.1 Office Chair

The chair itself has a direct impact on body posture (alignment). When musculoskeletal symptoms occur due to prolonged sitting, it is generally recommended to change the chair at the workplace. Replacing the chair is the most reasonable measure due to physical limitations to altering the work surface and an adjustable work surface is not a cost-efficient option (Niekerk et al., 2012). The seat must be adjustable in height, particularly where it is used by many individuals (Occupational Safety and Health Administration [OSHA], n.d.). In case the knee height exceeds the hip height, it results in loss of the lumbar curve and trigger back pains (Skilling, 2016)**.** OSHA mentioned that the knees are positioned at hip height, with the feet placed slightly forward**.** The Canadian Standards Association Group (CSA, 2000) suggests that a person should be seated in a neutral position by bending the knees at approximately 90 degrees. When the users are seated at the right height in relation to the desk and keyboard and are unable to place their feet on the floor, a footrest should be provided (McKeown, 2007). The seat pan must have three-inch gap between the edge of the chair and the back of the knee (CSA, 2000) to maintain adequate blood circulation to the lower legs (Western Connecticut State University). According to OSHA, the seat pan should be depth-adjustable to allow taller and shorter workers to position themselves fully onto the seat portion.

The backrests and the seat must be padded in order to prevent the body from pressing against the frame of the chair. The pressure distribution is impacted by the padding thickness and density (Skilling, 2016). The seat pan should be covered with a breathable material, be thick and slightly concave (Occupation Safety and Health Branch Labour Department , 2010), and rounded waterfall seat pan edge (OSHA). The rounded edges of the front of the seat pan minimise the pressure in the popliteal area (Human Factors and Ergonomics Society, 2007).

The seat back is supposed to support the lower back and the shoulders and allow the individual to sit in an upright posture without leaning forward (Herman & Watchman, 1997). The lumbar support must be positioned to fit in the small of the back to preserve the natural lumbar spine (CSA, 2000). This is further supported by McKeown (2007) which states that it should be positioned in relation to the user's lumbar region. The employee is supposed to be sitting in a reclined posture at around 95 - 110 degrees (CSA, 2000). In the case backrest recline angle is more than 120 degrees relative to horizontal, backrest must have a headrest (Human Factors and Ergonomics Society, 2007).

The arms comprise around 10% of the entire body weight. By supporting the weight of the arms, the spine is less stressed (Skilling, 2016). Hard material armrests or armrests with sharp edges irritate the nerves and blood vessels present in the forearm (OSHA). The Armrest should be adjustable in height, as overly high or low armrests result in awkward postures (Human Factors and Ergonomics Society, 2007). This is further supported by Western Connecticut State University, that adjustable height arm rests allow the user's arms and wrists to be in a parallel position, thereby relieving tension in the upper back, neck and shoulders. The armrests are to be placed in a way that the elbows are at a 90 - 120 degree bend, close to the body and shoulders in a relaxed manner (CSA, 2000;

OSHA). Further, OSHA recommends that armrests be wide enough to allow easy access and exit of the chair.

The chair must be on its five-prong base with casters (McKeown, 2007). In most cases, hard-wheel chair casters are applied to soft floors, and soft-wheel chair casters are applied to hard floors (Human Factors and Ergonomics Society, 2007)

### 2.3.2 Work Desk

The work surface should be at resting elbow height for most computer related work (OSHA). This is further supported by McKeown (2007), that the arms should be at 90 degrees to the desk and equipment (keyboard, mouse) and upper arm at its natural position.

Primary work zone equipped with the most used equipment (Human Factors and Ergonomics Society, 2007). The secondary work area is used for activities that occur on an irregular basis or for short periods of time (McKeown, 2007).

The hard edges on desks and computer equipment will cause contact stress. This affects nerves and blood vessels, and results in tingling and sore fingers (OSHA). Similarly, McKeown (2007) recommends that rounded or bull nosed edges are considered more appropriate than a 90-degree angle edge.

Adequate leg and foot clearance should be provided for the user in the chosen reference postures (Human Factors and Ergonomics Society, 2007). When horizontal clearance is too low, it leads to 'trapped thighs' cause when the user is forced to confine to uncomfortable and limited positions (OSHA).

### 2.3.3 Monitor

Ergonomics and quality of the computer display are the key considerations that can affect the physical comfort and productive output of employees. It has been shown that monitor height is an important predictor of concentration and task efficiency, and appropriate alignment allows for minimising fatigue (Ankamah-Lomotey, 2025). The height of the screen should be adjusted so that the top of the screen is at or slightly below the seated eye level of the worker (Sonne et al., 2012). This can be done using an articulating arm or with a building block such as a platform (screen risers) (McKeown, 2007). Additionally, research indicates that having screens above eye level are associated with greater musculoskeletal discomfort (Human Factors and Ergonomics Society, 2007). The screen should be positioned directly in front of the seated operator to avoid head rotation or twisting of the upper body (McKeown, 2007).

Images are harder to view, creating eye strain and exhaustion, when direct sources of light (such as windows, overheads) reflect light onto the operator (OSHA). Lighting must be sufficient to read the text and display on the monitor, but it should not produce glare or discomfort (Herman & Watchman, 1997). This can be reduced by positioning the display screen at a right angle to the lights and windows. Similarly, the Occupational Health Clinics for Ontario Workers (2021) recommend placing monitors between light panels and perpendicular to windows to minimise glare. The use of blinds or drapes on windows further reduces ambient glare. Additionally, anti-glare filters may be affixed to the monitor surface. Overhead lighting glare can be controlled through the implementation of light diffusers or suitable light covers (OSHA).

### 2.3.4 Keyboard

The wrist bends upward due to the keyboard tilt, either as a result of extending the legs located at the back of the keyboard or because of an excessively steep design angle. These uncomfortable wrist positions provide contact pressure to the tendon sheath and tendons due to repetitive keying (OSHA).

The keyboard must be front and centrally positioned in front of the user to avoid repeated twisting of the head or trunk (Chandra et al., 2009). The position of the keyboard must enable the worker to operate the keyboard with elbows at around 90 degrees and with a relaxed position of the shoulders (CSA, 2000). The keyboard and the mouse must be at a height where forearms, wrists and hands are parallel with the floor (Chandra et al., 2009).

### 2.3.5 Mouse

The size of the hand of a worker should fit in the mouse without requiring a pinch grip or creating pressure points (CSA, 2000). Inappropriate size and shape of pointers may contribute to stress and awkward positions, as well as overexertion (OSHA).

The pointer should be adjusted to allow the wrist to remain in a straight and neutral position (OSHA). Wrist movements during mouse use, involving extension or deviation, have been identified as risk factors for MSDs in the upper extremities (McAtamney & Corlett, 1993).

The mouse must be held at the side of the operator with the arm positioned closer to the body (Herman and Watchman, 1997). Greater distances of mouse movement are associated with increased muscle activity (Cook & Kothiyal, 1998).

### 2.3.6 Workstation Accessories

Research has shown that the deficiencies of workstation accessories contribute to neck, shoulder, hand and back pain (Shahwan et al., 2022). The main types of ergonomic accessories and performance requirements are as follows.

Position the telephone in the main or secondary work area based on its usage patterns. This will eliminate repetitive reach, which will minimise the risk of injury (OSHA). The telephone should be placed within 300 mm of the worker to avoid reaching (CSA, 2000). Extended phone calls with the phone between the head and the shoulder contribute to stress and neck discomfort (OSHA). Telephone headsets should be provided for tasks that require frequent phone use, allowing simultaneous interaction with the computer (McKeown, 2007).

A summary of the literature findings on ergonomic office workstation performance indicators is presented in Table 2.

## 2.4 LIMITATIONS IN EXISTING ERGONOMIC ASSESSMENT TOOLS

There are several limitations in existing ergonomic assessment tools, such as ROSA, RULA and REBA in evaluating workstation arrangements. These tools mainly aim to identify the ergonomic risks for developing MSD and to assess the postures (Yarandi et al., 2019).

Both REBA and RULA use snapshot observations, which lead to subjective interpretations and do not accurately reflect the evolving ergonomic risks of different work activities during the period (Graben et al., 2022). RULA is not designed to assess

the overall ergonomic suitability of office workstation arrangements as it only covers one side of the body and primarily upper limb and neck postures (Kee, 2022). Use of ROSA to assess office workstation arrangements must be carried out by an observer with expertise and training in the field. The tool needs further validation to set more specific action levels (Sonne et al., 2012). Most office ergonomics studies rely on subjective assessment, such as pain and discomfort. There is limited evidence that standardised methods of workstation assessment are effective in reducing ergonomic risk factors (Barros et al., 2022). These tools do not offer a systematic and clear component-based approach to overall ergonomic compliance for office workstation arrangements.

## 3. METHODOLOGY

A comprehensive literature review was conducted to identify the ergonomic performance indicators for evaluating office workstation arrangements. Expert validation was conducted to assess the applicability and relevance of the identified ergonomic performance indicators in evaluating workstation arrangements. Interviews were conducted with eleven experts in ergonomics and occupational health, who have more than 10 years of experience in Sri Lanka and the international context. The selection of experts was based on the number of years of professional experience in the field of ergonomics and occupational health, as well as on academic qualifications in the field. Table 1 demonstrates the profile of expert interviewees.

*Table 1: Profile of experts*

| Expert | Designation | Years of experience |
|---|---|---|
| E1 | Specialist in Occupational Health and Wellbeing | 15 years |
| E2 | Occupational Health Specialist | 29 years |
| E3 | Probationary lecturer in Occupational therapy | 13 years |
| E4 | Principal of the School of Physiotherapy and Occupational Therapy | 26 years |
| E5 | Occupational Therapist | 26 years |
| E6 | Occupation Health Physician | 10 years |
| E7 | Senior lecturer (Specialization in Ergonomics) | 30 years |
| E8 | Physiotherapist | 10 years |
| E9 | Occupational therapist | 21 years |
| E10 | Senior lecturer (Specialization in Design and Ergonomics) | 25 years |
| E11 | Physiotherapist | 26 years |

The interviews with the experts were conducted in two stages to ensure the reliability, accuracy and validity of the indicators. In the first round, a structured interview guideline was used as the primary data collection method to gather expert opinions on the identified indicators. Manual content analysis was used to analyse the responses received from this round. Which were systematically coded into the type of recommendation, such as retain, modify, remove and add. Based on this analysis, controlled feedback was developed and presented to the experts in the second round of interviews. In this round, the experts were allowed to revise their initial opinions based on the feedback from the first-round expert opinions. This repetitive cycle facilitates the finding of consensus between the experts.

The final decision on each indicator, including acceptance, rejection or modification, was determined in the second round using a consensus threshold. With at least seven respondents out of eleven (majority) approving the decision, while considering the qualitative justifications provided by the experts.

# 4. RESEARCH FINDINGS

## 4.1 EVALUATING ERGONOMIC PERFORMANCE INDICATORS

Expert interviews were conducted to validate each performance indicator on its importance in evaluating office workstation arrangements. E3 suggested including a footrest as a separate workstation component. The majority indicated that it is not mandatory and is only required when workstation adjustments do not allow the user's feet to rest on the floor.

### 4.1.1 Office Chair

E1 and E6 suggested specifying a knee angle range instead of a fixed 90° angle during seating. E1, E7, and E9 recommend a range of 90°-105° knee angle. However, the majority agreed that "maintaining approximately 90° minimizes pressure on the lower back and thighs while allowing feet to move freely". E8 highlighted that "hips and knees are positioned at approximately 90 angles to minimize pressure on the lower back and thighs. While 90° is preferred, a knee angle between 90° and 120° is acceptable if this posture cannot be maintained".

'Seat pan should be depth adjustable' was removed as most of the experts mentioned it as not a mandatory ergonomic requirement, since fixed depth ergonomically adequate in practice. However, E4 mentions that "back support should be movable with the seat pan". to maintain proper lumbar alignment. E4 mentioned that a one-inch gap should be maintained between the seat pan edge and the back of the knees, whereas other experts recommended a three-inch gap. E5 mentioned, "there should be a space approximately the width of a clenched fist between the front edge of the seat and the back of your knees".

E10 highlighted that "adjustability of lumbar support may not be necessary, as anthropometric variations in the Sri Lankan context are relatively small, but it should be included". However, most respondents agree that lumbar support should be adjustable. E5 mentioned that "backrest recline angle greater than 110° to enable occasional relaxation". E6 and E11 indicated that a backrest adjustable between 95 -110° is suitable for relaxation rather than active work, whereas E8 recommended a backrest angle of around 95° to support dynamic sitting. Accordingly, this indicator remained unchanged based on the majority vote of the experts. The indicator 'Backrest with a recline angle exceeding 120°, including a headrest' was removed, as most experts indicated that this condition is mainly suitable for resting. This is not a necessary ergonomic requirement for active work. However, E6 suggested 'providing an adjustable headrest' to support high-back chairs. This was supported by the majority.

Most experts proposed that the armrests should support the elbows at slightly more than a 90° angle. However, E7 observed that angles above 90° may be comfortable for seating but are not ideal for active work. E9 and E11 suggested a preferred range of angles as 90° - 95°. According to the majority, an elbow angle slightly greater than 90° was deemed to be appropriate. E1 suggested including the indicator "Armrests keep the arms close to the

body with slight shoulder abduction." Most experts agreed with maintaining slight shoulder abduction without excessive shoulder elevation or abduction.

#### 4.1.2 Desk and Work Surface

E1 suggested, "desk height allows approximately 90° elbow height with forearms parallel to the floor". Although majority of experts supported, as the seat height must be adjustable where the elbow height is at the desk level. E1 recommended that "the work surface have a non-reflective finish to minimize glare and reduce visual strain", which was agreed by majority.

#### 4.1.3 Monitor

E11 highlighted, "the monitor viewing distance should change based on the user's feasibility". However, many experts agreed that the monitor should be positioned at arm's length. E4 mentioned that "the monitor should not be positioned directly under a light source" to avoid glare, while E10 highlighted that "the light source should ideally be positioned behind the user".

#### 4.1.4 Keyboard

E8 mentioned that "the keyboard should be centered in front of the user and positioned either flat or angled slightly away from the user", most experts preferred positioning it at desk level. E8 noted that "when an adjustable keyboard tray is used, the tray's edge should be parallel to the user's forearms".

E4 highlighted that "the wrists should remain straight without side deviation to maintain proper ergonomic posture, as side deviations strain tendons and muscles in the wrist and forearm". Accordingly, the indicator was revised to state that 'the keyboard should allow wrists to remain straight without side deviations', reflecting the majority opinion.

#### 4.1.5 Mouse

E8 mentioned, "mouse size and shape should allow relaxed grip without excessive finger extension or palm compression". E7 highlighted that "the mouse should be positioned with slight shoulder abduction rather than in line with the shoulders, as it's uncomfortable during use". E8 further noted that "the mouse should be moved with the user's entire arm. When using the keyboard or mouse, the arms should be kept close to the body". Based on the majority opinion, the indicator was amended to 'Mouse positioned with slight shoulder abduction, with the arm kept close to the body'.

#### 4.1.6 Workstation Accessories

E1 recommended "placing the telephone within arm's reach in the primary working zone", and most experts agreed it should be positioned at arm's length for user convenience.

The final ergonomic performance indicators, incorporating literature findings and expert amendments, are summarized in Table 2.

*Table 2: Summary of ergonomic performance indicators for evaluating office workstation arrangements*

| Component | Performance Indicator (Literature) | Source | Comment from Experts | Final Indicator |
|---|---|---|---|---|
| Work chair | Seat height adjustable | [1] | - | Seat height adjustable |
| | Seat height allows knees bent at approximately 90° | [2] | Maintaining a constant 90° knee angle may reduce comfort; therefore, the indicator was revised to allow free foot movement | Seat height allows knees bent at approximately 90° while letting the feet move freely |
| | The seat height allows the feet to rest flat on the floor or on a footrest | [1],[3] | - | The seat height allows the feet to rest flat on the floor or on a footrest |
| | Seat depth allows approximately 3-inch clearance behind the knees | [2] | - | Seat depth allows approximately 3-inch clearance behind the knees |
| | Seat pan should be depth adjustable | [1] | Removed, as it was not considered a mandatory performance indicator | Removed |
| | Rounded waterfall seat pan edge provided | [1] | - | Rounded waterfall seat pan edge provided |
| | Seat pan should be made with dense foam and a breathable covering | [4] | - | Seat pan should be made with dense foam and a breathable covering |
| | Backrest design provides lumbar and upper back support | [5] | - | Backrest design provides lumbar and upper back support |
| | Height adjustable lumbar support | [1] | - | Height adjustable lumbar support |
| | Backrest adjustable between 95 - 110° | [2] | - | Backrest adjustable between 95 -110° |
| | Armrests are adjustable in height | [6] | - | Armrests are adjustable in height |

| Component | Performance Indicator (Literature) | Source | Comment from Experts | Final Indicator |
|---|---|---|---|---|
| | Armrest allows the elbow bent between 90 - 120° | [1] | An angle slightly greater than 90° improves comfort, as 120° was considered too high | Armrests support the elbows with the elbow bent at 90° or slightly greater |
| | Armrests are wide enough to allow easy entry to and exit from the chair | [1] | - | Armrests are wide enough to allow easy entry to and exit from the chair |
| | - | - | Armrests support the arms close to the body in a relaxed posture, without excessive shoulder abduction | Armrests keep the arms close to the body with slight shoulder abduction |
| | Armrests should be made of a soft material and have rounded edges | [1] | - | Armrests should be made of a soft material and have rounded edges |
| | Backrest with recline angle exceeding 120°, includes a headrest | [6] | Modified to specify an adjustable headrest, considering its relevance during both resting and working | There should be an adjustable headrest |
| | Five-point stable chair base (casters) | [6] | - | Five-point stable chair base (casters) |
| Work desk | Desk height allows approximately 90° elbow bent with forearms parallel to the floor | [3] | The desk height is at elbow level | Desk height should be approximately at elbow height, with forearms parallel to the floor |
| | Provides sufficient foot clearance for seated users | [6] | - | Provides sufficient foot clearance for seated users |
| | No contact between the upper thighs and structures beneath the work surface | [1] | - | No contact between the upper thighs and structures beneath the work surface |

| Component | Performance Indicator (Literature) | Source | Comment from Experts | Final Indicator |
|---|---|---|---|---|
| | Desk depth allows frequently used items to be placed within the primary work zone | [6] | - | Desk depth allows frequently used items to be placed within the primary work zone |
| | - | - | Reflective surfaces can cause glare | Work surface should have a non-reflective finish |
| | Desk edges rounded (no sharp edges) | [1] | - | Desk edges rounded (no sharp edges) |
| Monitor / Visual display | The top of the screen is at or slightly below eye level | [2] | - | The top of the screen is at or slightly below eye level |
| | Monitor viewing distance maintained at arm's length | [2] | - | Monitor viewing distance maintained at arm's length |
| | Monitor positioned directly in front of the user | [1] | - | Monitor positioned directly in front of the user |
| | Monitor tilt is adjustable with a slight backward tilt | [7] | - | Monitor tilt is adjustable with a slight backward tilt |
| | Screen height is adjustable using an articulating arm, screen riser or relevant mechanism | [3] | - | Screen height is adjustable using an articulating arm, screen riser or relevant mechanism |
| | Monitor is positioned perpendicular to the windows and between the overhead light panels | [4] | - | Monitor is positioned perpendicular to the windows and between the overhead light panels |
| | Use of blinds, light diffusers, anti-glare screens to minimize glare/reflection | [1] | - | Use of blinds, light diffusers, anti-glare screens to minimize glare/reflection |

| Component | Performance Indicator (Literature) | Source | Comment from Experts | Final Indicator |
|---|---|---|---|---|
| Keyboard | Keyboard has a flat or near-flat slope | [1] | - | Keyboard has a flat or near-flat slope |
| | Keyboard directly in front of the user | [1] | - | Keyboard directly in front of the user |
| | - | - | Recommended to place on desk/surface with the forearms parallel to the floor | Keyboard placed at desk/surface height |
| | Keyboard positioning allows the wrists to be straight | [8] | Side deviation leads to wrist strain | Keyboard allows the wrists to be straight and no side deviations |
| Mouse | The mouse should be positioned on the same level as the keyboard | [9] | - | The mouse should be positioned on the same level as the keyboard |
| | The mouse should be positioned at the operator's side with the arm close to the body | [5] | The mouse is used with full arm movement and slight relaxed shoulder abduction | Mouse positioned with the slightly abducted shoulder, with the arm kept close to the body |
| | Mouse size is appropriate to fit the user's hand | [2] | - | Mouse size is appropriate to fit the user's hand |
| | Mouse allows the user to maintain a straight, neutral wrist posture | [1] | - | Mouse allows the user to maintain a straight, neutral wrist posture |
| Accessories | Telephone is positioned within 300 mm reach | [2] | Place the telephone within arm's reach for user convenience | Telephone is positioned within arm's reach |
| | Headset provided for frequent telephone users | [1] | - | Headset provided for frequent telephone users |

[1] - OSHA, [2] - CSA (2000), [3] - McKeown (2007), [4] - Occupational Health Clinics for Ontario Workers (2021), [5] - Herman & Watchman (1997), [6] - Human Factors and Ergonomics Society (2007), [7] – Western Connecticut State University, [8] - Sonne et al. (2012), [9] - Chandra et al. (2009)

This study only identifies ergonomic performance indicators that have been validated by experts, which would serve as a foundation for developing a comprehensive ergonomic

evaluation assessment tool for computer workstation arrangements. It can be applied in the industry to evaluate computer workstations in a systematic manner.

## 5. CONCLUSIONS

This paper aims to identify and validate ergonomic performance indicators to assess office workstation ergonomics. A comprehensive set of performance indicators was first identified through a literature review from established standards/guidelines and peer-reviewed sources. Secondly, performance indicators obtained through the literature were improved through various contextually significant amendments suggested by the experts. The final ergonomic performance indicators, with literature findings and expert amendments, are fully summarised in Table 2 of the present paper.

There are few limitations that should be acknowledged when interpreting the results of this study. The framework is designed specifically for seated office computer users, and its applicability to standing workstations and hybrid work environments is beyond the scope of this study. The availability of the entire set of internationally ergonomic standards and guidelines was restricted at the literature review stage. The specialist validation was performed in the Sri Lankan context, where a limited pool of experts who possess dedicated ergonomic expertise is found.

This developed framework would have significant practical implications for a wide group of stakeholders. This allows the systematic analysis of workstation deficiencies and implementation of appropriate workstation adjustments. Moreover, the framework can easily be integrated into the office ergonomic policies, induction programmes and the routine workstation audit processes. Hence, it is a flexible tool that is used to foster a culture of ergonomic awareness and active workstation management in various organisational contexts.

Further studies are needed to create and test a standardised ergonomic assessment checklist or digital audit tool using the ergonomic indicators discussed in the current paper, which will allow a more consistent and scalable field implementation.

## 6. REFERENCES

Ankamah-Lomotey, S. A. (2025). Ergonomic design of workstations: Investigating the impact of ergonomic design on employee comfort, productivity and health. *International Journal of Current Business and Social Sciences*, *11(4)*, 59-72. https://doi.org/10.3390/su17219545

Barros, F. C., Moriguchi, C. S., Chaves, T. C., Andrews, D. M., Sonne, M., & de Oliveira Sato, T. (2022). Usefulness of the rapid office strain assessment (ROSA) tool in detecting differences before and after an ergonomics intervention. *BMC Musculoskeletal Disorders*, *23*(1), 526. https://doi.org/10.1186/S12891-022-05490-8

Berenyi, L., Szolnoki, B., & Banhegyesi, L. (2015). Office work: Ergonomic and medical aspects. *European Scientific Journal*, *11*(2). https://www.researchgate.net/publication/326589202_OFFICE_WORK_ERGONOMIC_AND_MEDICAL_ASPECTS

Berner, K., & Jacobs, K. (2002). The gap between exposure and implementation of computer workstation ergonomics in the workplace. Work, *19*(2), 193–199. https://doi.org/10.3233/WOR-2002-0024

Canadian Standards Association Group (CSA). (2000). *CSA-Z412-00 (R2011): Guideline on office ergonomics*. *https://webstore.ansi.org/standards/csa/csaz4122000r2005*

Carlson, N. G., Schwartz, A., Greenwell, J., & Casura, G. (2019). The office changes leading to sit-to-stand ergonomics. *Work*, *61*(4), 501–507. https://doi.org/10.3233/WOR-182820

Chandwani, A., Chauhan, M. K., & Bhatnagar, A. (2019). Ergonomics assessment of office desk workers working in Corporate Offices. *International Journal of Health Sciences & Research*, *9*(8), 367-375. https://www.ijhsr.org/IJHSR_Vol.9_Issue.8_Aug2019/IJHSR_Abstract.051.html

Chandra, A., Chandna, P., Deswal, S., & Kumar, R. (2009). Ergonomics in the office environment: A review. *Proceedings of International Conference on Energy and Environment* (pp.913–919). https://www.researchgate.net/profile/Surinder_Deswal/publication/270888471_Ergonomics_in_the_Office_Environment_A_Review/links/54b7c0960cf2bd04be33c6d8.pdf

Cook, C. J., & Kothiyal, K. (1998). Influence of mouse position on muscular activity in the neck, shoulder and arm in computer users. *Applied Ergonomics*, *29*(6), 439–443. https://doi.org/10.1016/S0003-6870(98)00008-8

Daneshmandi, H., Choobineh, A., Ghaem, H., & Karimi, M. (2017). Adverse effects of prolonged sitting behavior on the general health of office workers. *Journal of Lifestyle Medicine*, *7*(2), 69. https://doi.org/10.15280/jlm.2017.7.2.69

Gerr, F., Marcus, M., & Monteilh, C. (2004). Epidemiology of musculoskeletal disorders among computer users: Lesson learned from the role of posture and keyboard use. *Journal of Electromyography and Kinesiology*, *14*(1), 25–31. https://doi.org/10.1016/j.jelekin.2003.09.014

Graben, P. R., Schall, M. C., Gallagher, S., Sesek, R., & Acosta-Sojo, Y. (2022). Reliability analysis of observation-based exposure assessment tools for the upper extremities: A systematic review. *International Journal of Environmental Research and Public Health*, *19*(17), 10595. https://doi.org/10.3390/IJERPH191710595

Herman, A. M., & Watchman, G. R. (1997). *Working safely with video display terminals*. https://chemistry.osu.edu/sites/chemistry.osu.edu/files/OSHA%20Working%20Safely%20With%20Video%20Display%20Terminals.pdf

Human Factors and Ergonomics Society. (2007). *Human factors engineering of computer workstations.* https://www.hfes.org/Publications/Technical-Standards

International Ergonomics Association and Human Factor Association. (n.d.). *What is ergonomics (HFE).* IEA. https://iea.cc/about/what-is-ergonomics/

Kar, G., & Hedge, A. (2021). Effect of workstation configuration on musculoskeletal discomfort, productivity, postural risks, and perceived fatigue in a sit-stand-walk intervention for computer-based work. *Applied Ergonomics*, *90*, 103211. https://doi.org/10.1016/j.apergo.2020.103211

Khan, M., & Pope-Ford, R. (2015). Improving and modifying the design of workstations within a manufacturing environment. *Procedia Manufacturing*, *3*, 4927–4934. https://doi.org/10.1016/j.promfg.2015.07.631

Kee, D. (2022). Systematic comparison of OWAS, RULA, and REBA based on a literature review. *International Journal of Environmental Research and Public Health*, *19*(1), 595. https://doi.org/10.3390/ijerph19010595

Lee, S., de Barros, F. C., de Castro, C. S. M., & de Oliveira Sato, T. (2020). Effect of an ergonomic intervention involving workstation adjustments on musculoskeletal pain in office workers a randomized controlled clinical trial. *Industrial Health*, *59*(2), 78-85. https://doi.org/10.2486/indhealth.2020-0188

Makhbul, Z. M. (2013). Workplace environment towards emotional health. *International Journal of Academic Research in Business and Social Sciences*, *2*(1), 196-211.

Matos, M., & Arezes, P. M. (2015). Ergonomic evaluation of office workplaces with rapid office strain assessment (ROSA). *Procedia Manufacturing*, *3*, 4689–4694. https://doi.org/10.1016/j.promfg.2015.07.562

McAtamney, L., & Nigel Corlett, E. (1993). RULA: A survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*(2), 91–99. https://doi.org/10.1016/0003-6870(93)90080-S

McKeown, C. (2007). *Office ergonomics - Practical Applications*. Taylor & Francis.

Mishra, S., & Narendra, P. (2020). An overview of ergonomics. *Journal of Ergonomics Research*, *3*(1), 1–3. https://doi.org/10.37532/jeor.2020.3(1).111

Mohammadian, M., Mollahoseini, S., & Naghibzadeh-Tahami, A. (2025). Musculoskeletal disorders among office workers: prevalence, ergonomic risk factors, and their interrelationships. *Scientific Reports*, *15*(1), 45425. https://doi.org/10.1038/s41598-025-30155-6

Occupation Safety and Health Branch Labour Department. (2010). *A guide to work with computers.* https://www.labour.gov.hk/eng/public/oh/DisplayScreen.pdf

Occupational Health Clinics for Ontario Workers. (2021). *Office ergonomics reference guideline*. https://www.ohcow.on.ca/wp-content/uploads/2021/09/ergo_guide_print_FINAL.pdf

Occupational Safety and Health Administration. (n.d.). *Computer workstations eTool*. Occupational Safety and Health Administration.

Shahwan, B., D'emeh, W., & Yacoub, M. (2021). Evaluation of computer workstations ergonomics and its relationship with reported musculoskeletal and visual symptoms among university employees in Jordan. *International Journal of Occupational Medicine and Environmental Health*, *35*(2), 141–156. https://doi.org/10.13075/ijomeh.1896.01822

Skilling, E. J. (2016). Workstation, work area, and console design. *Human factors in the chemical and process industries: Making it work in practice* (pp.205–221). https://doi.org/10.1016/B978-0-12-803806-2.00012-1

Sonne, M., Villalta, D. L., & Andrews, D. M. (2012). Development and evaluation of an office ergonomic risk checklist: ROSA – Rapid office strain assessment. *Applied Ergonomics*, *43*(1), 98–108. https://doi.org/10.1016/j.apergo.2011.03.008

Suchitra, V. G., Vijayan, V., & Faseela, C. K. (2025). A study on the impact of workplace ergonomics on employee productivity. *EPRA International Journal of Multidisciplinary Research (IJMR)*, *11*(12), 681–685. https://doi.org/10.36713/epra25484

Van Niekerk, S., Louw, Q. A., & Hillier, S. (2012). The effectiveness of a chair intervention in the workplace to reduce musculoskeletal symptoms. A systematic review. *BMC Musculoskeletal Disorders*, *13*(1), 145. https://doi.org/10.1186/1471-2474-13-145

Western Connecticut State University. (n.d.). Ergonomic office furniture standard & information / resource guide. https://www.wcsu.edu/ehs/wp-content/uploads/sites/169/2025/05/Office-Furniture-Standard-InfoResource-Guide.pdf

Woo, E. H. C., White, P., & Lai, C. W. K. (2016). Ergonomics standards and guidelines for computer workstation design and the impact on users' health - A review. *Ergonomics*, *59*(3), 464–475. https://doi.org/10.1080/00140139.2015.1076528

Yarandi, M. S., Soltanzadeh, A., Koohpaei, A., Sajedian, A. A., Ahmadi, V., Sakari, S., & Yazdanirad, S. (2019). Effectiveness of three ergonomic risk assessment tools, namely NERPA, RULA, and REBA, for screening musculoskeletal disorders. Archives of Hygiene Sciences, *8*(3), 188–201. https://doi.org/10.29252/ARCHHYGSCI.8.3.188

Prakash, T.S. and Murugkar, K., 2026. Thermal performance evaluation of vernacular roofing systems in contemporary buildings. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 702-713. DOI: https://doi.org/10.31705/WCS.2026.52. Available from: https://ciobwcs.com/papers/

# THERMAL PERFORMANCE EVALUATION OF VERNACULAR ROOFING SYSTEMS IN CONTEMPORARY BUILDINGS

**T. S. Prakash[1] and K. Murugkar[2]**

## *ABSTRACT*

*This study explores the thermal performance of three vernacular roofing systems—Filler Slab, Hourdi Roof, and Jack Arch Roof—in the moderate climate of Bangalore, India. The objective was to evaluate and compare the thermal performance of these roofing systems under peak summer conditions. Temperature data were continuously monitored during the hottest month, April, using an eight-channel data logger that recorded outdoor air temperature, indoor air temperature, and roof surface temperatures. To evaluate thermal performance, two indicators were used: Maximum Temperature Difference (MTD), which measures the largest temperature difference between the outer and inner roof surfaces, and Temperature Difference Ratio (TDR), which reflects the roof's ability to reduce the impact of outdoor temperature fluctuations. The results showed clear differences in the thermal behavior of the three roofing systems. The Filler Slab Roof achieved the highest average TDR (0.451) and MTD (25.85°C), indicating the strongest resistance to heat transfer and the greatest ability to moderate external heat gains. The Jack Arch Roof also performed well, with a comparable TDR and MTD. The Hourdi Roof, however, recorded the lowest TDR and MTD, suggesting a comparatively lower capacity to resist heat flow under the climatic conditions studied. Overall, the findings indicate that the Filler Slab Roof offers the best thermal performance among the three vernacular roofing systems. These results highlight the continued relevance of vernacular roofing strategies and their potential application in contemporary sustainable architecture and energy-efficient building design.*

***Keywords:*** *Maximum Temperature Difference (MTD); Temperature Difference Ratio (TDR); Vernacular Roofing.*

## 1 INTRODUCTION

Cities are experiencing rapid increases in temperatures year after year. Modern buildings, primarily constructed from Reinforced Concrete (RC) and steel, often trap rather than deflect heat, resulting in higher indoor temperatures and increased energy consumption. As a result, dependence on fans, coolers, and air conditioning is increasing, thereby raising household energy costs and carbon emissions (India Energy Outlook 2021 World Energy Outlook Special Report, 2021). However, long before mechanical cooling systems were invented, traditional builders effectively used local materials and methods to manage thermal comfort (Srivastava & Das, 2023). Roofs are among the most critical

[1] Research Scholar, College of Architecture, Bharati Vidyapeeth University, India, sahana315@gmail.com
[2] Principal & Professor, College of Architecture, Bharati Vidyapeeth University, India, kavita.murugkar@bharatividyapeeth.edu

elements because they receive the greatest solar exposure, which contributes significantly to a building's heat gain. They often account for 50–70% of the total heat transfer into single-story buildings (Sharma & Sharma, 2023). The way a roof is designed its material composition, surface colour, thickness, ventilation strategy, and layering directly shapes indoor thermal comfort. When carefully designed, a roof can serve as a thermal buffer, reducing heat transfer during the day and releasing it gradually at night (Sharma et al., 2018). Traditional systems often relied on thermal mass and shading to regulate heat flow, but in recent decades, new approaches have emerged that combine vernacular knowledge with modern technology. Vernacular roofing can be seen as an evolved form of traditional roofing, characterised by context-specific design responses to environmental and cultural factors. These roofing systems, when rigorously evaluated for their thermal properties, can become integral to both contemporary Green building strategies and future innovations in climate-responsive design (Choi & Lee, 2015).

While many studies have explored passive cooling in buildings, very few have conducted on-field monitoring of vernacular roofs. Most prior research focuses on short-term experiments or thermal simulations (Singh et al., 2010), with limited attention to roofs. Additionally, seasonal variations in urban climates are rarely examined. In Bangalore, despite being considered a moderate-climate city, summer heat waves affect occupant comfort (Indian Meteorological Department, n.d.). Still, systematic monitoring of vernacular roof performance in this region is limited. This study aims to evaluate the thermal performance of several vernacular roofing systems, such as filler slab, jack arch roof, and Hourdi roof, in Bangalore. The objective of this study, which uses hourly surface and ambient temperature measurements over the summer critical month, is to compare the thermal properties of those roofing systems.

# 2 LITERATURE

## 2.1 VERNACULAR ROOFING

Vernacular roofing methods, such as jack-arch roofs and filler-slab constructions, were driven by functional performance rather than aesthetic style. These systems efficiently balanced thermal mass delaying heat transfer and natural insulation, thereby reducing indoor temperature fluctuations (Rawat & Singh, 2021). For example, mud and earth roofs, with their high thermal capacity, absorb solar heat during the day and release it at night, while jack arches utilise air cavities to reduce conduction. These roofs often utilise locally sourced materials and construction techniques to enhance natural thermal comfort (Srivastava & Das, 2023). With the increasing focus on sustainable design, such strategies are being reconsidered as alternatives to RCC slabs, which are energy-intensive to produce and less effective at controlling heat transfer. However, much of the current appreciation is based on observations rather than systematic analysis, with limited quantitative evaluation. Studying these roofing systems can provide invaluable insights into sustainable building design.

## 2.2 PREVIOUS STUDIES ON THERMAL PERFORMANCE OF VERNACULAR ROOFING

The thermal role of roofing in buildings has long been recognised. Globally, vernacular systems were designed to protect against climatic extremes without the aid of mechanical devices. Mediterranean adobe domes, for instance, demonstrated strong thermal

resistance by maintaining cooler interiors in summer. In Southeast Asia, steeply pitched thatch roofs enhanced ventilation and minimised overheating, while African earth-and-thatch systems reduced diurnal indoor fluctuations. These studies highlight vernacular ingenuity but often remain qualitative, focusing on cultural or morphological descriptions rather than rigorous thermal metrics. In the Indian context, research has examined traditional roof typologies across climatic zones. Mud roofs in Assam and Himachal Pradesh have been reported to delay the onset of peak indoor temperatures, thereby stabilising comfort conditions (Singh et al., 2010; Sharma & Sharma, 2023). Filler slabs in Kerala and Karnataka combine reduced cement usage with improved thermal moderation compared to reinforced cement concrete (Athmarajah et al., 2017). Jack arch roofs, once common in industrial structures, have been noted for their cavity-based insulation benefits. However, systematic performance evaluation of these systems under year-long climatic cycles remains scarce.

## 2.3 DESCRIPTION OF THE ROOFING SYSTEMS

### 2.3.1 Filler Slab with Hollow Blocks

In an RCC slab, the portion below the neutral axis is the tension zone. Concrete is good in compression and weak in tension. The concrete used in the tension zone primarily serves to cover the steel; therefore, some of it can be replaced (Jagadish et al., 2007).

*Figure 1: Image showing construction of a filler slab. Source: (Sathya Consultants, 2011)*

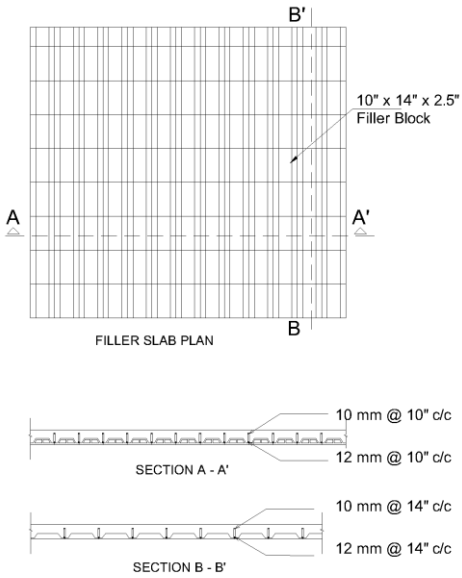



*Figure 2: Typical plan and section of a filler slab with hollow filler clay block*

Approximately 20–40% of the concrete below the neutral axis in an RCC slab can be replaced with a non-reactive material for various benefits. The material that replaces concrete is called the filler, and the slab is called the filler slab (Acharya et al., 2020). The filler material could be selected for its lower thermal conductivity, lighter weight, reduced dead load, and aesthetic appeal (Sainath & Das, 2020). Various filler materials used include Mangalore tiles, hollow clay blocks, stabilised mud blocks, and clay pots (Amit et al., 2015). For this study, a hollow clay block filler slab (locally known as Maruti blocks) is considered, with its roof section shown in figures 1 and 2.

### 2.3.2 Hourdi Roof

Hourdi blocks are crafted from natural clay and kiln-baked to produce a durable, hollow roof component. They are installed by placing them between prefabricated beams to form slabs. These blocks are lighter, which accelerates construction and removes the necessity for shuttering, unlike traditional Reinforced Cement Concrete systems. Traditionally, cross beams of stone or timber would be placed over the wall at roof level and filled in with wood planks, stone slabs, Madras terrace tiles, or flat clay tiles. (Harrison & Sinha, 1995).

*Figure 3: Image showing construction of Hourdi roof. Source: (Auroville Earth Institute, n.d.)*

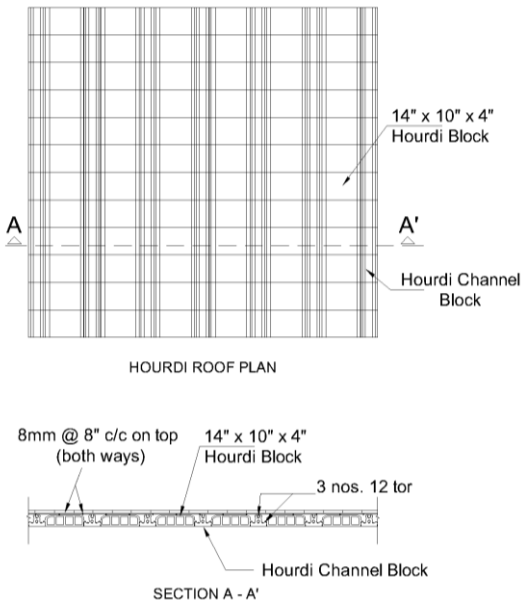



*Figure 4: Typical plan and section of Hourdi roof*

Over time, innovations led to the introduction of hollow clay blocks, known as 'Hourdi', as the infill material. The stone or timber crossbeams were replaced with precast RC inverted T-beams or precast Hourdi beam blocks (Varanashi, 2022) (refer figures 3 and 4).

### 2.3.3 Jack Arch Roof

The Jack arch masonry flooring system consists of elongated, shallow brick vaults supported on parallel steel I-beams, intermediate RC beams, or Hourdi channel beams. The spaces over the arches are then filled with concrete to create a flat floor (Maheri et al., 2012). Hollow clay blocks, known as Water-Proof Course tiles (WPC tiles), can serve as an alternative to regular bricks, potentially improving thermal performance and reducing the roof's self-weight. The intermediate beam could be cast in situ or precast, depending on the dimensions of the space to be roofed. They are spaced 1000 mm to 1500 mm centre-to-centre. The arch elevation is kept equal to 1/12 of the span (Ramesh, 2012).

*Figure 5: Image showing construction of Jack arch roof. Source: (Varanashi, 2011)*

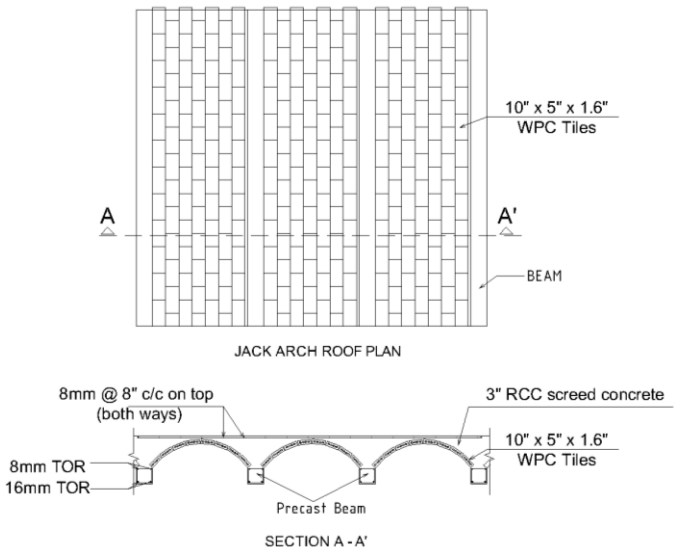



*Figure 6: Typical plan and section of Jack arch roof*

# 3 METHODOLOGY

## 3.1 RESEARCH DESIGN

This study used an experimental field-based research design to evaluate the thermal performance of three vernacular roofing systems; filler slab, jack arch, and Hourdi roof

in Bangalore, India. The focus was on quantifying roof performance using the Temperature Difference Ratio (TDR) and Maximum Temperature Difference (MTD), based on real-time temperature measurements.

## 1.2 SITE SELECTION AND CLIMATIC CONTEXT

Bengaluru is the capital city of Karnataka, located in Southern India. It is located at 12°58' N, 77°35' E, with an average elevation of 921m above sea level. Bengaluru falls under a moderate climate. The city experiences distinct summer (March–May), monsoon (June–September), and winter (October–February) periods, with average annual temperatures ranging from 15°C to 36°C (Indian Meteorological Department, n.d.). Bangalore having a moderate climate; summer is the critical season for thermal comfort. Three residences within the city were selected, with each having the above-mentioned vernacular roofs. The rooms were selected with similar orientations and were all naturally ventilated.

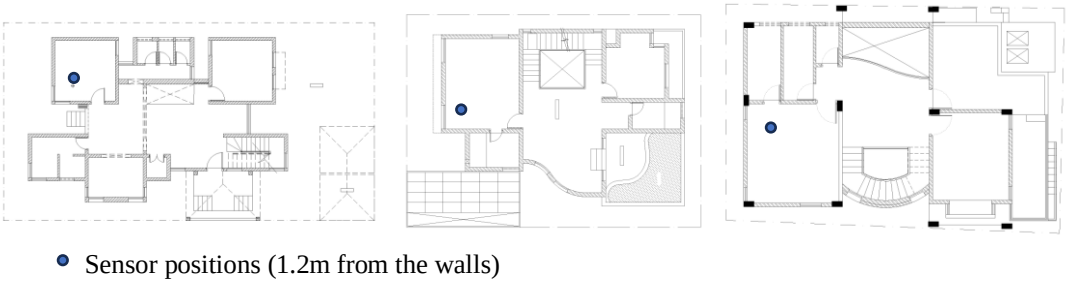



*Figure 4: Floor plans of the residences selected for case studies and the position of the sensors. Starting from the left residence with filler slab, Hourdi roof, and Jack arch roof.*

## 1.3 ROOF DETAILS

### 3.1.1 Filler Slab

The filler slab selected for the study had a thickness of 150mm. The lower part of the slab consisted of hollow clay filler blocks of dimensions 254mm x 355.6mm x 63.5mm. On top of this layer was reinforced concrete of 86.5mm thickness. The filler blocks consist of 60% burnt clay and 40% void.

### 3.1.2 Hourdi Roof

Hourdi roof selected for the study had a thickness of 150mm. The lower part consisted of hollow clay Hourdi blocks of dimensions 355.6mm x 254mm x 101.6mm. On top of this was a 50.8mm thick reinforced concrete layer. Hourdi blocks are composed of 42% burnt clay and 58% void.

### 3.1.3 Jack Arch Roof

The jack arch that was studied had arches of width 1200mm, with intermediate beams of width 152mm and depth 305mm. The arch was built using water-proof course tiles (WPC tiles) with a burnt-clay volume of 80% and a remaining 20% void. On top of this layer was a 50mm-thick concrete screed (at the centre of the arch).

## 3.4 INSTRUMENTATION AND DATA COLLECTION

### 3.1.4 Temperature Measurement

An eight-channel data logger was used to record outdoor and indoor ambient temperatures, as well as outer and inner roof surface temperatures. Thermocouples were securely fixed to surfaces to ensure accurate readings. Temperatures were recorded hourly throughout the critical summer month of April 2025 in Bangalore.

*Figure 4: An 8-channel data logger*

The sensors for outer ambient temperature were mounted in the shade over the roof; the sensors for outer surface temperature were mounted on the roof surface, ensuring no shadow fell on them. The sensors for the inside ambient temperature were mounted half a meter below the roof, and the sensors for the inside surface temperature were mounted exactly below the position of the outer surface temperature sensors. The sensors were positioned 1.2m from the walls.

### 3.1.5 Performance Indicators

**Temperature Difference Ratio (TDR)**

TDR is computed as the ratio of the indoor–outdoor temperature difference to the outdoor variation at a given time step:

$$TDR = (T_{max_out} - T_{max_in}) / (T_{max_out} - T_{min_out}) \qquad (01)$$

Where $T_{max_out}$ = Maximum outside ambient temperature, $T_{max_in}$ = Maximum inside ambient temperature, and $T_{min_out}$ = Minimum outside ambient temperature.

Higher TDR values indicate greater roof resistance and more effective temperature damping under changing external loads (Amos-Abanyie et al., 2013).

**Maximum Temperature Difference (MTD)**

MTD is the maximum instantaneous difference between the outer and inner roof surface temperatures over the course of a day (Ali & RehmanS, 2020).

$$MTD = Max\ (T_{surf\text{-}out} - T_{surf\text{-}in}) \qquad (02)$$

Where $T_{surf\text{-}out}$ = outer roof surface temperature, $T_{surf\text{-}in}$ = inner roof surface temperature.

Higher MTD indicates that the roof is effectively resisting heat flow through its thickness and preventing heat from reaching the inner surface. Thus, higher MTD values indicate lesser heat flow and better thermal insulation (Koenigshberger, 2010).

# 4 RESULTS AND DISCUSSIONS

The thermal performance of three vernacular roof types; filler slab, Hourdi roof, and jack arch roof were evaluated through a real-time field study of three residences in Bangalore, a moderate climatic zone. Hourly data were collected for April, the critical summer month, as it represents the period of maximum solar gain and thermal stress. The results were compared using TDR proposed by Givoni and MTD between the indoor and outdoor. In this comparison, higher MTD and TDR indicate better thermal performance (Ali & Rehman S, 2020). These indices collectively indicate each roof system's ability to moderate heat, withstand high temperatures, and effectively reduce heat gain.

## 4.1 TEMPERATURE DIFFERENCE RATIO (TDR)

In this study, the filler slab roof recorded the highest TDR, followed by the jack arch roof. The higher TDR of the filler slab suggests it attenuates the outer-to-inner temperature difference more effectively during outdoor fluctuations, even though its absolute inner temperatures are higher. The comparative chart (refer Figure 5) shows that the TDR values of the Jack arch roof are quite close to those of the Filler slab.

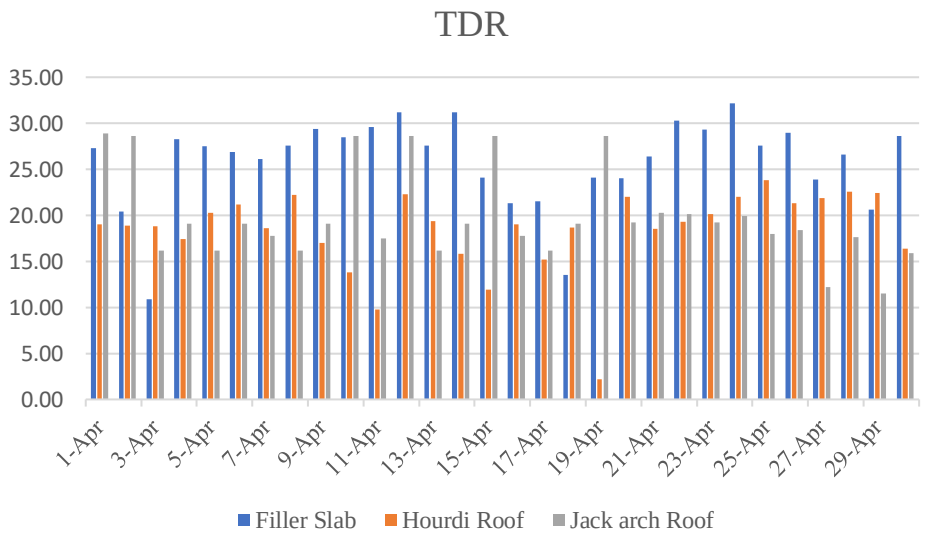



*Figure 5: Chart showing the TDR values of all three vernacular roofs.*

Thus, indicating that both the Filler slab and the Jack arch roof may offer better heat resistance.

## 4.2 MEAN TEMPERATURE DIFFERENCE (MTD)

In this study, the Filler slab had the highest MTD across many days. Hourdi roof and Jack arch seem to have similar MTD values, but they are lower than those of the filler slab. This indicates that the filler slab maintains a larger average temperature difference across its section, meaning less heat enters the interior over time. The filler slab, with terracotta fillers and a continuous concrete layer on the exterior, provides good thermal mass, reducing heat conduction. The Jack arch roof and hourdi roof, made of hollow clay blocks with a thin concrete layer on top, perform moderately, benefiting from air voids yet limited by the thin thermal barrier.

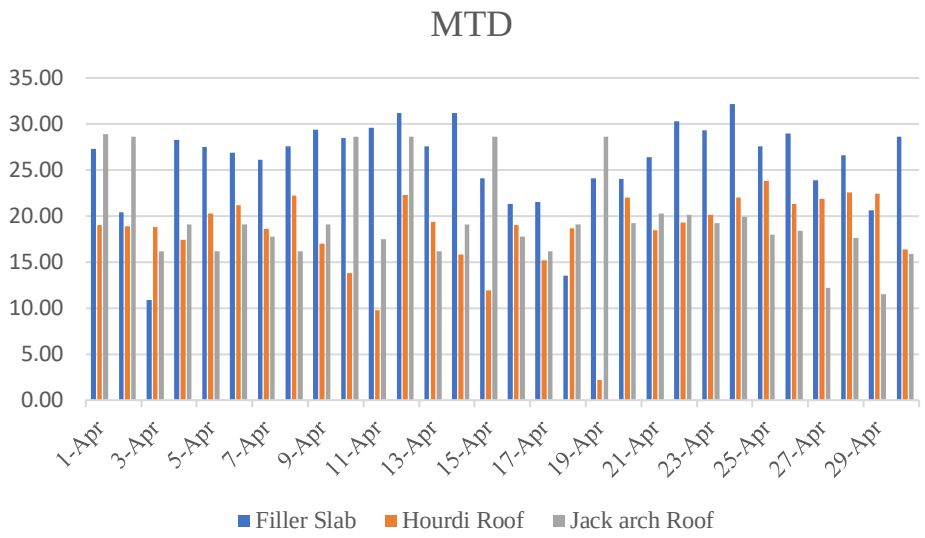



*Figure 6: Chart showing the MTD values of all three vernacular roofs.*

## 4.3 Discussion of Findings

The descriptive statistics indicate that the Filler Slab Roof has the best thermal performance among the vernacular roofing systems studied. It has the highest Temperature Difference Ratio (0.451), indicating a strong reduction in peak outdoor temperatures, and the highest Maximum Temperature Difference (25.85°C), reflecting a strong thermal gradient and increased resistance to heat transfer.

**Statistics**

| | | Filler_TDR | Filler_MTD | Hourdi_TDR | Hourdi_MTD | Jackarch_TDR | Jackarch_MTD |
|---|---|---|---|---|---|---|---|
| N | Valid | 30 | 30 | 30 | 30 | 30 | 30 |
| | Missing | 0 | 0 | 0 | 0 | 0 | 0 |
| Mean | | .4510 | 25.8500 | .2300 | 18.3933 | .4357 | 19.7933 |
| Median | | .4850 | 27.4000 | .2350 | 19.0000 | .4400 | 19.1000 |
| Std. Deviation | | .09887 | 4.87341 | .10079 | 4.47298 | .10546 | 4.92537 |
| Minimum | | .20 | 10.90 | -.20 | 2.20 | .27 | 11.50 |
| Percentiles | 25 | .4050 | 23.9750 | .1975 | 16.8500 | .3975 | 16.2000 |
| | 50 | .4850 | 27.4000 | .2350 | 19.0000 | .4400 | 19.1000 |
| | 75 | .5200 | 29.0750 | .2925 | 21.9250 | .4825 | 20.1500 |

*Figure 7: Comparative data analysis using a descriptive statistical method in SPSS.*

The Jack Arch Roof exhibits similar TDR values and moderate MTD values, suggesting good thermal performance. Conversely, Hourdi Roof shows the lowest values for both metrics, indicating lower thermal resistance and reduced heat transfer.

*Table 1: Interpretation of the statistical report*

| Roof Type | Mean TDR | Mean MTD | Overall Interpretation |
|---|---|---|---|
| Filler Slab | 0.4510 | 25.85 | High TDR and highest MTD |
| Hourdi Roof | 0.2300 | 18.39 | Lowest TDR and lowest MTD |
| Jack Arch Roof | 0.4357 | 19.79 | High TDR and relatively low MTD |

Overall, these findings suggest that the Filler Slab Roof provides the most effective thermal buffering under the climatic conditions studied.

### 4.4 IMPLICATIONS FOR CONTEMPORARY CONSTRUCTION

In the context of sustainable design, the findings suggest that reinterpreting vernacular roof systems, such as the filler slab, with modern materials can enhance indoor comfort while reducing reliance on mechanical cooling. The filler slab, popular for its material efficiency, also offers the added benefit of thermal insulation. The roof's thermal performance could be further improved with additional measures such as reflective coatings. Therefore, using design strategies that incorporate thermal mass and air insulation—as demonstrated by the filler slab can greatly enhance passive thermal regulation in modern architecture.

## 5 CONCLUSIONS

This study evaluated the thermal performance of three vernacular roofing systems Filler Slab, Hourdi Roof, and Jack Arch Roof through field-based temperature monitoring of residential buildings in Bangalore. Thermal performance was assessed using Maximum Temperature Difference (MTD) and Temperature Difference Ratio (TDR) during the peak summer period, representing the most thermally critical conditions of the year.

The results show that the thermal performance of each roofing system is strongly influenced by its material composition and structural design. The Filler Slab Roof had the highest average TDR and MTD values, reflecting its greater capacity to reduce outdoor temperature changes and sustain a significant thermal gradient across the roof. These features imply better resistance to heat transfer and more effective thermal buffering during intense solar exposure.

The Jack Arch Roof exhibited TDR values similar to those of the Filler Slab Roof, highlighting its ability to regulate heat transfer effectively. Its brick-vault design and built-in air cavities enhance thermal mass and slow heat flow, resulting in more consistent thermal performance. However, its MTD values were lower than those of the Filler Slab Roof, suggesting a smaller thermal gradient across the roof structure.

The Hourdi Roof had the lowest TDR and MTD values among the three systems. Although the hollow clay blocks offer some insulation and reduce short-term temperature fluctuations, the system's overall ability to reduce heat transfer was less effective than that of the Filler Slab and Jack Arch roofs under the given climate conditions.

Overall, the results indicate that the Filler Slab Roof demonstrates the highest thermal performance, followed closely by the Jack Arch Roof, while the Hourdi Roof exhibits comparatively lower thermal resistance. These findings highlight the significance of thermal mass, material composition, and roof geometry in improving the thermal efficiency of building envelopes in warm climates.

The study highlights that vernacular roofing principles remain important in modern sustainable architecture. Using traditional construction techniques with today’s materials, prefabricated parts, and innovative structural systems can significantly improve passive thermal performance while ensuring ease of construction and structural integrity. Incorporating these climate-responsive methods into current practices can help reduce

cooling energy needs and enhance occupant comfort, especially in rapidly urbanizing areas.

Future research should extend this work by combining surface temperature measurements with indoor comfort assessments, heat flux monitoring, energy simulations, and life-cycle performance evaluations to develop a more comprehensive understanding of the thermal and environmental benefits of vernacular roofing systems in contemporary buildings.

# 6 DECLARATION OF GENERATIVE AI

During the preparation of this work, the author(s) used ChatGPT to aid in structuring some of the sentences.

# 7 DECLARATION OF INTEREST

The author(s) hereby declare that there are no conflicts of interest regarding the publication of this manuscript. This includes financial, personal, or professional relationships that could have influenced the research, analysis, or interpretation of the findings. All sources of funding for the study, if any, have been fully disclosed in the manuscript.

# 8 REFERENCES

Acharya, R. R., Kishore, P., Raghuprem, M., Kini, P., Shetty, S., & Raj, A. (2020). Optimization-based feasibility study for filler slabs as a response towards the ECBC roof compliance with respect to thermal transmittance for five climatic zones of India. *Procedia Manufacturing*, *44*, 213–220. https://doi.org/10.1016/j.promfg.2020.02.224

Ali, A. M., & Rehman, S. (2020). Thermal performance of different types of roof in a naturally ventilated building in the warm and humid climate of Vijayawada. *Solid State Technology*, *63*(4), 593–598. https://www.solidstatetechnology.us/index.php/JSST/article/view/1251

Amit, M. R., Chougule, D., Manoj, M. R., & Mota, H. (2015). To study the filler slab as alternative construction technology - A review. *Journal of information, knowledge and research in civil engineering, 3*(2), 199-202.

Amos-Abanyie, S., Akuffo, F. O., & Kutin-Sanwu, V. (2013). Effects of thermal mass, window size, and night-time ventilation on peak indoor air temperature in the warm-humid climate of Ghana. *The Scientific World Journal*, *2013*(1). https://doi.org/10.1155/2013/621095

Athmarajah, G., Baskaran, K., & Thiruvarankan, P. (2017). Study on filler slab construction. In *111th Annual Sessions, Institution of Engineers Sri Lanka*. https://www.researchgate.net/publication/353519768

Auroville Earth Institute (n.d.). *Hourdi Roofing*. https://dev.earth-auroville.com/hourdi-roofing/

Choi, D.S., & Lee, M.E. (2015). Evaluation of the basic characteristics of thermal insulation performance for different parts of outer walls that considers year-on-year change. *International Journal of Applied Engineering Research*, *10*(10), 26871–26878. http://www.ripublication.com

Harrison, S. W., & Sinha, B. P. (1995). A study of alternative building materials and technologies for housing in Bangalore, India. *Construction and Building Materials*, *9*(4), 211–217. https://doi.org/10.1016/0950-0618(95)00012-5

*India energy outlook 2021 world energy outlook special report*. (2021). www.iea.org/t&c/

Indian Meteorological Department. (n.d.). *1981-2010 CLIM NORMALS (ALPHABETICAL) - IMD.*

Jagadish, K. S., Reddy, B.V.V., & Rao, K. S.N. (2007). *Alternative building materials and technologies*. New Age International Publishers.

Koenigshberger, O. H. (2010). *Manual of tropical housing and building: Climatic design*. University Press (India) Private Limited.

Maheri, M. R., Pourfallah, S., & Azarm, R. (2012). Seismic retrofitting methods for jack-arch masonry slabs. *Engineering Structures, 36*, 49–60. https://doi.org/10.1016/j.engstruct.2011.11.018

Ramesh, S. (2012). Appraisal of vernacular building materials and alternative technoligies for roofing and terracing options of embodied energy in buildings. *Energy Procedia, 14*, 1843–1848. https://doi.org/10.1016/j.egypro.2011.12.1177

Rawat, M., & Singh, R. N. (2021). A study on the comparative review of cool roof thermal performance in various regions. *Energy and Built Environment*, *3*(3), 327–347. https://doi.org/10.1016/j.enbenv.2021.03.001

Sainath, K., & Das, S. (2020). Benefits of filler slab over R.C.C. slab. *Journal of Emerging Technologies and Innovative Research, 7*(8), 1409-1412. https://www.jetir.org/view?paper=JETIR2008183

Sathya Consultants. (2011). *Reduce the concrete in filler slabs.* https://sathyaconsultants.wordpress.com/2011/08/06/reduce-the-concrete-in-filler-slabs/

Sharma, P., Sharma, S. K., & Preet, V. (2018). impact of modern construction practices as compare to traditional construction for sustainable rural houses in the northern eastern part of Rajasthan. *International Journal of Engineering Research & Technology*, *6*(11). https://www.ijert.org

Sharma, R., & Sharma, V. (2023). Thermal performance study of traditional slate roofed mud houses in the sub-tropical submontane and low hills of Himachal Pradesh. *Università Degli Studi Di Torino*. https://doi.org/10.13135/2384-8677/8940

Singh, M. K., Mahapatra, S., & Atreya, S. K. (2010). Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India. *Building and Environment*, *45*(2), 320–329. https://doi.org/10.1016/j.buildenv.2009.06.009

Srivastava, A., & Das, B. K. (2023). Vernacular architecture of India: An overview. *ISVS E-journal*, *10*(7), 435–448.

Varanashi, S. P. (2011, August). *Jack arch roofing*. The Hindu. https://www.thehindu.com/features/homes-and-gardens/jack-arch-roofing/article2399821.ece

Varanashi, S. P. (2022, March). *A roof with a fancy name.* The Hindu. https://www.thehindu.com/life-and-style/homes-and-gardens/a-roof-with-a-fancy-name/article65210963.ece

Wadu Mesthrige, J., Abeydeera, L.H.U.W., Maqsood, T. and Chandani, G.G.N., 2026. Exploring cost estimation accuracy and its implications for cost overruns and delays in small-scale construction projects: Evidence from Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 714-728. DOI: https://doi.org/10.31705/WCS.2026.53. Available from: https://ciobwcs.com/papers/

# EXPLORING COST ESTIMATION ACCURACY AND ITS IMPLICATIONS FOR COST OVERRUNS AND DELAYS IN SMALL-SCALE CONSTRUCTION PROJECTS: EVIDENCE FROM SRI LANKA

**J. Wadu Mesthrige[1], L.H.U.W. Abeydeera[2], T. Maqsood[3], G.G.N. Chandani[4]**

## *ABSTRACT*

*This study investigates the relationship between cost estimation accuracy and project outcomes, specifically cost overruns and project delays in small-scale construction projects in Sri Lanka. A qualitative research approach was adopted, supported by a descriptive-analytical, cross-sectional design. Data were collected through semi-structured interviews with construction professionals, including contractors, project managers, and quantity surveyors. Thematic analysis was employed to identify key patterns and relationships, while findings were contextualised through a review of relevant literature. The results reveal that cost estimation inaccuracies are widespread and arise from multiple interrelated factors, including incomplete project scope, lack of reliable cost data, limited professional expertise, and significant material price volatility. These inaccuracies were found to have a direct and substantial impact on project performance, with cost overruns commonly ranging between 20–40% and delays frequently extending project timelines. The study also highlights the presence of a "cost-delay spiral," where financial shortfalls lead to project interruptions, further escalating both time and cost. Additionally, systemic factors such as competitive bidding pressures, client preferences for low estimates, and informal contractual practices contribute to the persistence of estimation inaccuracies. Study concludes that improving cost estimation accuracy requires a holistic approach, including enhanced professional engagement, improved data systems, and stronger contractual frameworks. These improvements are essential for enhancing the reliability and sustainability of small-scale construction projects in Sri Lanka.*

***Keywords:*** *Cost Estimation Accuracy; Cost Overruns; Project Delays; Small-Scale Construction; Sri Lanka.*

[1] Senior Lecturer, School of Property, Construction and Project Management, RMIT University, wadu.jayantha@rmit.edu.au
[2] PhD Candidate, School of Property, Construction and Project Management, RMIT University, Australia, S3855817@student.rmit.edu.au*
[3] Senior Lecturer, School of Property, Construction and Project Management, RMIT University, tayyab.maqsood@rmit.edu.au
[4] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, navodag@uom.lk

# 1. INTRODUCTION

The construction industry is widely recognised as one of the most complex and resource-intensive sectors, characterised by high levels of uncertainty, capital investment, and coordination demands. Project success is evaluated against three core criteria: completion within the stipulated time, adherence to the approved budget, and achievement of the required quality standards (Alsharef et al., 2024). Challenges such as institutional constraints, market volatility, and limited resource availability collectively pose significant challenges to the simultaneous attainment of these three project objectives (Alaloul et al., 2020).

Within this context, construction cost estimation plays a critical role in shaping project outcomes. It serves as the foundation for financial planning, procurement strategies, contractual agreements, and overall project control. Accurate cost estimates enable construction project stakeholders, including clients, contractors, and quantity surveyors, to make informed decisions and allocate resources efficiently (Sayed et al., 2023). Conversely, inaccurate estimates can significantly distort project planning and execution. Empirical evidence suggests that cost overruns are a pervasive issue in construction; for instance, Flyvbjerg (2006) reports that approximately 90% of large-scale construction projects experience cost overruns, with average increases exceeding 28% of initial estimates. Such discrepancies often trigger cascading effects, including delays, scope reductions, and compromised quality.

Despite extensive research on cost estimation in large-scale infrastructure projects, small-scale construction has received comparatively less attention from the research community (Amade & Akpan, 2014). This gap is significant, as small-scale projects constitute the majority of construction activities in many developing countries. These projects are typically constrained by limited budgets, informal management practices, and reduced access to professional expertise, making them particularly vulnerable to estimation inaccuracies (Rowe, 2020).

Sri Lanka provides a pertinent case for examining these challenges. The country's construction sector has expanded due to urbanisation, post-conflict reconstruction, and infrastructure development; however, the 2022 economic crisis substantially intensified uncertainty in the sector. Recent studies report that currency depreciation, inflation, import restrictions, fuel shortages, and sharp material price escalation disrupted construction planning and delivery, particularly among smaller contractors with limited financial resilience (Perera et al., 2023; Rajapaksha et al., 2025; Weerakoon et al., 2023). These conditions made traditional estimating approaches less reliable because assumptions made at tender or planning stage were often invalidated during project execution.

Against this background, the aim of this study is to explore how cost estimation inaccuracies influence cost overruns and project delays in small-scale construction projects in Sri Lanka. The study is guided by four objectives: (1) to identify the key factors affecting cost estimation accuracy in Sri Lankan small-scale construction projects; (2) to examine how inaccurate estimates contribute to cost overruns; (3) to examine how inaccurate estimates contribute to project delays; and (4) to propose practical recommendations for improving estimation reliability within the small-scale construction context.

# 2. LITERATURE REVIEW

Cost estimation is widely recognised as a central pillar of construction project management, as it shapes early decision-making and establishes the financial boundaries within which a project must be delivered. At its core, cost estimation involves forecasting the total expenditure required to complete a defined scope of work, combining technical measurement with informed professional judgement (Flyvbjerg, 2006; Holm & Schaufelberger, 2021). Because these estimates guide procurement planning, cash flow allocation, and contractual commitments, their accuracy plays a decisive role throughout the project lifecycle. This is particularly true in small-scale construction projects, where financial buffers are limited and even minor deviations from the estimated cost can have significant consequences.

When cost estimates are inaccurate, most commonly due to underestimation, the effects tend to emerge progressively as the project moves from planning into execution. One of the earliest and most immediate consequences is financial strain. As actual costs begin to exceed the initial budget, clients and contractors may face funding shortfalls, forcing them to pause work while seeking additional resources or reconsidering project scope (Sayed et al., 2023). These interruptions disrupt construction schedules, lead to the withdrawal of labour and equipment, and create inefficiencies that are often difficult to reverse (Potts & Ankrah, 2014). In small-scale construction projects, where access to additional financing is often constrained, such disruptions can quickly translate into substantial project delays.

Closely linked to this is the impact of estimation accuracy on procurement. Reliable cost estimates enable project teams to plan the timing, quantity, and specification of materials and resources with a reasonable degree of confidence (Fry et al., 2016). However, when estimates are flawed, procurement plans become misaligned with actual project needs. This may result in insufficient funds to secure essential materials or delays in ordering key inputs. In developing countries such as Sri Lanka, where construction supply chains are frequently affected by long lead times and import dependencies, these disruptions can halt progress for extended periods (Oke & Ogunsemi, 2011). As a result, initial estimation errors begin to cascade, affecting both time and cost performance simultaneously.

The connection between cost estimation and cost overruns is even more direct. By definition, a cost overrun occurs when actual expenditure exceeds the original estimate, meaning that inaccurate estimation inherently increases the likelihood of such outcomes. Research has consistently shown that underestimation is often driven by factors such as optimism bias, incomplete project definition, and insufficient allowance for risk (Bayram & Al-Jibouri, 2016; Flyvbjerg, 2006). In small-scale construction, these challenges are often intensified by limited access to reliable cost data, informal estimation practices, and the absence of structured contingency planning.

## 2.1 SMALL CONSTRUCTION PROJECTS IN SRI LANKA

For the purpose of this study, small-scale construction projects in Sri Lanka are defined as projects undertaken by lower-grade contractors registered under the Construction Industry Development Authority (CIDA), specifically contractors classified within Grades C6 to C9. This classification is considered appropriate because the CIDA contractor registration and grading system serves as the nationally recognized framework for categorizing contractors according to their financial capability, technical competence,

availability of skilled personnel and equipment, and previous construction experience (Shivananthan, 2017).

Under the current CIDA grading structure for main construction contractors, Grade C6 contractors are eligible to undertake projects valued above LKR 20 million and below LKR 50 million, Grade C7 contractors are authorized for projects above LKR 10 million and below LKR 20 million, Grade C8 contractors for projects above LKR 4 million and below LKR 10 million, while Grade C9 contractors are limited to projects below LKR 4 million (Shivananthan, 2017). Accordingly, this study conceptualizes small-scale construction projects as projects generally not exceeding LKR 50 million and predominantly executed by contractors operating within the C6–C9 grading categories. This definition is consistent with prior construction management studies, which commonly classify project scale based on contractor capacity, financial thresholds, and organizational resources, particularly in developing-country construction contexts where contractor grading systems are used as industry benchmarks for project categorization (Ofori, 2012). Therefore, adopting the CIDA grading framework provides an industry-recognized and contextually relevant basis for defining small-scale construction projects in Sri Lanka.

Sri Lanka's construction sector operates within a context that presents a unique and particularly challenging environment for accurate cost estimation. While many of the difficulties associated with estimation are consistent with those identified in international literature, recent economic disruptions have significantly intensified these challenges. The 2022 economic crisis, in particular, exposed the vulnerability of existing estimation practices (Weerakoon et al., 2023). Projects that were costed under relatively stable conditions in 2021 were subsequently executed in an environment characterised by rapid inflation, currency depreciation, and severe supply constraints. As a result, contractors were often compelled to deliver projects under conditions that differed substantially from those assumed at the estimation stage (Perera et al., 2023).

A key structural issue underpinning this challenge is the heavy import dependency of Sri Lanka's construction materials market. Essential inputs such as steel, electrical components, and finishing materials are either directly imported or rely on imported raw materials. Consequently, fluctuations in exchange rates and restrictions on foreign currency availability have a direct and often unpredictable impact on construction costs. Under such conditions, traditional estimation approaches, typically based on stable pricing assumptions, become less reliable (Rajapaksha et al., 2025). This necessitates a greater emphasis on incorporating realistic escalation allowances and flexible contractual provisions to manage price variability. Labour market conditions further complicate the estimation process. Even prior to the crisis, the sector experienced shortages of skilled workers; however, this issue has been exacerbated by increased labour migration (Sivachelvy & Seneviratne, 2023). The resulting scarcity not only drives up wage rates but also affects productivity, as contractors may need to rely on less experienced workers. These dynamics introduce additional uncertainty into labour cost forecasting, making it difficult to accurately predict both cost and project duration (Pathirana, 2021). Finally, the prevalence of informal or weakly structured contractual arrangements adds another layer of complexity. In the absence of clearly defined mechanisms for variation pricing, payment scheduling, and dispute resolution, cost overruns and delays become more difficult to manage effectively. This often leads to misunderstandings and disputes, further undermining project performance and stakeholder relationships.

## 3. METHODOLOGY

This study employed a qualitative, descriptive–analytical, cross-sectional research design to examine how cost estimation inaccuracies contribute to cost overruns and project delays in Sri Lankan small-scale construction projects. Rather than statistically testing causal relationships, the study explored perceived relationship patterns through the experiences of industry practitioners, focusing on how estimation errors influence financial and schedule performance during project delivery. A cross-sectional design was considered appropriate because the research sought to capture prevailing industry conditions at a specific point in time, particularly in the context of Sri Lanka's recent economic instability. However, this approach does not permit the observation of changes in estimation practices over time, and this limitation is acknowledged in the study.

A qualitative approach was adopted because cost estimation practices in small-scale construction are frequently informal, context-specific, and influenced by professional judgement, client behaviour, market conditions, and contractual arrangements (Dandan et al., 2020; Lim et al., 2016). The study was guided by a deductive orientation grounded in established concepts such as estimation accuracy, optimism bias, incomplete project information, contingency planning, and project performance, while remaining sufficiently flexible to capture context-specific insights emerging from the data. Data were collected through semi-structured interviews, which are well suited to exploring practitioners' experiences and perceptions while allowing relevant themes to emerge during discussion (Evans & Lewis, 2017). 12 Participants were selected using purposive sampling based on three criteria: (i) direct involvement in cost estimation or project delivery, (ii) experience in small-scale construction projects, and (iii) familiarity with cost overruns or project delays encountered during project execution. The participant group comprised contractors, project managers, and quantity surveyors as shown in Table 1.

*Table 1: Interviewee profiles*

| Code | Position | Years Experience |
|---|---|---|
| QS1 | Quantity Surveyor | 12 |
| QS2 | Quantity Surveyor | 8 |
| QS3 | Quantity Surveyor | 7 |
| QS4 | Quantity Surveyor | 9 |
| QS5 | Quantity Surveyor | 10 |
| QS6 | Quantity Surveyor | 8 |
| PM1 | Project Manager | 15 |
| PM2 | Project Manager | 10 |
| PM3 | Project Manager | 11 |
| CT1 | Contractor | 18 |
| CT2 | Contractor | 11 |
| CT3 | Contractor | 9 |

Interview data were analysed using thematic analysis, following a process of transcript familiarisation, initial coding, theme development, comparison across participant categories, and interpretation of relationships between estimation inaccuracies and project outcomes (Evans & Lewis, 2017). As the analysis was qualitative and interpretive, the reported relationships represent practice-based thematic insights rather than statistically verified associations.

## 4. RESEARCH FINDINGS

This section presents a structured discussion of the findings in relation to the research objectives, with a focus on cost estimation accuracy, its determinants, and its implications for project delays and cost overruns in Sri Lanka's small-scale construction sector. The discussion is organised into four interrelated thematic areas to ensure clarity and analytical coherence.

*Table 2: Analytical link between cost estimation inaccuracy and project outcomes*

| Estimation issue | Small-scale project context | Effect on cost overrun | Effect on delay |
|---|---|---|---|
| Incomplete scope/design information | Projects often commence with limited drawings or changing client requirements. | Variations and rework increase actual costs beyond the original estimate. | Design clarifications and changes interrupt work sequencing. |
| Limited professional estimating input | Clients may avoid QS involvement to reduce upfront cost. | Missing items, weak measurement, and insufficient allowances increase budget gaps. | Incorrect resource planning delays procurement and mobilisation. |
| Lack of reliable cost data | Small contractors rely heavily on experience and supplier quotations. | Outdated prices and weak benchmarking lead to underestimation. | Budget shortfalls slow down purchasing and progress payments. |
| Material price volatility | Import dependency and crisis-related inflation affect prices. | Escalation increases actual expenditure, especially under fixed-price arrangements. | Delayed purchasing exposes projects to further price and supply shocks. |
| Weak contingency and contractual mechanisms | Informal agreements often lack price-adjustment provisions. | Unexpected costs are not absorbed within the original budget. | Disputes and renegotiations extend project duration. |

Table 2 illustrates the analytical link between cost estimation inaccuracies and project outcomes in Sri Lankan small-scale construction projects. The findings indicate that estimation errors typically originate from incomplete project information, limited professional involvement, inadequate cost data, material price volatility, and weak contingency or contractual mechanisms. These issues contribute directly to cost overruns through variations, rework, inaccurate measurements, underestimation of costs, and unplanned expenditure. At the same time, they adversely affect project schedules by

disrupting procurement, delaying decision-making, causing funding shortages, and triggering disputes or renegotiations. The table demonstrates that cost overruns and project delays are interconnected consequences of estimation inaccuracies, highlighting the critical importance of improving estimation practices to enhance overall project performance.

## 4.1 DETERMINANTS OF COST ESTIMATION ACCURACY

The findings indicate that cost estimation inaccuracies in small-scale construction are not incidental but arise from a combination of structural and practice-based limitations. Key factors identified include incomplete project scope at the estimation stage, limited professional expertise, lack of access to reliable cost data, and heightened material price volatility. These findings are consistent with established literature, which emphasises the importance of project definition and estimator competence in achieving reliable cost forecasts (Oberlender & Trost, 2001; Odeyinka et al., 2008).

Evidence from the interview data provides deeper insight into how these factors manifest in practice. Several respondents emphasised that estimates are often prepared based on incomplete or evolving designs, which significantly undermines accuracy. *QS3* noted that "in many small projects, we are asked to price based on basic drawings or even verbal descriptions, and later design changes make the original estimate irrelevant." This highlights the practical consequences of inadequate scope definition, where early estimates are built on assumptions that are subsequently invalidated. This phenomenon is not unique to Sri Lanka but is widely documented across developing countries, particularly within small-scale construction sectors where formal design processes are often compressed or bypassed. Studies have consistently shown that incomplete project definition at the estimation stage is one of the most significant predictors of cost inaccuracy (Oberlender & Trost, 2001). Similarly, research in developing construction contexts indicates that projects frequently commence before detailed designs are finalised, leading to continuous revisions that disrupt both cost and schedule performance (Mahamid, 2015).

The issue of limited professional expertise also emerged strongly. *CT2* explained that "most small contractors do their own estimates without involving a quantity surveyor, mainly to reduce costs, but this leads to mistakes that only become visible during construction." This reflects a broader structural challenge in which professional cost management services are underutilised, resulting in a reliance on experience-based rather than methodologically rigorous estimation practices. This challenge is widely recognised in construction literature, particularly in developing country contexts where access to qualified professionals is uneven. Studies have consistently demonstrated that the competence and formal training of the estimator are among the most critical determinants of estimation accuracy (Ekung et al., 2021; Odeyinka et al., 2008). When estimates are prepared without the involvement of trained professionals, there is a greater tendency to overlook key cost components, underestimate risks, and rely on informal heuristics rather than systematic measurement and pricing methods.

Another recurring theme was the absence of reliable and up-to-date cost data. Respondents consistently highlighted the difficulty of accessing accurate local pricing information, particularly in a volatile economic environment. As *PM1* stated, "we don't have a proper database to rely on, everyone uses their own past experience, but prices are changing too fast for that to be reliable." This limitation directly constrains the ability of

practitioners to benchmark estimates or apply data-driven techniques. Research has shown that the quality and availability of cost data are critical determinants of estimation accuracy, often outweighing even the choice of estimation technique (Sayed et al., 2023). In rapidly changing economic environments, such as those characterised by inflation and supply chain disruptions, historical data quickly becomes outdated, further diminishing its usefulness. Studies in developing construction sectors also highlight that the absence of centralised cost information systems limits knowledge sharing and prevents the development of industry-wide benchmarks (Fazil et al., 2021).

Material price volatility was identified as an especially critical factor in the Sri Lankan context. Interviewees described how rapid and unpredictable cost fluctuations, particularly following the 2022 economic crisis, have made traditional estimation approaches increasingly unreliable. *QS5* observed that "even if you prepare a careful estimate today, within a few months the prices can double, and the estimate becomes useless." This reinforces the need for incorporating realistic escalation allowances and adaptive estimation practices. failure to adequately account for price escalation is a key contributor to cost overruns, especially in projects with longer durations where exposure to market changes is greater (Ekung et al., 2021). Furthermore, Flyvbjerg (2006) highlights that traditional estimation practices often underestimate uncertainty, leading to systematic bias in cost forecasts. In the context of rapidly changing material prices, this tendency is exacerbated, as estimators may rely on outdated cost data or assume short-term price stability that does not hold in practice. Collectively, these insights demonstrate that cost estimation inaccuracies are not merely technical errors but are shaped by systemic constraints within the industry. Furthermore, the absence of structured cost data limits the application of advanced forecasting approaches such as reference class forecasting, which depend on historical benchmarks to improve estimation reliability.

## 4.2 IMPACT OF COST ESTIMATION ON COST OVERRUNS

The analysis confirms a strong and direct relationship between cost estimation accuracy and the occurrence of cost overruns. A substantial proportion of projects examined in this study experienced cost increases in the range of 20–40% above initial estimates, aligning with prior findings in the Sri Lankan context (Kawmudi & Jayasooriya, 2020). These overruns are largely attributable to underestimated material costs, inadequate contingency allowances, and changes in project scope.

Insights from the interview data provide a more grounded understanding of how these overruns unfold in practice. Several respondents highlighted that cost overruns are often anticipated but difficult to prevent under current industry conditions. *CT1* noted that "almost every project we do goes over budget, it's not because we don't try to estimate properly, but because too many things change after we start." This reflects a shared perception among practitioners that cost overruns are not exceptional events but rather a normalised feature of small-scale construction projects. This perception is strongly supported by existing research, which consistently identifies cost overruns as a widespread and systemic issue in construction projects across both developed and developing contexts. Flyvbjerg (2006) found that cost overruns occur in the vast majority of projects globally, suggesting that they are not anomalies but predictable outcomes of underlying structural and behavioural factors. Similarly, Awosina et al. (2018) demonstrated that systematic underestimation is embedded within project planning

processes, reinforcing the idea that overruns are, to a large extent, institutionalised within industry practice.

Respondents also emphasised the role of insufficient contingency planning in amplifying overruns. *QS2* explained that "clients usually resist adding contingencies because they want to keep the budget low, but later they end up paying much more when unexpected costs come in." This highlights a disconnect between initial budgeting expectations and the realities of construction risk, where the absence of adequate financial buffers leaves projects vulnerable to even routine uncertainties. Empirical studies further suggest that resistance to contingency inclusion is often driven by client expectations and competitive pressures. Flyvbjerg (2006) argues that initial project budgets are frequently shaped by optimism bias, where stakeholders prefer lower estimates to secure project approval, even at the expense of realism. Similarly, Asiedu and Adaku (2020) found that inadequate contingency planning is a recurring cause of cost overruns, particularly in environments where clients prioritise affordability over risk preparedness during the early stages of project planning.

Beyond technical limitations, the findings indicate that systemic and behavioural factors significantly influence cost overruns. In particular, competitive bidding pressures were repeatedly identified as a key driver of underestimation. As *PM3* observed, "if you price the job realistically, you won't win it, so many contractors submit lower estimates just to secure the project and deal with the consequences later." This aligns with the concept of strategic underestimation described in the literature, where initial bids may be deliberately or unconsciously optimistic in order to remain competitive (Flyvbjerg, 2006). Research by Shane et al. (2009) further highlights the prevalence of the "low-bid" phenomenon, where contractors knowingly underprice projects to secure contracts, accepting the risk of future financial adjustments. In many cases, this behaviour is reinforced by information asymmetry between clients and contractors, where clients may lack the technical expertise to critically evaluate whether a bid is realistically priced. This creates conditions in which underestimation becomes a rational, albeit risky, strategy within the market. More broadly, these findings suggest that cost overruns in small-scale construction are not solely the result of isolated estimation errors but emerge from an interplay of technical shortcomings, market dynamics, and client expectations. The persistence of these patterns indicates a systemic issue, where industry practices and incentive structures collectively reinforce estimation inaccuracies. As a result, cost overruns become embedded within the project delivery process, rather than being treated as deviations from expected outcomes.

## 4.3 IMPACT OF COST ESTIMATION ON PROJECT DELAYS

The study highlights a clear and consistent linkage between inaccurate cost estimation and the occurrence of project delays. Delays were frequently reported by respondents, with many indicating extensions ranging from several weeks to a few months beyond the planned completion period. Interview data provides valuable insight into how these delays materialise in practice. *CT2* explained that "when the money runs short halfway, everything slows down, we have to stop work, wait for the client to arrange funds, and by then the schedule is already affected." This illustrates the central role of financial disruption as a key mechanism through which estimation inaccuracies translate into delays. In developing country contexts, this issue is often more pronounced due to limited access to contingency funding and weaker financial planning mechanisms. Research by

Rathi et al. (2016) demonstrated that cost overruns and delays are closely interrelated, with financial shortfalls frequently triggering work stoppages and prolonging project duration. This aligns closely with the experiences reported by respondents in this study, who described delays as a direct consequence of insufficient funds resulting from inaccurate initial estimates.

Respondents also emphasised that such disruptions are rarely isolated incidents but tend to cascade across project activities. *PM3* noted that "once there is a delay in one part, like funding or materials, it affects everything else, and it's very difficult to bring the project back on track." This reflects the interconnected nature of construction processes, where delays in one component can quickly propagate through the entire project schedule. This observation is consistent with established research, which identifies construction projects as complex systems in which time, cost, and resource flows are tightly linked (Sambasivan & Soon, 2007). Delays in critical path activities, in particular, have a disproportionate impact, often leading to cumulative schedule slippage that is difficult to recover without significant additional resources. Furthermore, studies have shown that once a project falls behind schedule, corrective measures such as acceleration or resequencing often introduce inefficiencies and increased costs, further compounding the initial disruption (Rathi et al., 2016).

In addition to financial constraints, procurement-related challenges were repeatedly identified as a major contributing factor. Several interviewees highlighted that inaccurate estimates often lead to insufficient budgeting for materials, resulting in delays in procurement and mobilisation. *PM2* stated, "sometimes we realise too late that the allocated budget is not enough to purchase materials at current prices, so we have to wait or change plans." In the Sri Lankan context, where construction supply chains are highly sensitive to economic fluctuations and import dependencies, such disruptions can be particularly severe. This finding aligns with research that emphasises the critical role of procurement planning in project performance, where inaccuracies in early cost estimation can lead to misaligned purchasing schedules and resource shortages (Oke & Ogunsemi, 2011). In developing country contexts, these challenges are often intensified by supply chain constraints, including long lead times, import dependencies, and market volatility. Studies have shown that disruptions in material supply not only delay construction activities but also create knock-on effects such as labour idle time and increased overhead costs (Panova & Hilletofth, 2018). These findings reinforce the concept of the "cost-delay spiral," whereby initial estimation inaccuracies lead to delays, which in turn generate additional costs through extended overheads, labour inefficiencies, and exposure to price escalation. Respondents' experiences suggest that this cycle is not only theoretically valid but also a common reality in small-scale construction projects.

## 4.4 PROFESSIONAL AND CONTEXTUAL INFLUENCES

The research reveals that cost estimation practices are deeply shaped by the professional and market context in which projects are delivered. While many experienced professionals demonstrate a strong understanding of the factors contributing to estimation inaccuracies, they often operate within constraints that limit their ability to apply best practices. Interview responses consistently pointed to market pressures and client expectations as key limiting factors. *QS4* noted that "even if we know the correct way to estimate, clients often push for lower figures, and there is pressure to adjust the estimate to match their budget." This highlights the tension between professional judgement and

commercial realities. Similar dynamics have been identified in previous studies, where client-driven budget constraints often override technical recommendations, leading to compromised estimation accuracy (Odeyinka et al., 2008). Moreover, research by Flyvbjerg (2006) suggests that such pressures contribute to optimism bias, where estimates are adjusted downward to align with stakeholder expectations rather than realistic cost projections.

Client preference for the lowest bid was identified as a particularly influential factor. Respondents indicated that this practice discourages realistic pricing and incentivises underestimation. *CT1* explained that "clients usually compare only the final price, not how the estimate is prepared, so naturally contractors try to keep it as low as possible to win the job." This reinforces a competitive environment in which accuracy is often secondary to affordability, ultimately contributing to downstream project challenges. This finding aligns with the well-documented "lowest-bid procurement" problem, where selection based primarily on cost encourages contractors to submit unrealistically low bids (Shane et al., 2009). Studies have shown that such procurement practices are strongly associated with increased risks of cost overruns, disputes, and compromised project performance, particularly in developing construction markets (Sambasivan & Soon, 2007).

The limited willingness to engage professional estimation services also emerged as a recurring concern. Several respondents observed that small-scale clients tend to view quantity surveying services as an unnecessary expense. As *PM2* stated, "many clients think hiring a QS is an extra cost, but they don't realise that it can actually save money by avoiding mistakes." This perception restricts the involvement of trained professionals and increases reliance on informal estimation practices. Existing literature supports this observation, indicating that professional expertise plays a critical role in improving estimation reliability and overall project cost control (Oberlender & Trost, 2001). However, in small-scale and cost-sensitive projects, the perceived short-term cost of professional services often outweighs their long-term benefits, leading to their underutilisation (Wang & Cheng, 2020).

Contractual informality further compounds these challenges. Respondents highlighted that many small-scale projects operate under loosely defined agreements, lacking clear provisions for cost adjustments, variations, or dispute resolution. This creates uncertainty in managing cost overruns and delays. As a result, contractors, particularly smaller firms, face significant financial exposure when estimates prove inaccurate. *CT1* remarked that "sometimes we just have to absorb the loss because there is no proper agreement to recover additional costs." This finding is consistent with agency theory, which emphasises the risks arising from weak contractual frameworks and information asymmetry between project stakeholders (Shane et al., 2009). Collectively, these insights suggest that cost estimation challenges in Sri Lanka's small-scale construction sector are not solely technical but are deeply embedded in the broader professional, economic, and institutional context. Addressing these issues therefore requires systemic improvements, including greater professional engagement, improved cost data infrastructure, and more robust and transparent contractual practices.

## 5. CONCLUSIONS

This study set out to examine the relationship between cost estimation accuracy and project performance in small-scale construction projects in Sri Lanka, with particular emphasis on cost overruns and project delays. The findings clearly demonstrate that cost estimation accuracy is a critical determinant of project success, influencing not only financial outcomes but also the timely completion of projects. The research reveals that estimation inaccuracies are not isolated technical errors but are rooted in a combination of structural, professional, and contextual challenges. Factors such as incomplete project scope, limited access to reliable cost data, insufficient professional expertise, and material price volatility significantly undermine the reliability of cost estimates. These challenges are further intensified within the Sri Lankan context by economic instability, supply chain disruptions, and labour market constraints. As a result, estimators often operate under conditions of high uncertainty, limiting their ability to produce accurate and reliable forecasts.

The study also establishes a strong and direct link between inaccurate cost estimation and the occurrence of cost overruns and project delays. Cost overruns were found to be widespread, frequently ranging between 20 - 40% above initial estimates, while delays were commonly attributed to financial disruptions and procurement challenges arising from estimation errors. Importantly, these issues are not independent; rather, they form a reinforcing cycle, where cost overruns contribute to delays, and delays further escalate project costs. This “cost-delay spiral” highlights the systemic nature of the problem. Furthermore, the research underscores the influence of market dynamics and professional practices on estimation outcomes. Competitive bidding pressures, client preference for low-cost estimates, underutilisation of professional services, and informal contractual arrangements collectively contribute to a culture in which estimation inaccuracies are often normalised. In conclusion, improving cost estimation accuracy in Sri Lanka’s small-scale construction sector requires a holistic approach. This includes enhancing professional engagement, improving access to reliable cost data, incorporating realistic contingency and escalation provisions, and strengthening contractual frameworks. Addressing these issues is essential not only for improving project performance but also for enhancing the overall sustainability and credibility of the construction industry in Sri Lanka.

## 6. LIMITATIONS AND FUTURE RESEARCH

This study is subject to several limitations. First, the qualitative and cross-sectional research design facilitated an in-depth exploration of practitioners’ experiences and perceptions; however, it does not enable statistical examination of the magnitude or causality of relationships between cost estimation inaccuracies, cost overruns, and project delays. Consequently, the findings should be interpreted as thematic and practice-based insights rather than empirically verified causal associations. Second, the study relied on purposively selected construction professionals, and therefore the findings reflect the perspectives of the participants involved and may not fully represent the diversity of small-scale construction projects across Sri Lanka. Third, the scope of the research was confined to small-scale construction projects; therefore, caution should be exercised when applying the findings to large-scale infrastructure developments or more complex construction projects operating under different organisational and contractual conditions.

Future research could build upon these findings by adopting quantitative or mixed method approaches to examine the relationship between cost estimation accuracy and project performance across a larger and more representative sample of projects. Longitudinal studies would also provide valuable insights into how cost estimates evolve throughout the project lifecycle and how estimation accuracy is affected by changing project and market conditions. Furthermore, future investigations could focus on the development of industry-specific cost databases, price escalation forecasting models, and decision-support tools tailored to the Sri Lankan small-scale construction sector, particularly in response to persistent challenges associated with market volatility, inflation, and supply chain disruptions.

# 7. REFERENCES

Alaloul, W. S., Liew, M. S., Zawawi, N. A. W. A., & Kennedy, I. B. (2020). Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Engineering Journal, 11*(1), 225–230. https://doi.org/10.1016/j.asej.2019.08.010

Alsharef, A., Ovid, A., Uddin, S. M. J., & Albert, A. (2024). Biggest challenges facing the construction industry. In *Construction Research Congress 2024*. https://doi.org/10.1061/9780784485286.065.

Amade, B., & Akpan, E. O. P. (2014). Project cost estimation: Issues and possible solutions. *International Journal of Engineering and Technical Research, 2*(5), 181–188. https://www.researchgate.net/publication/280805190_Project_Cost_Estimation_Issues_and_the_Possible_Solutions

Awosina, A., Ndihokubwayo, R., & Fapohunda, J. (2018). Effects of inaccurate cost estimate on construction project stakeholders. *Journal of Construction Project Management and Innovation, 8*(2), 1886–1904.https://doi.org/10.36615/jcpmi.v8i2.164

Bayram, S., & Al-Jibouri, S. (2016). Efficacy of estimation methods in forecasting building projects' costs. *Journal of Construction Engineering and Management, 142*(11), Article 05016012. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001188

Dandan, T. H., Sweis, G. J., Sukkari, L., & Sweis, R. J. (2020). Factors affecting the accuracy of cost estimate during various design stages. *Journal of Engineering, Design and Technology, 18*(4), 787–819. https://doi.org/10.1108/JEDT-08-2019-0202

Ekung, S., Lashinde, A., & Adu, E. (2021). Critical risks to construction cost estimation. *Journal of Engineering, Project, and Production Management, 11*(1), 1–13. https://doi.org/10.2478/jeppm-2021-0003

Evans, C., & Lewis, J. (2017). *Analysing Semi-Structured Interviews using thematic Analysis: Exploring voluntary civic participation among adults*. https://doi.org/10.4135/9781526439284

Fazil, M. W., Lee, C. K., & Tamyez, P. F. M. (2021). Cost estimation performance in construction projects: A systematic review and future directions. *International Journal of Industrial Management, 11*, 217–234. https://doi.org/10.15282/ijim.11.0.2021.6170

Flyvbjerg, B. (2006). From Nobel Prize to project management: Getting risks right. *Project Management Journal, 37*(3), 5–15. https://doi.org/10.1177/875697280603700302

Fry, T. D., Leitch, R. A., Philipoom, P. R., & Tian, Y. (2016). Empirical analysis of cost estimation accuracy in procurement auctions. *International Journal of Business and Management, 11*(3), 1–13. https://doi.org/10.5539/ijbm.v11n3p1

Holm, L., & Schaufelberger, J. E. (2021). *Construction cost estimating (2nd ed.).* Routledge.

Kawmudi, N., & Jayasooriya, S. (2020). Identification of significant factors influencing cost overruns in construction projects of Sri Lanka. In *Annual Technical Sessions of the Institute of Quantity Surveyors Sri Lanka (IQSSL),* 37- 46. https://iqssl.lk/docs/publications/publication-iqssl-2020-08-27-uid661.pdf

Lim, B. T. M., Nepal, M. P., Skitmore, M., & Xiong, B. (2016). Drivers of the accuracy of developers' early-stage cost estimates in residential construction. *Journal of Financial Management of Property and Construction, 21*(1), 4–20. https://doi.org/10.1108/JFMPC-01-2015-0002

Mahamid, I. (2015). Factors affecting cost estimate accuracy: Evidence from Palestinian construction projects. *International Journal of Management Science and Engineering Management, 10*(2), 117–125. https://doi.org/10.1080/17509653.2014.936802

Oberlender, G. D., & Trost, S. M. (2001). Predicting accuracy of early cost estimates based on estimate quality. *Journal of Construction Engineering and Management, 127*(3), 173–182. https://doi.org/10.1061/(ASCE)0733-9364(2001)127:3(173)

Odeyinka, H. A., Lowe, J., & Kaka, A. P. (2008). An evaluation of risk factors impacting construction cash flow forecast. *Journal of Financial Management of Property and Construction, 13*(1), 5–17. https://doi.org/10.1108/13664380810882099

Ofori, G. (2012). Developing the Construction Industry in Ghana: the case for a central agency. *A concept paper prepared for improving the construction industry in Ghana. National University of Singapore, 13*(1), 3-18. https://ghanatrade.com.gh/old/file/Developing%20the%20Construction%20Industry%20in%20Ghana%20BUILDING.pdf

Oke, A. E., & Ogunsemi, D. R. (2011). Value management in the Nigerian construction industry: Militating factors and perceived benefits. In *Proceedings of the Second International Conference on Advances in Engineering and Technology* (pp. 353–359). Makerere University. https://ghanatrade.com.gh/old/file/Developing%20the%20Construction%20Industry%20in%20Ghana%20BUILDING.pdf

Panova, Y., & Hilletofth, P. (2018). Managing supply chain risks and delays in construction projects. *Industrial Management & Data Systems, 118*(7), 1413–1431. https://doi.org/10.1108/IMDS-09-2017-0422

Pathirana, L. (2021). Construction industry and factor condition prospective of Sri Lanka: A special reference to skill labour shortage. *Journal of Business and Management, 23*(2), 35–41. https://www.researchgate.net/publication/349656955_Construction_Industry_and_Factor_Condition_Prospective_of_Sri_Lanka_A_Special_Reference_to_Skill_Labour_Shortage

Perera, M., Gunarathna, K., & Karunaratne, B. (2023). Effect of current economic crisis on construction contractors in Sri Lanka: An exploratory study on small-scale contractors. In Proceedings of the International Conference on Sustainable Built Environment (ICSBE 2023) (p. 1077). https://www.researchgate.net/publication/380401958_EFFECT_OF_CURRENT_ECONOMIC_CRISIS_ON_CONSTRUCTION_CONTRACTORS_IN_SRI_LANKA_AN_EXPLORATORY_STUDY_ON_SMALL-_SCALE_CONTRACTORS

Potts, K., & Ankrah, N. (2014). *Construction cost management: Learning from case studies.* Routledge.

Rajapaksha, A., Perera, B., & Liyanawatta, T. (2025). Framework for avoidance of disputes arising in the construction industry due to the economic crisis. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 17*(1), Article 04524039. https://doi.org/10.1061/JLADAH.LADR-1104

Rathi, A., Khandve, P., El-Kholy, M., Patel, C. H., Chaturvedi, H., Megha, R., Rao, P., Katta, K., Prasad, Overrun, N., Azhar, R., Farooqui, Syed, M., Ahmed, Apolot, R., Alinaitwe, H., & Tindiwensi, D. (2016). Study of Factors Influencing cost Overruns: An Overview. *International Journal of Science and Research, 5*(3), 334–336. https://doi.org/10.21275/v5i3.nov161792

Rowe, S. F. (2020). *Project management for small projects.* Berrett-Koehler Publishers.

Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry. *International Journal of Project Management, 25*(5), 517–526. https://doi.org/10.1016/j.ijproman.2006.11.007

Sayed, M., Abdel-Hamid, M., & El-Dash, K. (2023). Improving cost estimation in construction projects. *International Journal of Construction Management, 23*(1), 135–143. https://doi.org/10.1080/15623599.2021.1886839

Shane, J. S., Molenaar, K. R., Anderson, S., & Schexnayder, C. (2009). Construction project cost escalation factors. *Journal of Management in Engineering, 25*(4), 221–229. https://doi.org/10.1061/(ASCE)0742-597X(2009)25:4(221)

Shivananthan, S. (2017). *Study on the evaluation of contractor selection criteria in Sri Lanka. http://ir.lib.seu.ac.lk/handle/123456789/5326.*

Sivachelvy, U., & Seneviratne, S. (2023). The impact of challenges of the current economic crisis on the performance of Sri Lankan building construction projects. *International Research Symposium*. https://www.researchgate.net/profile/K-T-P-C-Somarathna/publication/383605700_Implementation_of_School-Based_Management_School_Leadership_Challenges_and_Opportunities_Faced_by_School_Principals/links/66d34fbffa5e11512c432742/Implementation-of-School-Based-Management-School-Leadership-Challenges-and-Opportunities-Faced-by-School-Principals.pdf#page=487

Wang, X., & Cheng, Z. (2020). Cross-sectional studies: Strengths, weaknesses, and recommendations. Chest, 158(1 Suppl.), S65–S71. https://doi.org/10.1016/j.chest.2020.03.012

Weerakoon, T. G., Wimalasena, S., & Fedotova, K. (2023). Economic crisis adaptation in the Sri Lankan construction industry: Pathway to prosperity. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1), 240–256. https://doi.org/10.2478/bjreecm-2023-0019

Bandara, M.D.K.S., Kulatunga, U. and Subhasingha, H.D., 2026. Exploring multi-level biomimicry in building façade construction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 729-739. DOI: https://doi.org/10.31705/WCS.2026.54. Available from: https://ciobwcs.com/papers/

# EXPLORING MULTI-LEVEL BIOMIMICRY IN BUILDING FAÇADE CONSTRUCTION

**M.D.K.S. Bandara[1], U. Kulatunga[2] and H.D. Subhasingha[3]**

## *ABSTRACT*

*The built environment consumes about 75% of the world's energy, and building facades are a key component in controlling heat, light and energy exchange. Biomimicry is becoming a popular design approach for sustainability, but its use at various scales in building façade design is not yet fully developed. This study aims to fill this gap by systematically reviewing the literature using Google Scholar, Scopus, Web of Science and Emerald databases, using specific keyword searches to identify and analyse peer-reviewed studies. Based on the defined inclusion criteria (English-language, peer-reviewed articles published between 2013 and 2025 on biomimicry and façade performance), a total of 46 relevant sources were selected. The review explores the potential for three levels of biomimicry – organism, behaviour and ecosystem – to be applied to the design of building façades to meet performance targets that include thermal performance, daylighting, solar control, energy efficiency and carbon reduction. Bio-inspired structures like cactus-rib geometry at the organism level can decrease the solar heat gain by 20-50%. The principles of termite-mound ventilation and stomata-inspired kinetic panels at the behaviour level can save 35% and 85.5% of energy, respectively, and enhance daylighting. Coral inspired materials decrease the embodied carbon by up to 48.76% at the ecosystem level. A conceptual framework is created that connects biological inspirations, levels of biomimicry and façade performance targets to a structured design instrument, which offers practitioners a systematic and evidence-based approach to bio-inspired façade design.*

***Keywords:*** *Biomimicry; Bio-inspired Building Façades; Building Performance Targets; Energy Efficiency; Multi-Level Biomimicry.*

## 1. INTRODUCTION

The built environment consumes a large portion of global energy and contributes to greenhouse gas emissions, which has raised concerns about sustainability and environmental impact (Al-Obaidi et al., 2022). The built environment consumes 75% of the global energy consumption (Gursel et al., 2023) and building components and structural materials are significant contributors to greenhouse gas emissions (Zhong et al., 2021). The energy consumption and emissions are also greatly influenced by non-structural elements like façades, interiors, and windows (Gursel et al., 2023).

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, sampathkavindu915@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulaunga@uom.lk
[3] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, subhasingahhd.20@uom.lk

The building façade is the main interface between the indoor and outdoor spaces, which controls heat, light, moisture, air flow and aesthetics (Faragalla & Asadi, 2022). Façades are a significant factor in the energy gain or loss of buildings (Gonçalves et al., 2024) and are a key element in the way that natural light is directed into interior spaces (Balafoutis, 2025). Furthermore, façades improve the aesthetic value and adapt to the changing climatic conditions (Athauda et al., 2023). The design of the façade is one of the most important aspects to consider when meeting performance targets, such as energy efficiency, daylighting, solar control, thermal performance, and carbon reduction (Cucuzzella et al., 2023; Minaei, 2025; Rahubadda et al., 2025).

Biomimicry, which involves copying the forms, processes and systems found in nature to solve design problems, is a potential approach to improving façade performance (Shan & Junghans, 2023). Zari and Hecht (2020) state that knowledge of natural organisms and systems can be used to develop more adaptable and resilient buildings. Bio-inspiration can be used in the construction industry in two ways: design inspired by biology (top-down) and biology influencing design (bottom-up) (Othmani et al., 2022). Moreover, biomimicry can be studied at three different scales: organism, behaviour and ecosystem, which can enhance the efficiency and performance of building façades (Faragalla & Asadi, 2022).

The aim of this literature review is to critically examine existing knowledge on biomimicry in architectural design, with a particular focus on multi-level biomimicry applications in building façades, in order to identify relevant biological principles, design strategies, and performance outcomes. Based on this synthesis, the review seeks to establish the theoretical foundation necessary for developing a conceptual framework for integrating multi-level biomimicry into façade design to enhance environmental responsiveness and energy efficiency in buildings. To fill this gap, the contribution of each level to thermal comfort, energy efficiency, daylighting, durability and sustainability should be evaluated (El-Rahman et al., 2020; Hassan et al., 2023; Sheikh & Asghar, 2019; Zaki, 2023). Therefore, the purpose of this study is to establish a conceptual framework that connects biological inspirations, levels of biomimicry, and building façade performance targets, and to create a structured design tool for bio-inspired façade design.

## 2. RESEARCH METHODOLOGY

A systematic literature review was used to identify key concepts of biomimicry, performance targets of building façades, and bio-inspired façade applications, which were used to inform the development of a conceptual framework. The review was conducted in three stages, (1) database searching and source selection, (2) screening, and (3) data extraction and synthesis, as shown in Figure 1.

Google Scholar, Scopus, Web of Science, and Emerald were the four databases searched. The main search terms used were: "Biomimicry AND Building facades", "Building facades AND Performance targets", "Biomimicry OR Biomimetic AND Building facades", and "Building facades AND Performance targets OR Performance". Only publications in English and peer-reviewed were searched. The studies published from 2013 to 2025 were given priority to ensure the studies are current, and seminal studies published earlier were also included if relevant. Conference abstracts, non-peer-reviewed sources, and studies that were not relevant to the façade performance or biomimicry level were excluded.

Following the initial screening of titles and abstracts, 46 sources were included for full-text analysis. The sources cover various fields such as architecture, building engineering, environmental science, and materials science, and are geographically distributed in Asia, Europe, Africa, the Middle East, and the Americas. Key performance targets were taken from the literature, and the conceptual framework was developed to communicate the synthesised results.

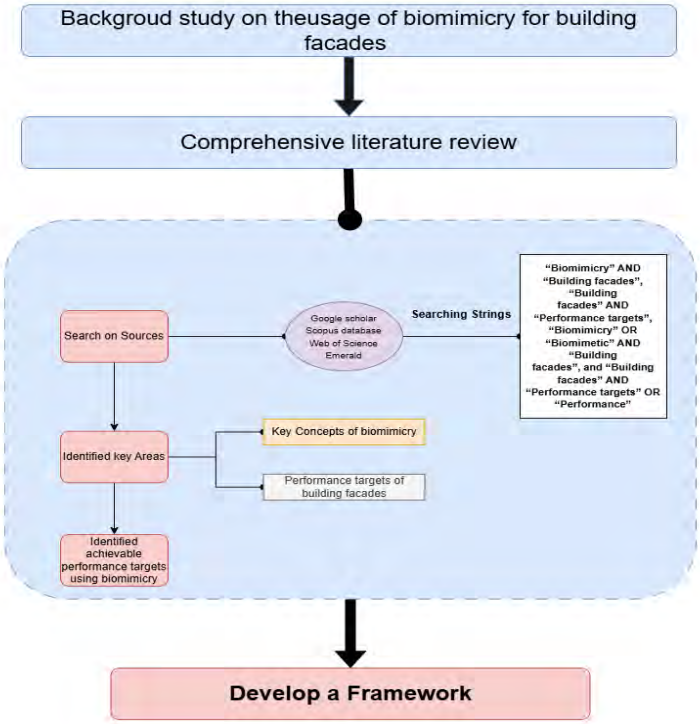



*Figure 1: Research methodology*

# 3. RESULTS AND FINDINGS

## 3.1 LEVELS OF BIOMIMICRY

Biomimicry has become an important design approach in architecture, enabling designers to draw upon nature to address technical and environmental challenges (Jamei & Vrcelj, 2021). It is generally perceived at three levels: organism, behaviour, and ecosystem, each with a different view of how natural systems can guide architectural design (Panjwani & Sahu, 2023). These levels are not only the basis for the development of innovative architectural forms but also enable sustainable practices by incorporating biological logic into the selection of materials and structural optimisation (Bijari et al., 2025).

### 3.1.1 Organism Level

Biomimicry in architecture is inspired by the shape, form and structure of living organisms like plants, animals and natural elements at the organism level (Panjwani & Sahu, 2023). This method involves incorporating physical characteristics from the natural world into architectural design, which can manifest as facades, roofs, or interior layouts that mimic natural forms and enhance their performance (Panjwani & Sahu, 2023). For example, architects can use the curvature of shells, the structure of leaves, or the lightweight yet strong skeletal structures of animals to design efficient and visually

appealing structures (Bijari et al., 2025). This level focuses on the organism itself, making it possible to directly apply natural shapes and structures to the built environment, where designers can integrate functionality with nature-inspired creativity (Panjwani & Sahu, 2023).

### 3.1.2 Behaviour Level

At the behaviour level, instead of copying the shape or structure of nature, imitate the ways living things work and interact with their surroundings (Panjwani & Sahu, 2023). The model examines how natural systems control the flow of energy, the movement of water, the thermal stability, and adapts these processes to architectural applications (Panjwani & Sahu, 2023). According to Panjwani and Sahu (2023), a typical example is the application of termite mound ventilation principles to design buildings with a greater degree of natural ventilation and lower energy demand. In the same way, biomimetic approaches have led to the development of water management systems that emulate either the root system of plants, or hydrological patterns found in nature, in design for architecture to harvest rainwater and minimize runoff (Bijari et al., 2025). By replicating these adaptive behaviours, architects can create buildings that not only better respond to their immediate environment but also contribute to resource efficiency and sustainability (Bijari et al., 2025).

### 3.1.3 Ecosystem Level

The ecosystem level of biomimicry consists of using sophisticated interactions in the ecosystems and the physics (Jamei & Vrcelj, 2021). On such a scale, architects observe the interdependence of the living systems and the balance of the ecosystem in their adaptive and circular nature (Panjwani & Sahu, 2023). For example, designs can blend into the surrounding landscapes, promote biodiversity, or represent the principles of the circular economy, like minimisation of waste generation and resource cycling (Bijari et al., 2025). Buildings constructed using this paradigm are not self-contained buildings, but active members of their ecosystems, which develop symbiotic relationships with their native flora, fauna, and environmental processes (Cucuzzella et al., 2023). According to Bijari et al. (2025) A further benefit of ecosystem-level biomimicry is its ability to integrate features found in organism and behavior level approaches, resulting in integrated solutions for sustainability outcomes.

## 3.2 BUILDING FAÇADES: FUNCTIONS AND PERFORMANCE TARGETS

The first elements that the outside world sees are the facades, which are the architectural style and the architect's vision (Tantawy, 2023). The word "façade" comes from Vulgar Latin and means "front" or "face", as it is the main visual element of a building (Cucuzzella et al., 2023). In addition to their visual appeal, façades play a crucial role in energy efficiency by controlling heat gain and loss, managing natural light, preventing moisture infiltration, and adapting to changing climatic conditions (Athauda et al., 2023; Gonçalves et al., 2024).

The performance targets for building façades include a variety of quantitative and qualitative targets (GRESB, 2018). The U-factor is used to evaluate the thermal performance of the building envelope, which is the rate of heat transfer through the envelope (Minaei, 2025), and the thermal resistance of opaque elements is the ability of solid building elements to resist heat transfer (Shen et al., 2014). Daylighting performance is assessed by Daylight Autonomy (DA) which is the percentage of occupied hours during

which sufficient daylight illuminance is provided without artificial lighting, and Work Plane Illuminance (WPI) which is the amount of daylight illuminance at the working surface (Hegazy et al., 2013; Troup et al., 2019). The window-to-wall ratio is used to evaluate solar control, and it is directly related to the amount of solar heat gain and daylighting in a façade (Gadelhak & Lang, 2016). The energy efficiency is measured by Total Source Energy Consumption (Troup et al., 2019), Lighting Source Energy (Maleki & Dehghan, 2020), Heating Source Energy, and Cooling Source Energy (Eisazadeh et al., 2018). Carbon reduction is assessed by taking into account the carbon emissions from the production and construction of materials (embodied carbon) and the carbon emissions generated during the building's occupied life (operational carbon) (Rahubadda et al., 2025).

### 3.3 APPLICATIONS OF BIOMIMICRY IN BUILDING FAÇADES ACROSS LEVELS

The use of biomimicry in the design of building facades has been used to achieve sustainable performance at all three levels (Jamei & Vrcelj, 2021). The Gherkin Tower in London is inspired by the Venus flower basket sponge, which optimises wind deflection and natural ventilation, and uses 20% less material than a conventional building, with a diagrid structural system (Sun, 2024). The Esplanade Theatres in Singapore are covered with aluminium sunshades that are patterned after the durian fruit, which helps to minimize solar heat gain and artificial lighting (Sidhu & Singh, 2021). The multi-layered timber louvres at Council House 2 in Melbourne are inspired by tree bark, enhancing energy efficiency and reducing the effects of climate change (Helmy & Aboulnaga, 2020). Furthermore, morphological textures inspired by elephant skin have been used to realize passive thermoregulation in hot and dry climates (Hays et al., 2024), and bio-inspired ventilated façades have been demonstrated to decrease energy consumption by 20–55% (Alyahya et al., 2025).

The Eastgate Centre in Harare, Zimbabwe, is an example of a building that uses termite-mound ventilation principles to achieve passive cooling, which results in a 35% reduction in energy consumption compared to buildings of similar size and type that are conventionally air-conditioned, and a 10% reduction in capital costs (Sun, 2024). The kinetic screen of Al Bahar Towers in Abu Dhabi is based on the concept of Mashrabiya, which is an adaptive shading system inspired by the cactus flower, to minimize the solar heat gain and enhance thermal comfort (El-Abedin et al., 2022). Likewise, adaptive façades based on stomata mechanisms have shown an 85.5% daylighting performance improvement using kinetic panel systems (Farmani et al., 2025).

The Sahara Forest Project in Jordan is based on the water-harvesting mechanisms of desert ecosystems, specifically the Namib Desert beetle, which extracts moisture from fog and uses it to grow desert vegetation (Hammond, 2023). The Pearl River Tower in Guangzhou, China, is inspired by sea sponge ecosystem principles to optimise airflow and water efficiency (AlAli et al., 2023). Algae-panel bio-façades sequester CO2 and actively mitigate carbon emissions (Metwally, 2025), and carbon-sequestration materials inspired by corals reduce embodied carbon by up to 48.76% (Rahubadda et al., 2025).

### 3.4 INTEGRATING MULTI-LEVEL BIOMIMICRY TO ENHANCE FAÇADE PERFORMANCE

Biomimicry levels in building façade design result in compounded performance benefits in thermal, energy and environmental aspects (Moghaddam et al., 2023). As shown in

Table 1, bio-inspired façades at the organism, behaviour and ecosystem levels can deliver measurable improvements in multiple performance targets simultaneously. Organism-level designs focus on structural optimisation and solar shading, whereas designs that incorporate behaviour-level principles include dynamic environmental responsiveness. These benefits are expanded to regenerative and carbon-sequestering outcomes at the ecosystem level (Bijari et al., 2025).

*Table 1: Performances achieved using levels of biomimicry in building facades*

| Level | Description | Example in Building Facades | Inspiration | performance | References |
|---|---|---|---|---|---|
| **Organism** | Mimics forms and structures of individual organisms for static optimization | Gherkin Tower | Venus flower basket sponge for wind reduction and ventilation | Reduced material usage (20% less steel) | (Sun, 2024) |
| | | Esplanade Theatres | Durian fruit for shading and heat block | Less energy usage for lighting | (Sidhu & Singh, 2021) |
| | | Council House 2 | Tree bark for multi-layered shading | Mitigates climate change mitigation, Energy Efficiency | (Helmy & Aboulnaga, 2020) |
| **Behaviour** | Replicates dynamic processes and environmental interactions for adaptability | Eastgate Centre | Termite Mound for Ventilation | Reduce 35% of energy consumption and save 10% on the capital cost | (Sun, 2024) |
| | | Al Bahar Towers | Cactus flower for adaptive shading | Improve user comfort through natural lighting and thermal comfort | (El-Abedin et al., 2022) |
| **Ecosystem** | Emulates full system interactions for regenerative and holistic integration | Sahara forest project | Inspired by the desert ecosystems | Removal of moisture from fog to regenerate dry lands on an ecosystem scale | (Hammond, 2023) |
| | | Pearl River Tower | sea sponge ecosystem for air/water flow | Achieving water and energy efficiency | (AlAli et al., 2023) |

The research has shown that bio-inspired façades that incorporate all three levels of biomimicry perform better than those that use only one level of biomimicry (Bijari et al., 2025). Furthermore, the three levels can be used as a conceptual framework to guide designers in choosing the right biological inspiration for the desired performance goals

(AlAli et al., 2023). For example, bio-inspired ventilated façades can reduce energy consumption by 20-55% when inspired by both organism and behaviour level (Alyahya et al., 2025).

## 3.5 CONCEPTUAL FRAMEWORK FOR BIO-INSPIRED BUILDING FAÇADE DESIGN

The conceptual framework (Figure 2) is derived from two key design approaches in biomimicry identified in the literature review, the bottom-up and top-down approaches. The bottom-up approach is knowledge-driven and starts from existing biological inspirations, studying the biological principles and translating them into façade design strategies. This method is not always the best way to solve the real performance problems of a building, however. The bottom-up approach, on the other hand, is problem-driven and starts with the building performance requirements, including thermal performance, daylighting, solar control, energy efficiency, and carbon reduction. The biological inspirations that are relevant are then chosen according to their capability to solve these performance problems, leading to a more performance-oriented bio-inspired façade design approach.

The middle section of the framework shows how building performance goals, biological inspirations, and various degrees of biomimicry relate to each other during the design process. It demonstrates that various performance objectives can be achieved through different biological inspirations and biomimicry levels. Inspirations from the physical shape or surface of organisms are examples of organism-level biomimicry, and inspirations from resource cycles, energy flows, and regenerative environmental systems are examples of ecosystem-level biomimicry.

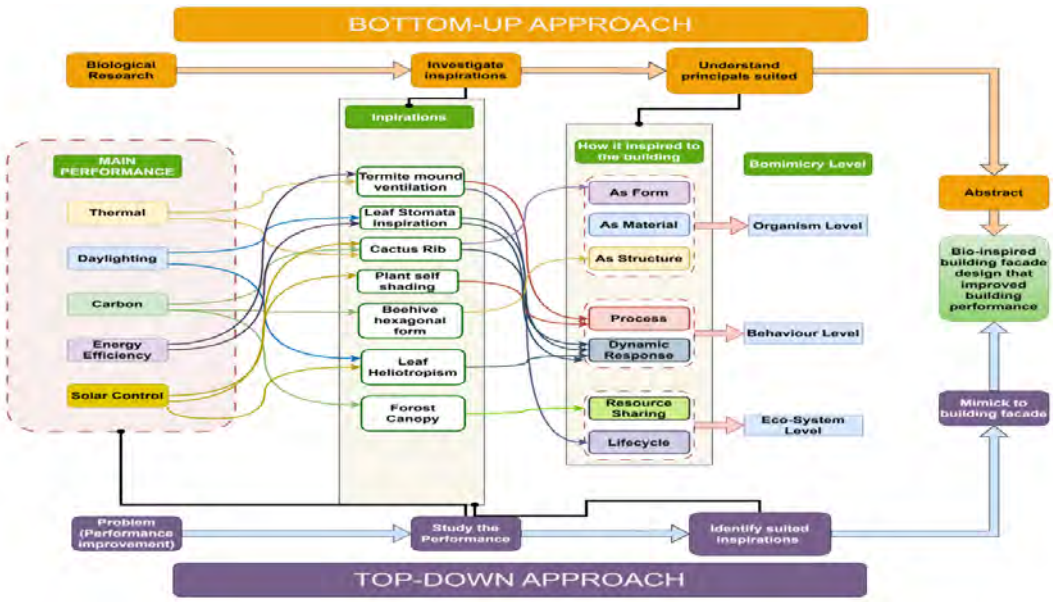



*Figure 2: Proposed conceptual framework for the integration of multi-level biomimicry in building façade design to achieve enhanced environmental and energy performance*

The review demonstrates that multi-level biomimicry provides an effective approach to improving building façade performance, with the integration of organism, behaviour, and ecosystem levels producing greater benefits than any single level alone (Bijari et al., 2025).

Organism-level biomimicry enhances structural efficiency and passive solar control through the replication of biological forms, as seen in the Gherkin Tower's sponge-inspired diagrid system (Sun, 2024). However, these solutions are generally static and cannot adapt to changing environmental conditions.

Behaviour-level biomimicry addresses this limitation by enabling dynamic responsiveness. Examples such as the termite-inspired ventilation of the Eastgate Centre and stomata-inspired kinetic façades demonstrate significant energy savings and improved daylight performance (Sun, 2024; Farmani et al., 2025). Despite these advantages, such systems often involve greater design complexity and maintenance requirements.

Ecosystem-level biomimicry adopts a holistic approach by integrating buildings into ecological cycles through innovations such as coral-inspired carbon-sequestering materials and algae-panel bio-façades, contributing to carbon reduction goals (Metwally, 2025; Rahubadda et al., 2025). However, these technologies remain largely emerging and face challenges related to scalability and regulatory compliance.

A common limitation across all levels is the lack of context-specific performance data under varying climates and building conditions. Future research should focus on empirical simulations and post-occupancy evaluations across diverse climatic regions, while practitioners and policymakers should promote the integration of multi-level biomimicry into early-stage design and supportive regulatory frameworks.

## 4. CONCLUSIONS AND RECOMMENDATIONS

This study establishes that multi-level biomimicry encompassing the organism, behaviour, and ecosystem levels constitutes a valid and evidence-based approach to improving building façade performance across five key targets, thermal performance, daylighting, solar control, energy efficiency, and carbon reduction. The systematic literature review confirms that each level contributes distinct performance benefits, organism-level inspirations improve structural and solar performance; behaviour-level approaches enable dynamic environmental responsiveness; and ecosystem-level strategies facilitate regenerative and carbon-sequestering outcomes.

The conceptual framework developed in this study advances existing knowledge by integrating biological inspirations, biomimicry levels, and performance targets into a unified, structured design instrument. By accommodating both top-down and bottom-up design approaches, the framework supports systematic, performance-oriented decision-making and addresses the gap in multi-level biomimicry evaluation identified in the literature (Hassan et al., 2023). The framework enables practitioners to move beyond isolated, single-level applications and leverage the compounded benefits of multi-level bio-inspired façade design, a shift with significant implications for the sustainability of the built environment.

The broader significance of these findings lies in their applicability across the full spectrum of façade design decision-making: from material selection and form generation to adaptive mechanism design and ecosystem integration. As the building sector faces intensifying pressure to meet net-zero targets, multi-level biomimicry offers a nature-tested, evidence-based path forward. Future work should focus on empirical validation across diverse climatic contexts, integration of the framework into building information

modelling workflows, and exploration of the regulatory and economic conditions necessary to enable widespread adoption.

Further research is required to develop a comprehensive framework for the design and construction of multi-level integrated biomimetic façades. Such a framework should provide practical guidelines for combining organism, behaviour, and ecosystem-level strategies within a single façade system. In addition, future studies should evaluate and validate whether this integrated approach delivers significant improvements in energy efficiency, environmental performance, and overall building sustainability compared with single-level biomimetic applications.

# 5. REFERENCES

AlAli, M., Mattar, Y., Alzaim, M. A., & Beheiry, S. (2023). Applications of biomimicry in architecture, construction and civil engineering. *Biomimetics*, *8*(2), 202. https://doi.org/10.3390/biomimetics8020202

Al-Obaidi, K. M., Hossain, M., Alduais, N. A. M., Al-Duais, H. S., Omrany, H., & Ghaffarianhoseini, A. (2022). A review of using IoT for energy efficient buildings and cities: A built environment perspective. *Energies*, *15*(16), 5991. https://doi.org/10.3390/en15165991

Alyahya, A., Lannon, S., & Jabi, W. (2025). Biomimetic opaque ventilated façade for low-rise buildings in hot arid climate. *Buildings*, *15*(14), 2491. https://doi.org/10.3390/buildings15142491

Athauda, R. S., Asmone, A. S., & Conejos, S. (2023). Climate change impacts on facade building materials: A qualitative study. *Sustainability*, *15*(10), 7893. https://doi.org/10.3390/su15107893

Balafoutis, T. (2025). Architectural lighting simulations as a method to evaluate emotions on cultural heritage building facades. *Architecture*, *5*(1), 3. https://doi.org/10.3390/architecture5010003

Bijari, M., Aflaki, A., & Esfandiari, M. (2025). Plants inspired biomimetics architecture in modern buildings: A review of form, function and energy. *Biomimetics*, *10*(2), 124. https://doi.org/10.3390/biomimetics10020124

Cucuzzella, C., Rahimi, N., & Soulikias, A. (2023). The evolution of the architectural façade since 1950: A contemporary categorization. *Architecture*, *3*(1), 1–32. https://doi.org/10.3390/architecture3010001

Eisazadeh, N., Allacker, K., & de Troyer, F. (2018). Investigating the energy efficiency, environmental and daylighting performance of coated glazing. *Challenging Glass 6: Conference on Architectural and Structural Applications of Glass* (pp. 175–184). https://doi.org/10.7480/cgc.6.2131

El-Abedin, E. Z., Ali, S., Saleh, A., & Foad, M. (2022). Biomimicry as a catalyst to improve the behaviour of building performance. *International Journal of Innovative Research in Science, Engineering and Technology*, *11*(9), 1111–1122. https://doi.org/10.15680/IJIRSET.2022.1109001.

El-Rahman, S. M. A., Esmail, S. I., Khalil, H. B., & El-Razaz, Z. (2020). Biomimicry inspired adaptive building envelope in hot climate. *Engineering Research Journal*, *166*, 30–47. https://www.researchgate.net/publication/348217036_Biomimicry_inspired_Adaptive_Building_Envelope_in_hot_climate

Faragalla, A. M. A., & Asadi, S. (2022). Biomimetic design for adaptive building façades: A paradigm shift towards environmentally conscious architecture. *Energies*, *15*(15), 5390. https://doi.org/10.3390/en15155390

Farmani, F., Hosseini, S. M., Assadi, M. K., & Hassanzadeh, S. (2025). Computational evaluation of a biomimetic kinetic façade inspired by the Venus flytrap for daylight and glare performance. *Buildings*, *15*(11), 1853. https://doi.org/10.3390/buildings15111853

Gadelhak, M. I., & Lang, W. (2016). Optimization of office building façade to enhance daylighting, thermal comfort and energy use intensity. *BSO16: Building simulation and optimization-third IBPSA-England conference* (pp 467-474). University of Newcastle. https://www.researchgate.net/publication/308612413_OPTIMIZATION_OF_OFFICE_BUILDING_FACADE_TO_ENHANCE_DAYLIGHTING_THERMAL_COMFORT_AND_ENERGY_USE_INTENSITY

Gonçalves, M., Figueiredo, A., Almeida, R. M. S. F., & Vicente, R. (2024). Dynamic façades in buildings: A systematic review across thermal comfort, energy efficiency and daylight performance. *Renewable and Sustainable Energy Reviews*, *199*, 114474. https://doi.org/10.1016/j.rser.2024.114474

GRESB. (2018, December 19). Performance targets — "Metrics as measures". https://www.gresb.com/nl-en/performance-targets-%E2%80%9Cmetrics-as-measures%E2%80%9D/

Gursel, A. P., Shehabi, A., & Horvath, A. (2023). Embodied energy and greenhouse gas emission trends from major construction materials of U.S. office buildings constructed after the mid-1940s. *Building and Environment*, *234*, 110196. https://doi.org/10.1016/j.buildenv.2023.110196

Hammond, V. (2023). *Utilizing biomimicry to design sustainable architecture* (Architecture Undergraduate Honors Theses, University of Arkansas). https://scholarworks.uark.edu/cgi/viewcontent.cgi?params=/context/archuht/article/1070/&path_info=Hammond_Utilizing_Biomimicry_to_Design_Sustainable_Architecture_Honors_Capstone_Final.pdf

Hassan, F. H. F., Ali, K. A. Y., & Ahmed, S. A. M. (2023). Biomimicry as an approach to improve daylighting performance in office buildings in Assiut city, Egypt. *Journal of Daylighting*, *10*(1), 1–16. https://doi.org/10.15627/jd.2023.1

Hays, N., Badarnah, L., & Jain, A. (2024). Biomimetic design of building facades: An evolutionary-based computational approach inspired by elephant skin for cooling in hot and humid climates. *Frontiers in Built Environment*, *10*, 1309621. https://doi.org/10.3389/fbuil.2024.1309621

Hegazy, M. A., Attia, S., & Moro, J. L. (2013). Parametric analysis for daylight autonomy and energy consumption in hot climates. *Proceedings of BS2013:13th Conference of international building performance simulation association* (pp 2232-2239). https://www.researchgate.net/publication/286163023_Parametric_analysis_for_daylight_autonomy_and_energy_consumption_in_hot_climates

Helmy, S. E., & Aboulnaga, M. M. (2020). Future cities: The role of biomimicry architecture in improving livability in megacities and mitigating climate change risks. In L. Scott, M. Dastbaz, & C. Gorse (Eds.), *Sustainable Ecological Engineering Design* (pp. 35–49). Springer. https://doi.org/10.1007/978-3-030-44381-8_3

Jamei, E., & Vrcelj, Z. (2021). Biomimicry and the built environment, learning from nature's solutions. *Applied Sciences*, *11*(16), 7514. https://doi.org/10.3390/app11167514

Maleki, A., & Dehghan, N. (2020). Optimization of energy consumption and daylight performance in residential buildings regarding windows design in hot and dry climate of Isfahan. *Science and Technology for the Built Environment*, *27*(3), 351–366. https://doi.org/10.1080/23744731.2020.1812294

Metwally, W. M. (2025). Biomimicry and green architecture: Nature-inspired innovations for sustainable buildings. *Sustainability*, *17*(16), 7223. https://doi.org/10.3390/su17167223

Minaei, A. (2025). A framework for performance-based façade design: Approach for automated and multiobjective simulation and optimization. [*Doctoral dissertation, University of Massachusetts Amherst*]. https://doi.org/10.7275/17635856

Moghaddam, F. B., Banihashemi, S., Bakhshoodeh, R., Fort Mir, J. M., & Delgado, I. N. (2023). Biomimicry green façade: Integrating nature into building façades for enhanced building envelope efficiency. *SSRN, Ahead-of-Print*. https://ssrn.com/abstract=4506662

Othmani, N. I., Mohd Yunos, M. Y., Ramlee, N., Abdul Hamid, N. H., Mohamed, S. A., & Yeo, L. B. (2022). Biomimicry levels as design inspiration in design. *International Journal of Academic Research in Business and Social Sciences*, *12*(8), 2041–2054. https://doi.org/10.6007/ijarbss/v12-i8/14679

Panjwani, P., & Sahu, K. (2023). Biomimetic adaptive facades. *International Research Journal of Engineering and Technology*, *10*(6), 470–476. https://www.irjet.net/archives/V10/i6/IRJET-V10I671.pdf

Rahubadda, R. V. A. D., Kulatunga, U., & Rathnasinghe, A. P. (2025). Learning from nature: Biomimicry-inspired building design for carbon reduction in urban living. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratna, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium* (pp. 1003–1015). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2025.75

Shan, R., & Junghans, L. (2023). Multi-objective optimization for high-performance building façade design: A systematic literature review. *Sustainability, 15(*21), 15596. https://doi.org/10.3390/su152115596

Sheikh, W. T., & Asghar, Q. (2019). Adaptive biomimetic facades: Enhancing energy efficiency of highly glazed buildings. *Frontiers of Architectural Research*, *8*(3), 319–331. https://doi.org/10.1016/j.foar.2019.06.001

Shen, H., Chan, Y.-C., & Tzempelikos, A. (2014). *Development of a façade retrofit performance guide using climate-based analysis including dynamic façade systems*. 3rd International High Performance Buildings Conference at Purdue, 14-17 July 2014. http://docs.lib.purdue.edu/ihpbc/162

Sidhu, R. K., & Singh, V. N. (2021). Biomimicry for developing energy efficient facades. *International Journal of Innovative Research in Technology*, *7*(12), 50–59. https://ijirt.org/publishedpaper/IJIRT151150_PAPER.pdf

Sun, L. (2024). Biomimicry as an approach to sustainable architecture. *International Journal of High School Research*, *6*(1), 87–94. https://doi.org/10.36838/v6i1.15

Tantawy, A. (2023). A proposed study to measure the impact of buildings functions on their architectural facades. *Arts and Architecture Journal, 4*(2), 78–105.

Troup, L., Phillips, R., Eckelman, M. J., & Fannon, D. (2019). Effect of window-to-wall ratio on measured energy consumption in US office buildings. *Energy and Buildings, 203*, 109434. https://doi.org/10.1016/j.enbuild.2019.109434

Zaki, S. H. (2023). Biomimicry as an approach to create architectural resilient projects. *Engineering Research Journal, 179*, A16–A34. https://orcid.org/0000-0001-9646-3242

Zari, M. P., & Hecht, K. (2020). Biomimicry for regenerative built environments: Mapping design strategies for producing ecosystem services. *Biomimetics, 5*(2), 18. https://doi.org/10.3390/biomimetics5020018

Zhong, X., Hu, M., Deetman, S., Steubing, B., Lin, H. X., Hernandez, G. A., Harpprecht, C., Zhang, C., Tukker, A., & Behrens, P. (2021). Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060. *Nature Communications*, *12*(1), 6126. https://doi.org/10.1038/s41467-021-26212-z

Ranasinghe, W.M.N.D., Manawadu, S.M. and Poovahiya, R., 2026. Exploring porcelain tableware waste as a sustainable material for internal wall construction in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 740-753. DOI: https://doi.org/10.31705/WCS.2026.55. Available from: https://ciobwcs.com/papers/

# EXPLORING PORCELAIN TABLEWARE WASTE AS A SUSTAINABLE MATERIAL FOR INTERNAL WALL CONSTRUCTION IN SRI LANKA

**W.M.N.D. Ranasinghe[1], S.M. Manawadu[2] and R. Poovahiya[3]**

## *ABSTRACT*

*Industrial waste has a significant impact on the environment. This research introduces a sustainable solution for industrial waste management. Porcelain tableware waste is a landfill problem, so this research proposes reusing biscuit waste from tableware to support sustainable practices. This research aims to explore the feasibility of using bisqueware waste for internal wall construction. Bisqueware waste is a fired clay material with good strength and workability. It can be used as a composite material to develop new materials. This research is based on an experimental approach; earthenware red clay is used as an additive, mixed with porcelain bisqueware powder to increase plasticity and develop a new material. To achieve different material behaviors, different clay compositions and firing conditions were tested. These conditions provide varying workability and natural qualities. The proposed sustainable material has the qualities of workability, flexibility, strength, and heat absorption. This material can be introduced for modular development in interior partition applications. The design also reflects cultural and traditional aesthetics. The findings provide practical recommendations for sustainable interior construction and further innovation in this field. The developed modular unit is sustainable and eco-friendly, featuring indoor cooling and partition units that create a sense of cultural and traditional vibrancy. The findings offer practical recommendations for enhancing interior partitions and underscore the potential for sustainable interior constructions and continued innovation in this field.*

***Keywords:*** *Bisqueware waste; Construction materials; Porcelain tableware; Product innovation; Sustainability.*

## 1. INTRODUCTION

Solid waste generation has increased significantly in Sri Lanka due to urbanisation, rising consumption, and rapid technological advances. The country faces ongoing challenges in waste management, particularly in handling non-biodegradable materials commonly disposed of in landfills (Menikpura et al., 2012). Among the different types of waste deposited, some stages of porcelain tableware waste can be identified as reusable

[1] Senior Lecturer, Department of Integrated Design, University or Moratuwa, Sri Lanka, dilshanir@uom.lk
[2] Professor Emeritus, Department of Architecture, University or Moratuwa, Sri Lanka, samithama@uom.lk
[3] Professor, Industrial Design Center, Indian Institute of Technology, India, ravi@iitb.ac.in

material. Rapid urbanisation and changes in consumption patterns have contributed to this rise in solid waste. These waste streams, including discarded tableware such as ceramic bisque products, glazed ware, and fired ceramic items, receive limited attention in recycling or reuse processes, despite their advantageous material properties, including high compressive strength and durability.

In the Porcelain Tableware sector, bisque waste comprises large volumes of damaged bisque ceramic ware disposed of in Sri Lanka's landfills daily. Some broken bisque ware is used to produce glaze, and a small percentage of bisque is recycled to create clay pug rolls, but neither amount exceeds 5% of the total waste (Liyanage & Ranasinghe, 2019). The research aims to conserve resources or reuse them through sustainable production methods. Porcelain Tableware waste is classified as either low-temperature-fired(850°C) or high-temperature-fired (1300°C). Low-temperature-fired porcelain has the potential to be classified as sustainable waste. This research tests whether bisque waste, which solidifies after low-firing and becomes insoluble for reuse, can be recycled. Because it has already been fired at 850°C, this study aims to explore the feasibility of using bisqueware waste for internal wall construction.

The objectives are as follows.

1. To evaluate the most suitable clay body mixture and firing temperature for the use of bisqueware waste in internal wall construction.
2 To design a suitable modular unit using bisqueware waste for internal wall construction.

This innovative approach aims to repurpose waste streams into useful resources to minimize the ecological footprint of construction activities and promote the principles of the circular economy within the built environment by converting them into environmentally friendly building materials. Dankotuwa Porcelain PLC was selected as the context for this study. Waste bisque clay materials and red earthenware clay were used in the experimental approach to achieve sustainable reuse for new production. Only the industrial background, material attributes, and behavior of the bisque ware were evaluated to inform the development of an innovation for interior construction.

# 2. LITERATURE REVIEW

## 2.1 CONCEPT OF WASTE

Waste comprises materials, substances, or products that are no longer useful, wanted, or needed and are discarded after use. Waste is any substance or object that the holder discards, intends to discard, or is required to discard (United Nations Environment Programme, 2011). Waste is defined as materials that are not prime products for which the generator has no further use in terms of production, transformation, or consumption, and which the generator discards or intends to discard. In the industrial context, waste comprises materials, energy, or resources that are lost, unused, or rejected during manufacturing and production, or consumption. Waste is typically classified into five categories: solid waste, industrial waste, organic waste, hazardous waste, and production waste (Organization for Economic Co-operation and Development, 2025). This study specifically addresses industrial waste, with an emphasis on waste from tableware production and from factories and manufacturing operations.

## 2.2 SUSTAINABLE WASTE

Sustainable waste management involves reducing and disposing of waste in ways that protect the environment, conserve resources, and support long-term ecological balance. It focuses on minimizing waste generation and promoting practices such as reuse, recycling, and responsible disposal, according to the United Nations Environment Programme. Sustainable waste management can be defined as the systematic management of waste through reduction, reuse, recycling, and recovery of materials to minimize environmental impacts and conserve natural resources (UNEP, 2011). Similarly, the World Bank describes sustainable waste management as the collection, treatment, and disposal of waste in ways that protect human health, preserve the environment, and promote resource efficiency. In research and industrial contexts, sustainable waste practices aim to transform waste materials into valuable resources, reduce landfill disposal, and support environmentally responsible production systems.

## 2.3 APPLICATION OF SUSTAINABLE MATERIALS FOR CONSTRUCTION

Sustainable materials are widely promoted in interior construction because they reduce environmental impacts, conserve natural resources, and improve indoor environmental quality. Sustainable building materials are those that have minimal environmental impact throughout their life cycle, including extraction, processing, use, and disposal (Kibert, 2016).

Reusing existing materials reduces resource extraction and keeps valuable materials out of the waste stream (McDonough & Braungart, 2002). Cork is a renewable material harvested from the bark of cork oak trees without harming the tree. According to the Forest Stewardship Council, cork is a sustainable, renewable natural material widely used in flooring and insulation for its durability and thermal properties. Recycled glass is used in tiles, decorative panels, and countertops. According to UNEP (2011), recycling materials such as glass reduces landfill waste and decreases demand for virgin raw materials in the construction industry. Sustainable materials used in interior construction include bamboo, reclaimed wood, cork, recycled glass, clay-based materials, and recycled ceramics. These materials contribute to resource efficiency, reduced environmental impact, and improved indoor environmental quality, supporting sustainable building practices

## 2.4 APPLICATION OF CLAY AS AN INTERNAL WALL CONSTRUCTION MATERIAL

There are various types of environmentally friendly materials used in building solutions. Clay plaster and terracotta are environmentally friendly and help regulate humidity. Earthen materials provide sustainable building solutions due to their low energy requirements and natural thermal regulation properties (Houben & Guillaud, 1994). Waste ceramics and porcelain materials can be reused in interior construction as aggregates or decorative materials. According to the United Nations Environment Programme, the reuse and recycling of industrial waste materials support sustainable resource management and reduce environmental impacts (UNEP, 2011). Clay is a popular material that was used in ancient civilisations in equatorial regions. There is substantial evidence that clay was used as a firing material in Sri Lanka even seven decades ago (Ariyapala, 1956). Both domestic and construction use can be identified in the history of Sri Lankan clay. Clay has served many purposes. Cooling was one of the purposes of

clay, as seen in the use of *Guruleththuwa, Pinthaliya, Piliheliya,* and wattle. As a construction material, "further, *walauwas* often had thick mud walls, which would transmit less external heat than stone walls" (Uragoda, 2000, p. 216).

### 2.4.1 The Usage of Ceramic Waste

Environmental protection is a growing concern in the twenty-first century, and demand for it is increasing as China implements its sustainable development policy. Reducing environmental pollution and reusing ceramic waste are examples of industrial environmental protection (Shuying et al., 2015). Reducing manufacturing waste can benefit individual enterprises, the global economy, and the environment. Manufacturing companies will experience lower costs, fewer overtime hours, and higher-quality goods by minimizing waste in operations and manufacturing. Pollution and carbon footprints will be reduced simultaneously, improving the environment for everyone (Sable & Dakhore,2014). According to the research paper (Andres et al., 2010), ceramic aggregates were recycled for use in the construction and civil engineering industries after being crushed to reduce their size, sieved, and subjected to laboratory analysis.

### 2.4.2 Material Behaviour of Porcelain Tableware Products

Tableware comprises a range of ceramic products used for serving and consuming food and beverages, including teacups, saucers, teapots, creamers, sugar bowls, plates, platters, and dishes (Tea set & Dinner set). These items are commonly used in domestic settings and in the hospitality sector, including hotels and restaurants. Porcelain is a type of ceramic material consisting of inorganic, non-metallic solids produced at high temperatures. Ceramic materials, including porcelain, are typically composed of oxides, carbides, and nitrides, which confer heat-resistant and refractory properties (Midwest Research Institute, 1996). During firing, temperature, kiln atmosphere, and firing duration significantly influence the chemical reactions and microstructural development of the ceramic body. Tableware manufacturer Dankotuwa Porcelain is known for its cutting-edge designs. Although the methods used centuries ago seem relatively primitive by today's standards, they still convey a level of creativity that was essential to the business of the time. The people are inspired to give our items an elegant touch by their creativity and passion. Quartz, feldspar, talc, bauxite stone, Bentonite, Alumina, Kaolinite (China clay), Water, and bisque (3%) are the clay body materials used in porcelain.

Variations in kiln conditions can therefore affect the final qualities and performance of porcelain products. Within the ceramic industry, porcelain is commonly associated with whiteware production, where firing processes play an important role in determining product quality and production efficiency. Optimising firing conditions can help reduce production costs by improving energy efficiency (Carty & Senapati, 1998). Porcelain is typically produced from a composition of quartz, feldspar, and clay (kaolin). In this composition, clay provides plasticity and mechanical strength during forming and contributes to the formation of mullite and the glassy phase during firing. Feldspar acts as a flux, forming a liquid phase at lower temperatures, thereby aiding densification and reducing porosity. Quartz, with its high melting point, contributes to the final product's dimensional stability and thermal resistance (De Noni et al., 2009).

## 2.5 DANKOTUWA PORCELAIN PLC AND TABLEWARE PRODUCTION PROCESS

The study was based on Dankotuwa Porcelain PLC in Sri Lanka, which has a 38-year history and is the largest tableware manufacturer with a well-known brand reputation in the country's porcelain tableware market. The company has a diverse portfolio of designs and ever-evolving items to satisfy consumer demand. In line with industry best practices and worldwide standards, the company offers its products to domestic and global markets. The business is an ISO 9001:2008-certified maker of premium porcelain tableware. Buyers for Dankotuwa come from 25 different nations, including Belgium, the Czech Republic, Colombia, Dubai, Germany, Greece, India, Iceland, Italy, Kuwait, Norway, Pakistan, Poland, Russia, Spain, Switzerland, the United States, the United Kingdom, and Ukraine, among others (Export Development Board Sri Lanka, 2020). Due to the increasing volume of industrial waste, recycling has become a major environmental concern worldwide. This study focuses on the waste generated from damaged bisque ware in porcelain manufacturing. In large-scale production processes, a significant number of items pass through the factory daily, resulting in unavoidable defects. According to statistics from the bisque ware department, approximately 5–6% of the total production is damaged at the bisque stage. Figure 1 and 2 presents the tableware manufacturing and firing process.

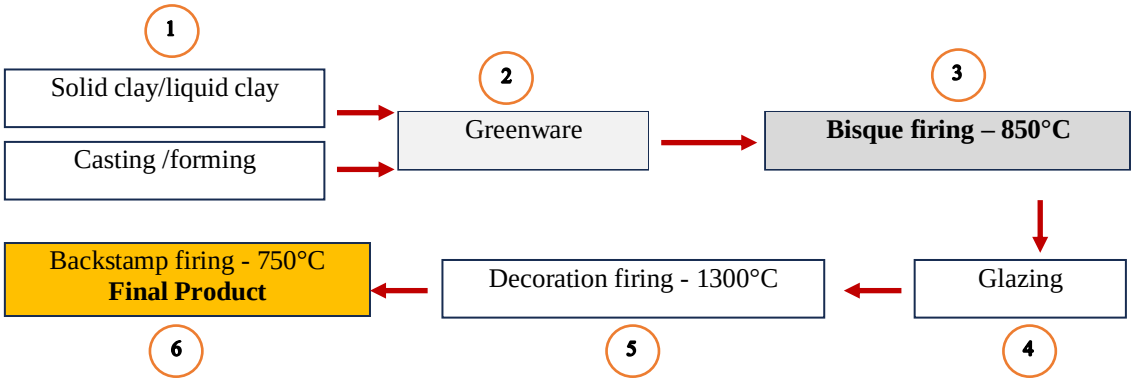



*Figure 1: Production process of the tableware industry*

*Figure 2: Greeware production process and greenware cart [Source: Dankotuwa Porcelain PLC]*

Four firing processes can be identified in porcelain tableware manufacturing. A special reason is that the product from the clay stage to the bisque-ware firing can be reused as waste, but after glazing and back-stamping firing, the body cannot be reused easily and is difficult to crush or grind due to its hardness and altered composition.

## 2.6 BISQUEWARE WASTE IN DANKOTUWA PLC

Bisque, bisqueware, or biscuit ware refers to pottery that has undergone the first low-temperature firing in a kiln (750°C to 850°C), during which the clay becomes partially matured but remains porous, making it suitable for further processes such as glazing. After the firing, the clay particles are bonded together, a process known as sintering; the particles become slightly attached, which strengthens the whole piece so that the clay itself, the body of clay, becomes stronger, more robust, and more handleable, which is one of the main reasons for the bisque firing. At this stage, the ceramic body becomes durable enough for handling and glazing while maintaining sufficient porosity to absorb glaze materials. After the bisque stage, products are inspected for defects before proceeding to glazing and final firing (Shears, 2020). Bisqueware has a soaking quality. It will soak up water and glaze over after being dipped in glaze. The pottery transforms from greenware to bisque when the temperature climbs from 0°C to 850°C. Materials become less porous; bisque firing will cause them to lose at least 16% of their weight. This is consistent with the research paper (Carty & Senapati,1998). The following images show the types of damage that occur during firing (Figure 3).

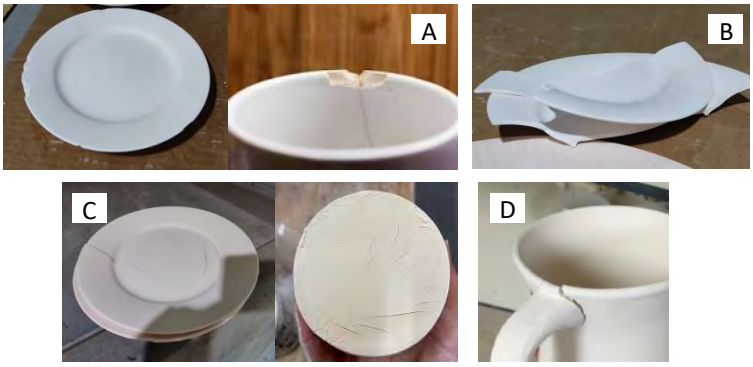



*Figure 3: Tableware bisque ware waste: **A**-Edge Crack, **B**-Body Crack, **C**-Bottom Crack, **D**-Handle Crack [Source: Dankotuwa Porcelain PLC]*

Ceramics have a long history and continue to evolve as important materials in modern industries. Porcelain, a refined ceramic, has been developed and refined over many generations, resulting in distinctive physical and aesthetic qualities. These products are exported worldwide and contribute to the national economy (Export Development Board Sri Lanka, 2020). However, large-scale production also brings challenges, including high resource consumption and increased industrial waste (Figure 4).

*Figure 4: Tableware Bisque Ware Waste [Source: Dankotuwa Porcelain PLC]*

It examines sustainable manufacturing practices in the ceramic sector. It explores the historical context of porcelain production in Sri Lanka, the material characteristics of bisque ware, and effective strategies for managing resources and waste sustainably. Every industrial sector is increasingly adopting sustainable production practices to protect the environment for future generations.

*Table 1: 6 Months of bisque damage in Dankotuwa porcelain plc*

| Month | Total Bisque Issued | Damaged Bisque Ware | Damaged Percentage |
|---|---|---|---|
| Jan-22 | 4 31 261 | 16 540 | 3.69% |
| Feb-22 | 4 00 534 | 13 737 | 3.31% |
| Mar-22 | 5 21 341 | 19 584 | 3.62% |
| Apr-22 | 3 23 801 | 13 109 | 3.89% |
| May-22 | 4 63 031 | 18 261 | 3.79% |
| Jun-22 | 4 34 098 | 15 177 | 3.37% |
| ***Total*** | ***2 104 066*** | ***96 408*** | |

The table (Table 1) above shows bisque ware waste at Dankotuwa Porcelain PLC over 6 months in 2022. The term was broadened to encompass the art and science of producing and using solid products made from earthy raw materials (Richerson & Lee, 2018). This definition states that a ceramic is anything other than an organic substance or a metal. Sustainable materials play an important role in interior construction by helping reduce environmental impacts and promoting efficient resource use. Sustainable building materials have minimal environmental impact throughout their life cycle, from extraction and processing to use and disposal (Kibert, 2016). The use of recycled and waste materials in construction is increasingly encouraged as a strategy to reduce industrial waste and conserve natural resources. Reusing existing materials prevents valuable resources from entering the waste stream and supports circular material flows in sustainable design (McDonough & Braungart, 2002).

In the ceramic industry, waste materials such as damaged porcelain and bisque ware offer opportunities for reuse as alternative construction materials. Recycling and reusing industrial waste can significantly reduce landfill disposal while contributing to sustainable manufacturing practices (UNEP, 2011). Therefore, incorporating bisque-ware waste into clay-based materials can offer a sustainable solution. Researchers also emphasize that sustainable production practices in the ceramic industry include improving kiln efficiency, optimizing raw material usage, and reusing ceramic waste such as damaged bisque ware (Dornfeld, 2009; Carty & Senapati, 1998). These strategies contribute to environmental protection while maintaining efficient and economically viable porcelain manufacturing. According to the Dankotuwa porcelain annual report for 2022/24, the company sold leftover clay to local small-scale manufacturers at a nominal price. It implemented strategies to optimize material efficiency and reduce waste, which are the main concerns of the company's decisions. Not only that, but they are also concerned about Industry Innovation and Infrastructure Development, which are expanded and enhanced through research and technological advancements. Measures were implemented to enhance production efficiency and minimize waste and defects. Proper waste disposal and reprocessing of materials to minimize solid waste are the main

considerations. As a result, the company is willing to sell its leftovers, such as bisque ware and plaster moulds, to outsiders and researchers for innovation rather than landfill them.

Bisque-ware waste has been identified as a promising material to address the research gap. Research idea to fill the gap, as it is often discarded without effective long-term solutions despite its valuable properties. As a first-fired ceramic material, bisque ware has distinctive characteristics, including porosity, light weight, surface gaps, and water absorption. These properties present opportunities for material developments and innovations. Therefore, further research is needed to explore new materials or recycling methods to provide sustainable solutions for managing bisque-ware waste.

## 3. METHODOLOGY

The table (Table 1) above shows bisque ware waste at Dankotuwa Porcelain PLC over 6 months in 2022. The term was broadened to encompass the art and science of producing and using solid products made from earthy raw materials (Richerson & Lee, 2018). This definition states that a ceramic is anything other than an organic substance or a metal. Sustainable materials play an important role in interior construction by helping reduce environmental impacts and promoting efficient resource use. Sustainable building materials have minimal environmental impact throughout their life cycle, from extraction and processing to use and disposal (Kibert, 2016). The use of recycled and waste materials in construction is increasingly encouraged as a strategy to reduce industrial waste and conserve natural resources. Reusing existing materials prevents valuable resources from entering the waste stream and supports circular material flows in sustainable design (McDonough & Braungart, 2002).

In the ceramic industry, waste materials such as damaged porcelain and bisque ware offer opportunities for reuse as alternative construction materials. Recycling and reusing industrial waste can significantly reduce landfill disposal while contributing to sustainable manufacturing practices (UNEP, 2011). Therefore, incorporating bisque-ware waste into clay-based materials can offer a sustainable solution. Researchers also emphasize that sustainable production practices in the ceramic industry include improving kiln efficiency, optimizing raw material usage, and reusing ceramic waste such as damaged bisque ware (Dornfeld, 2013; Carty & Senapati, 1998). These strategies contribute to environmental protection while maintaining efficient and economically viable porcelain manufacturing. According to the Dankotuwa porcelain annual report for 2022/24, the company sold leftover clay to local small-scale manufacturers at a nominal price. It implemented strategies to optimize material efficiency and reduce waste, which are the main concerns of the company's decisions. Not only that, but they are also concerned about Industry Innovation and Infrastructure Development, which are expanded and enhanced through research and technological advancements. Measures were implemented to enhance production efficiency and minimize waste and defects. Proper waste disposal and reprocessing of materials to minimize solid waste are the main considerations. As a result, the company is willing to sell its leftovers, such as bisque ware and plaster moulds, to outsiders and researchers for innovation rather than landfill them.

Bisque-ware waste has been identified as a promising material to address the research gap. Research idea to fill the gap, as it is often discarded without effective long-term

solutions despite its valuable properties. As a first-fired ceramic material, bisque ware has distinctive characteristics, including porosity, light weight, surface gaps, and water absorption. These properties present opportunities for material developments and innovations. Therefore, further research is needed to explore new materials or recycling methods to provide sustainable solutions for managing bisque-ware waste.

## 3.1 EXPERIMENTAL APPROACH TO RESEARCH

There is a significant gap in the literature on combining bisque ware and clay for sustainable material development. This research adopts an experimental approach to address porcelain bisque waste and develop new materials for sustainable interior applications. As a high-porosity by-product of porcelain manufacturing, bisque ware can potentially be used as an aggregate material when combined with clay. Its porosity and heat-absorption properties provide opportunities to develop a composite material with beneficial characteristics such as improved permeability and structural strength. Therefore, the study focuses on transforming bisque waste into a sustainable material solution for interior construction applications. An experimental process for Material Testing is presented in Figure 5.

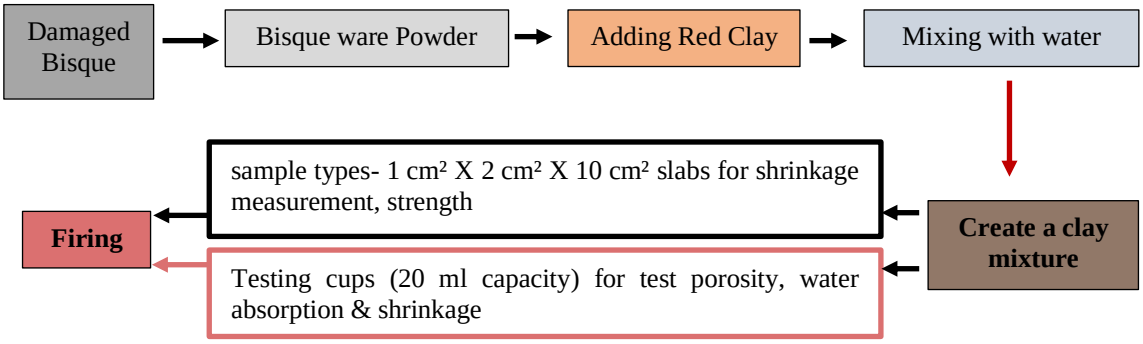



*Figure 5: Design framework for material testing process [Source: Authors' Creation]*

Figure 5 outlines how bisque ware can be combined with clay to create novel composite materials for interior applications. Together, these steps define the material development process and experimental conditions, ensuring alignment with the core objectives of sustainability, ecological restoration, and effective interior design practices. During the material development phase, the testing was conducted using various combinations of bisque ware and clay (Natural Red Clay) to determine the optimal mix. The bisque ware will be combined with clay in the following ratios (Table 2).

*Table 2: Bisque Ware Firing Temperatures [Authors' Creation]*

| Porcelain Bisque ware | Red Clay | Firing Temperature | | | |
|---|---|---|---|---|---|
| 20% | 80% | 500°C | 650°C | 750°C | 850°C |
| 50% | 50% | 500°C | 650°C | 750°C | 850°C |
| **60%** | **40%** | 500°C | 650°C | **750°C** | 850°C |
| 80% | 20% | 500°C | 650°C | 750°C | 850°C |

This material-mixing process aims to identify the most effective material combination for interior applications, thereby creating new opportunities for the use of porcelain-bisque waste.

# 4. RESEARCH FINDINGS AND ANALYSIS

## 4.1 RESEARCH FINDINGS FROM BISQUEWARE WASTAGE

The study investigated several combinations of bisque ware and clay to identify the most effective mixture to improve material characteristics for interior applications. Through this experimental process, the research aimed to determine the optimal composition that enhances the strength, porosity, and overall performance of the developed material. The rationale for selecting these ratios was to evaluate how different proportions of bisque ware, which is characterised by high porosity and strength, would affect the material. In contrast, higher proportions (50%, 60%, and 80%) were anticipated to increase porosity and water absorption capacity, potentially enhancing the material's suitability for moisture absorption in interior environments. The objective of testing these variations was to identify an optimal balance between structural integrity and functional performance, ensuring that the developed material possesses both durability and beneficial characteristics for interior applications. This study's findings indicate apparent new material experimental findings from bisque waste.

*Table 3: Firing temperatures & material behaviors [Authors' Creation]*

| Temperature | Qualities of the Experimental Clay Body |
|---|---|
| 500°C Fired Samples | These samples exhibit an earthy colour and rustic appearance with the lowest shrinkage rate, allowing precise shaping. They also demonstrate good water absorption while maintaining structural integrity. Additionally, the low firing temperature makes the process cost-effective, enhancing the material's suitability for various applications. |
| 650°C Fired Samples | Compared to the 500°C samples, those fired at 650°C exhibit increased strength and a different colour. The material has improved fired clay qualities but experiences higher shrinkage and water absorption. This temperature enhances the material's durability but may limit its application due to these changes. |
| **750°C Fired Samples** | Samples fired at 750 °C show increased strength and reduced shrinkage compared to lower temperatures. However, they exhibit high water absorption, with some samples absorbing up to 8 ml of water in less than 10 minutes. Their darker colour and uniform appearance make them suitable for strength-focused applications, although the high-water absorption may limit their use. |
| 850°C Fired Samples | The highest firing temperature produces materials with exceptional strength, darker colour, and a more uniform appearance. However, these samples show significant shrinkage and very high-water absorption rates, with some draining 8 ml of water in less than five minutes. While these properties may benefit certain applications, the higher production costs and excessive water absorption must be carefully considered. |

Among the test pieces shown in the table (Table 3) above, the 750°C sample with a 60:40 clay composition was selected because the tested bisque ratio exhibited the most suitable properties for interior applications. It exhibited low shrinkage, allowing for accurate casting and consistent forms while maintaining a lightweight structure and a rustic aesthetic. These characteristics make it suitable for interior and penetration applications, particularly where moisture absorption and strength support are beneficial. This clay body is a newly developed material with remarkable material values. The reliability of the newly developed material provides design ideas for the construction industry and offers a solution for bisqueware waste by introducing a new system chain.

## 4.2 DEVELOPMENT OF A MODULAR UNIT USING BISQUEWARE FOR INTERNAL WALL CONSTRUCTION

The selected clay body offers a balance of water absorption and strength. The developed shape and form provide additional functional value, and the modules have been cast to rotate around a supporting bar, enabling flexible interior partition arrangements and improved airflow from the exterior (See Figures 6 and 7). Furthermore, during firing, the design enables efficient stacking within the kiln, maximising space utilisation and reducing wasted capacity. Unlike conventional temporary partitions, which often rely on high-cost or difficult-to-handle synthetic materials, the developed clay module serves as a non-load-bearing partition system. In addition to its individual functional role, the module can serve as an indoor partition curtain, providing flexible and sustainable spatial organisation.

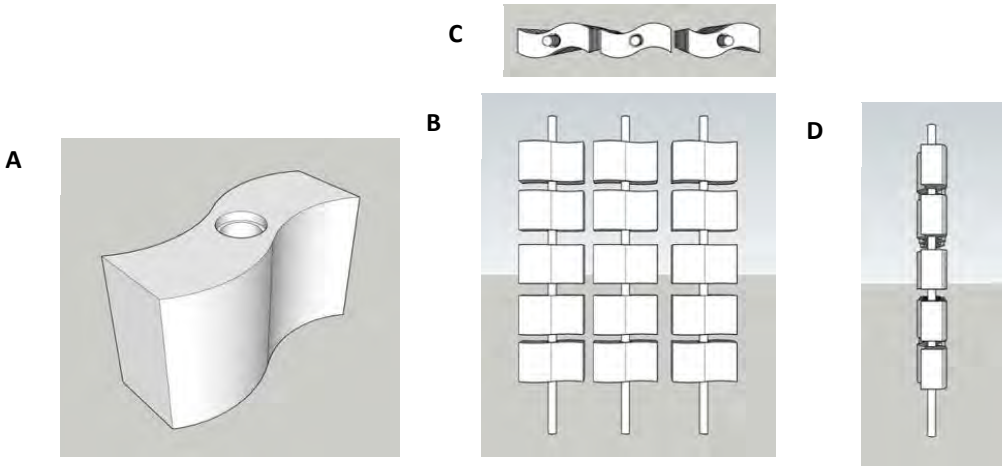



*Figure 6: A-Modular unit, B-Front View, C- Top View, D-Side View [Source: Authors' Creations]*

The modular units can be arranged according to specific interior requirements. They can also serve as temporary partition elements, enabling flexible spatial organisation without damaging the original building structure. It is fixed to the floor using a 1-inch diameter stainless steel bar.

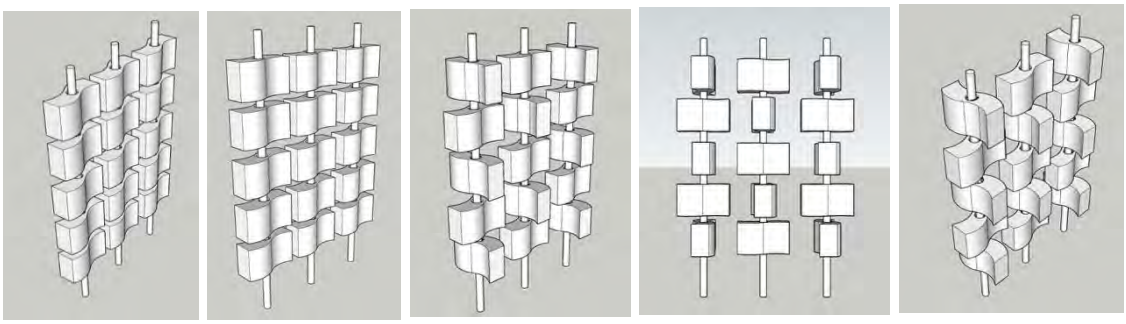


*Figure 7: Interior arrangement [Source: Authors' Creations]*

## 5. CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

This research's findings demonstrate and describe the potential of porcelain bisque waste as an environmentally sustainable alternative for interior construction, while promoting the reuse of ceramic waste and supporting circular economy practices. This research highlighted the potential of using porcelain bisque waste as a sustainable material for interior construction in Sri Lanka. This composition exhibits physical and functional properties, including water absorption, thermal performance that contributes to a cooler environment, aesthetic appeal, and good strength and flexibility. Based on these qualities, the findings indicate that combining porcelain bisque waste with red earthenware clay can produce a new modular unit. It can be introduced for non-load-bearing interior partitions fixed to the floor. The proposed modular unit can be applied to the interior partition system, offering lightweight construction, easy installation, straightforward arrangement, and replacement. The proposed material properties can be modified by altering the material composition and the firing temperature to suit the required indoor environment. As an interior arrangement, the modular configuration enables a variety of design possibilities and spatial arrangements.

The proposed design solution addresses porcelain tableware bisque-ware waste while introducing a modular system as a novel, sustainable application in interior construction. For further development, the proposed material and modular design can be enhanced by incorporating water retention within the modular units, allowing moisture to penetrate the clay structure, and promoting cross-ventilation for cooling in indoor environments. This will support evaporative cooling and improve air circulation, thereby reducing energy consumption for indoor climate control. Future research should investigate the optimal percentage of porcelain bisque waste in the material composition, as well as the feasibility of large-scale manufacturing, production processes, production costs, and market unit pricing. These aspects are essential for assessing the commercial viability and practical implementation of the proposed modular system in the interior construction industry.

The proposed solution has the potential to be adopted by other ceramic manufacturers in Sri Lanka and internationally for the sustainable reuse of porcelain bisque waste. However, further research and industry-scale validation are required to assess its technical feasibility, economic viability, and adaptability to different manufacturing contexts. The system's cooling performance has not yet been fully validated under real-world operating conditions. This area is reserved for future researchers to continue this experimental study. Further long-term assessments are required to evaluate and optimise its effectiveness under real-world conditions.

## 6. ACKNOWLEDGEMENTS

This research was conducted in collaboration with Dankotuwa Porcelain PLC as part of a study of porcelain tableware production. We express our sincere gratitude to the management and staff of Dankotuwa Porcelain PLC, particularly the members of the Design Department, for their valuable support, discussions, and guidance. We also extend our sincere thanks to the University of Moratuwa, especially the Department of Materials Science and Engineering and the Department of Integrated Design, for their academic support and encouragement in completing this research.

## 7. REFERENCES

Andres, L., & Wyn, J. (2010). *The making of a generation: the children of the 1970s in adulthood* (1st ed., Vol. 23). University of Toronto Press. https://doi.org/10.3138/9781442699830

Ariyapala, M. B. (1956). *Society in Mediaeval Ceylon: The state of society in Ceylon as depicted in the Saddharma-ratnāvaliya and other literature of the thirteenth century*. Department of Cultural Affairs Colombo Ceylon. https://archive.org/details/societyinmediaev0000mbar/page/n9/mode/2up

Carty, W. M., & Senapati, U. (1998). Porcelain—Raw materials, processing, phase evolution, and mechanical behavior. *Journal of the American Ceramic Society*, 81(1), 3–20. https://doi.org/10.1111/j.1151-2916.1998.tb02290.x

De Noni, A., Hotza, D., Soler, V. C., & Vilches, E. S. (2009). Influence of composition on mechanical behaviour of porcelain tile. Part I: Microstructural characterization and developed phases after firing. *Materials Science and Engineering A*, 527(7–8), 1730–1735. https://doi.org/10.1016/j.msea.2009.10.057

Dornfeld, D. (2013). *Green manufacturing: Fundamentals and applications* (1st ed.). Springer New York. https://doi.org/10.1007/978-1-4419-6016-0.

Export Development Board Sri Lanka. (2020). *Dankotuwa Porcelain PLC - EDB Sri Lanka*. https://www.srilankabusiness.com/exporters-directory/company-profiles/dankotuwa-porcelain-plc/

Houben, H., & Guillard, H. (1994). *Earth Construction: A Comprehensive Guide* (1st ed.). Intermediate Technology Publications.

Kibert, C. J. (2016). *Sustainable construction: Green building design and delivery* (4th ed.). John Wiley & Sons, Inc. https://download.e-bookshelf.de/download/0007/6913/92/L-G-0007691392-0013787786.pdf

Liyanage, S., & Ranasinghe, W. M. N. D. (2019). Identification of the possibility to reuse the ceramics glazed tile waste as an eco-friendly raw material for the manufacturing industry in Sri Lanka. *In Proceedings of the 12th International Conference of Faculty of Architecture Research Unit (FARU)*, University of Moratuwa. http://dl.lib.uom.lk/handle/123/16579

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. Farrar, Straus and Giroux.

Menikpura, S. N. M., Gheewala, S. H., & Bonnet, S. (2012). Sustainability assessment of municipal solid waste management in Sri Lanka: problems and prospects. *Journal of Material Cycles and Waste Management*, 14(3), 181–192. https://doi.org/10.1007/s10163-012-0055-z

Midwest Research Institute. (1996). Ceramic Industry Technical Report - Kansas City. In *Midwest Research Institute*.

Organisation for Economic Co-operation and Development. (2025). *Environment at a Glance Indicators*. https://www.oecd.org/en/publications/environment-at-a-glance-indicators_ac4b8b89-en/full-report/component-5.html

Richerson, D. W., & Lee, W. E. (2018). *Modern Ceramic Engineering: Book Modern Ceramic Engineering Properties, Processing, and Use in Design* (4th ed.). CRC Press. https://doi.org/10.1201/9780429488245.

Sable, C. S., & Dakhore, M. M. (2014). Reducing waste in production by lean thinking - A Case study. *International Journal of Engineering Research & Technology (IJERT)*, 3(6), 381–

386. https://www.ijert.org/research/reducing-waste-in-production-by-lean-thinking-a-case-study-IJERTV3IS060650.pdf

Shears, E. (2026, April 10). Bisqueware Ceramics Definition The chemistry lurking behind. *Artabys*. https://artabys.com/bisqueware-ceramics-definition-the-chemistry-lurking-behind/

Shuying, Q., Bin, Z., Chen, S., & Jin, L. (2015). Application of ceramic wastes in concrete. *The Open Civil Engineering Journal*, 8(1), 368–372. https://doi.org/10.2174/1874149501509010368

United Nations Environment Programme. (2011). Towards a green economy: Pathways to sustainable development and poverty eradication. In *United Nations Environment Programme*. https://wedocs.unep.org/bitstreams/b7d87581-4f53-4e85-83e3-4bb87f49f6ad/download

Uragoda, C. G. (2000). *Traditions of Sri Lanka: A selection with a scientific background* (1st ed.). Vishva Lekha Ratmalana.

Madanayake, B.W. and Nissanka, S., 2026. Exploring the current status of retrofitting or rebuilding in construction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 754-767. DOI: https://doi.org/10.31705/WCS.2026.56. Available from: https://ciobwcs.com/papers/

# EXPLORING THE CURRENT STATUS OF RETROFITTING OR REBUILDING IN CONSTRUCTION

**B.W. Madanayake[1] and S. Nissanka[2]**

## *ABSTRACT*

*In Sri Lanka, construction professionals face a recurring dilemma: retrofit an existing building or rebuild it from scratch. This decision is not merely technical, it involves cost, environmental impact, policy constraints and heritage. While international research offers retrofit first models, they rarely fit Sri Lanka's economic and regulatory reality. This study explores how global research addresses retrofit versus rebuild decisions and identifies the limitations of applying those frameworks locally. A mixed methods approach was used: semi structured interviews with ten Technical Officers (analysed via NVivo thematic coding) and a questionnaire survey of 26 industry professionals plus the same 10 Technical Officers (total N=36, analysed using Relative Importance Index). Results show that structural condition (RII=0.89), cost (RII=0.86) and sustainability (RII=0.71) are the top three decisive factors. Retrofitting is preferred for cost efficiency, shorter timelines and lower waste; rebuilding is chosen when structural safety or modern standards cannot be met. Key barriers include hidden defects, lack of skilled labour and weak institutional support. The study culminates in a local decision-making framework that integrates technical, economic, environmental and policy criteria, helping practitioners make transparent, data driven choices aligned with national climate resilience goals.*

***Keywords:*** *Decision making framework; Rebuilding; Retrofitting; Sri Lanka; Sustainability.*

## 1. INTRODUCTION

The construction industry is a major consumer of resources and contributor to carbon emissions. In developing economies like Sri Lanka, much of the building stock is ageing, structurally inadequate or functionally obsolete. Consequently, professionals constantly face a dilemma: retrofit an existing structure or demolish and rebuild. This decision is complex, involving economic, environmental, social and regulatory factors.

Retrofitting is promoted in sustainable construction because it reduces embodied carbon, cuts waste and extends building life. Rebuilding is seen as more reliable when a building is severely deteriorated or fails modern safety standards. However, most retrofit first guidelines come from developed countries with strong incentives, advanced skills and clear policies. Applying them directly in Sri Lanka is problematic.

[1] Sri Lanka Institute of Information Technology, Sri Lanka, buthmi2001@gmail.com
[2] Sri Lanka Institute of Information Technology, Sri Lanka, shavindree.n@sliit.lk

In Sri Lanka, decisions are often based on professional judgement, cost limits and perceived risk, not on structured tools. The lack of local guidelines, combined with skilled labour shortages and weak institutional support, leads to inconsistent outcomes. Rising sustainability expectations and pressure to preserve existing urban fabric add further complexity.

Therefore, this study aims to develop a structured decision-making framework specifically for retrofit versus rebuild decisions in Sri Lanka. It investigates current practices, identifies influencing factors, evaluates benefits and challenges, and extracts best practices. By combining literature, survey data and interviews, the study bridges international theory and local practice.

# 2. LITERATURE REVIEW

## 2.1 RETROFITTING VERSUS REBUILDING IN SUSTAINABLE CONSTRUCTION

International research consistently shows that retrofitting reduces embodied energy, carbon and waste compared to demolition and new build (Ferreira et al., 2015; Peng et al., 2021). Retrofitting also preserves community continuity and heritage (Josa & Borrion, 2025; Power, 2010). However, rebuilding is unavoidable when a building has extensive structural damage, very short remaining life, or cannot meet modern safety codes (Power, 2010; Rønning et al., 2009). Thus, the decision is context dependent.

## 2.2 KEY FACTORS INFLUENCING RETROFIT OR REBUILD DECISIONS

Economic feasibility is the dominant factor, retrofitting usually has lower upfront cost and faster payback (Bullen & Love, 2011). Environmental impact is second: studies from China and Ukraine show retrofitting cuts carbon significantly (Peng et al., 2021; Troian et al., 2024). Structural integrity and remaining lifespan also matter; a building with complex geometry or limited life may not justify retrofitting (Chen et al., 2024). Social and cultural aspects matter in historic areas (Dişli & Ankaralıgil, 2023). Policy and regulations strongly affect adoption – developing countries often lack incentives and clear guidance (Rønning et al., 2009). A systematic review by Liu et al. (2022) identified 689 factors grouped into seven categories, highlighting that homeowner characteristics and belief about energy retrofit consequences are as important as technical factors.

## 2.3 BARRIERS AND OPPORTUNITIES ASSOCIATED WITH RETROFITTING

Barriers include high upfront cost, hidden defects, lack of skilled labour, weak supply chains and fragmented policy (Fasna & Gunatilake, 2020; Jagarajan et al., 2017). Opportunities are long term savings, lower operational energy, better comfort and increased property value (Periyannan et al., 2023). In seismic contexts, Egbelakin et al. (2014) found that economic impediments (unattractive payback, uncertainty) are the strongest barriers to retrofit adoption, a finding that resonates strongly in Sri Lanka where disaster risk is real but financial buffers are small.

*Table 1: Comparison between barriers/challenges vs. benefits/opportunities.*

| Aspect | Barriers and Challenges | Benefits and Opportunities |
|---|---|---|
| Financial | High upfront cost | Long term cost savings |
| | Unattractive payback schemes | Increased property value |

| Aspect | Barriers and Challenges | Benefits and Opportunities |
|---|---|---|
| | Uncertainty over long-term savings | Reduced operational energy cost |
| Technical | Lack of skilled labour and expertise<br>Weak supply chains<br>Complexity of processes<br>Limited availability of materials | Opportunities for technological innovation<br>Improved building performance<br>Modernized systems |
| Policy | Absence of strong incentives<br>Fragmented regulations<br>Poor government support | Potential alignment with climate policies<br>Contribution to national sustainability targets |
| Social | Client reluctance<br>Disruption to occupants<br>Poor communication among stakeholders<br>Low awareness of benefits | Improved occupant comfort and satisfaction<br>Enhanced working and living environments<br>Greater stakeholder value |
| Environmental | Uncertainty about effectiveness of green technologies<br>Higher costs in some contexts | Reduced carbon emissions<br>Resource efficiency<br>Waste minimization<br>Climate change mitigation |

### 2.4 RESEARCH GAP AND NEED FOR A LOCAL DECISION FRAMEWORK

Most existing decision models (e.g., Menassa & Baer, 2014; Steskens et al., 2015) are built for high income countries with stable regulations, strong incentives and advanced technical capacity. They do not account for Sri Lanka's informal construction sector, weak enforcement of building codes, and very limited financial support for green retrofits. Although Jayarathne et al. (2024) and Ranawaka and Mallawaarachchi (2018) proposed decision frameworks relevant to sustainable retrofitting in Sri Lanka, their studies focus on specific aspects such as green retrofit implementation and smart retrofit decision-making. They do not provide a comprehensive framework that systematically guides practitioners in choosing between retrofitting and rebuilding under the technical, economic, environmental, and regulatory constraints commonly encountered in the Sri Lankan construction industry. Therefore, there remains a need for a practical, context-specific decision-making framework that integrates these multiple criteria into a single decision-support approach. This study fills that gap by developing a localised, multi criteria framework that works under Sri Lanka's real constraints – low budget flexibility, variable skill levels, and minimal policy support. Unlike generic models, our framework explicitly includes a rule for "structural safety first" and uses simple inputs (visual inspection, basic cost estimates) so that a Technical Officer can apply it without specialised software.

## 3. RESEARCH METHODOLOGY

A mixed methods design was used to capture both deep professional insights and broad industry trends.

### 3.1 LITERATURE REVIEW

A systematic review was conducted to identify decision factors, barriers, benefits and existing models. This informed the interview guide and questionnaire.

### 3.2 QUALITATIVE INTERVIEWS

Semi-structured interviews were conducted with ten Technical Officers (TOs) involved in ongoing building projects located in Colombo, Kandy and Galle. Participants were selected using purposive sampling based on two criteria: a minimum of five years of professional experience in building construction and direct involvement in at least two retrofit or rebuild decisions within the previous three years. The interviews explored participants' perceptions of retrofitting and rebuilding, decision-making factors, barriers, challenges and best practices. Prior to data collection, the interview protocol was pilot tested with two Technical Officers who were not included in the final sample. Interviews lasted between 45 and 60 minutes and were audio-recorded and transcribed verbatim. The qualitative data were analysed using NVivo 14 following Braun and Clarke's (2006) six-phase thematic analysis procedure. This process generated 31 initial codes which were subsequently consolidated into eight overarching themes. Reliability was enhanced through independent coding by two researchers, resulting in an agreement level of 86%, while validity was strengthened through member checking with three participants. Ethical procedures included obtaining informed consent, anonymising participants as TO1–TO10 and securely storing all research data on a password-protected university drive.

### 3.3 QUESTIONNAIRE SURVEY

A questionnaire survey was undertaken to obtain quantitative evidence regarding the factors influencing retrofit and rebuild decisions. Purposive sampling was employed through professional networks including IESL, CIOB Sri Lanka and CIDA. A total of 150 questionnaires were distributed, resulting in 87 returned responses and a response rate of 58%. Following data screening and matching with interview participants, 36 complete responses were retained for analysis, comprising 26 industry professionals and the ten Technical Officers interviewed during the qualitative phase. Respondents included engineers (42%), quantity surveyors (28%), architects (18%) and project managers (12%), with an average professional experience of 11 years. The questionnaire employed a five-point Likert scale ranging from 1 (not important) to 5 (extremely important). Prior to distribution, the questionnaire was pilot tested with ten industry professionals and revised for clarity. Data were analysed using the Relative Importance Index (RII), calculated as $RII = \Sigma(w)/(A \times N)$, where w represents the weighting assigned by respondents, A is the highest possible weighting (5), and N is the total number of respondents. RII values range from 0 to 1, with higher values indicating greater importance.

### 3.4 INTEGRATION OF QUALITATIVE AND QUANTITATIVE FINDINGS

The final stage of the study involved integrating the qualitative and quantitative findings to develop a comprehensive understanding of retrofit versus rebuild decision-making within the Sri Lankan construction industry. A triangulation approach was adopted whereby the themes emerging from the qualitative interviews were compared with the Relative Importance Index (RII) rankings obtained from the questionnaire survey. The qualitative findings provided contextual explanations for the quantitative results, enabling

a deeper understanding of why certain factors were perceived as more important than others. For example, while sustainability emerged as an important consideration, interview participants consistently highlighted that structural safety and cost considerations remained the primary drivers of decision-making, which was subsequently confirmed through the higher RII rankings assigned to these factors.

Conversely, the quantitative findings were used to validate the prevalence and significance of the themes identified during the thematic analysis. This integration process ensured that the final conclusions were supported by both practitioner experiences and broader industry perceptions. The combined findings were subsequently synthesized to identify key decision criteria, barriers, benefits, and best practices associated with retrofit and rebuild projects. These empirical findings formed the basis for the development of the proposed integrated multi-criteria decision-making framework presented in this study.

# 4. RESULTS AND DISCUSSION

This section presents and discusses the findings derived from the qualitative interviews and questionnaire survey. The results are structured in accordance with the research objectives and interpreted through the integration of NVivo-based thematic analysis and Relative Importance Index (RII) rankings. The discussion also links the empirical findings with relevant literature to explain how retrofit versus rebuild decisions are shaped within the Sri Lankan construction context.

## 4.1 PERCEPTION OF RETROFITTING VERSUS REBUILDING

The interview findings indicate that practitioners generally adopt a “retrofit-first” position when the existing building is structurally sound and capable of accommodating the required functional improvements. Several Technical Officers viewed retrofitting as a practical option because it can reduce demolition-related disruption, lower project costs, shorten construction duration, and minimize material waste. For example, TO2 noted that “if the frame is good, retrofitting saves time and money”, while TO5 explained that client confidence in retrofitting often improves once successful retrofit projects are experienced.

However, this preference for retrofitting was conditional rather than absolute. Rebuilding was considered necessary where the building exhibited severe deterioration, extensive reinforcement corrosion, inadequate foundations, or an inability to comply with current safety and performance standards. TO7 emphasized this point by stating that when concrete carbonation and exposed reinforcement are present, “rebuilding” becomes the safer option. This demonstrates that practitioners do not view retrofitting and rebuilding as competing solutions in all cases; rather, they regard them as context-dependent alternatives shaped primarily by structural feasibility and project constraints.

The questionnaire findings supported this interpretation. Most respondents agreed that retrofitting should be considered as the preferred option where structural assessment confirms its feasibility. This suggests that the industry recognizes the potential of retrofitting but remains cautious about its adoption in cases where safety and durability are uncertain.

## 4.2 FACTORS INFLUENCING THE RETROFITTING OR REBUILDING DECISION

The RII analysis identified structural condition and safety as the most influential factor affecting retrofit versus rebuild decisions, with an RII value of 0.89. This was followed by cost and budget constraints (RII = 0.86), sustainability considerations relating to energy, waste and carbon (RII = 0.71), project timeline (RII = 0.68), regulatory compliance (RII = 0.65), and availability of skilled labour (RII = 0.59). These results are presented in Table 2.

*Table 2: Relative Importance Index (RII) of decision factors*

| Factors | RII Value | Rank |
|---|---|---|
| Structural condition / safety | 0.89 | 1 |
| Cost and budget constraints | 0.86 | 2 |
| Sustainability (energy, waste, carbon) | 0.71 | 3 |
| Project timeline | 0.68 | 4 |
| Regulatory compliance | 0.65 | 5 |
| Availability of skilled labour | 0.59 | 6 |

The ranking demonstrates that retrofit versus rebuild decisions are strongly influenced by technical and financial priorities. Although sustainability ranked third, the interview data revealed that environmental considerations are often secondary to safety and affordability. TO4 explained that while sustainability is increasingly discussed, clients typically first ask whether the option is safe and financially viable. Similarly, TO9 observed that excessive emphasis on sustainability may reduce client confidence if it results in cost escalation.

This finding indicates a gap between sustainability awareness and sustainability-led decision-making. While most respondents acknowledged that retrofitting is environmentally preferable due to reduced demolition waste and lower embodied carbon, only a minority had selected retrofitting primarily for environmental reasons. This suggests that sustainability benefits alone are insufficient to drive retrofit adoption in the absence of clear financial incentives, regulatory support, and technical assurance. The finding is consistent with previous studies which suggest that retrofit uptake is often constrained by economic uncertainty, risk perception and limited policy support.

## 4.3 BARRIERS AND CHALLENGES IN RETROFITTING AND REBUILDING PROJECTS

The findings revealed that the main barriers to retrofitting and rebuilding can be grouped into technical, economic, and institutional challenges. From a technical perspective, hidden defects were the most frequently reported concern. Participants noted that defects such as reinforcement corrosion, termite damage, weak foundations, poor concrete quality, and concealed structural deterioration are often discovered only after work begins. TO1 explained that unexpected defects can significantly increase project cost and delay completion, making retrofitting more uncertain than rebuilding.

A further technical challenge concerns the lack of skilled labour and specialist expertise required for retrofit interventions. Techniques such as structural strengthening, fibre wrapping, foundation improvement, and careful integration of new building services into

existing structures require specialized knowledge. Where such expertise is unavailable or costly, practitioners may consider rebuilding to be less risky and easier to manage.

Institutional and regulatory barriers were also significant. Participants observed that approval processes are often clearer for new construction than for retrofit projects. TO6 described retrofitting as a "grey area" within the approval process, indicating uncertainty in how such projects are assessed by relevant authorities. The absence of tax relief, fast-track approval mechanisms, or dedicated retrofit guidelines further discourages clients and professionals from prioritizing retrofit solutions.

Economic barriers were closely linked to these technical and institutional issues. Although retrofitting may reduce costs in many cases, the risk of unforeseen defects and uncertain long-term savings can make clients hesitant. The survey findings supported this concern, with lack of financial incentives emerging as a major barrier. These findings suggest that retrofit adoption in Sri Lanka cannot be improved through technical solutions alone; it also requires policy support, financial mechanisms, and institutional clarity.

## 4.4 BENEFITS AND OPPORTUNITIES OF RETROFITTING AND REBUILDING

Despite the identified barriers, practitioners recognized significant benefits associated with retrofitting. Retrofitting was valued for its potential to reduce project cost, shorten construction duration, minimize demolition waste, and limit disruption to occupants. Several participants indicated that retrofit projects can be completed in a shorter time than complete rebuilding, particularly when the structural frame remains sound. TO3 illustrated this advantage by explaining that a school retrofit was completed within three months, whereas rebuilding would have taken considerably longer and displaced many students.

Retrofitting also provides environmental benefits by reducing material consumption, demolition waste, and embodied carbon. In this respect, it aligns with sustainable construction principles and national climate resilience objectives. However, the findings show that these environmental benefits are more likely to influence decision-making when they are supported by cost savings, regulatory incentives, or client awareness.

Rebuilding, by contrast, was recognized for offering greater design flexibility, clearer regulatory compliance, improved structural performance, and reduced uncertainty regarding hidden defects. Participants considered rebuilding more appropriate where existing buildings are severely deteriorated, structurally unsafe, functionally obsolete, or unable to meet modern standards through retrofit interventions. TO8 described rebuilding as more predictable because the outcome can be designed and controlled from the beginning, whereas retrofitting involves greater uncertainty due to the condition of the existing structure.

The results therefore indicate that neither retrofitting nor rebuilding can be considered universally superior. Instead, the appropriate intervention depends on project-specific conditions, including structural feasibility, cost, timeline, sustainability objectives, regulatory requirements, and available technical capacity.

## 4.5 BEST PRACTICES AND IMPLICATIONS FOR DECISIONS-MAKING

The interview findings highlighted several practices that can improve the quality and reliability of retrofit versus rebuild decisions. The most frequently recommended practice was to undertake a detailed structural assessment, including non-destructive testing where

possible, before committing to either option. This is essential because structural conditions were identified as the highest-ranked decision factor and directly determines whether retrofitting is feasible.

Participants also emphasized the importance of early multidisciplinary collaboration. Structural engineers, quantity surveyors, architects, MEP specialists, sustainability consultants, contractors, and client representatives should be involved at the initial decision-making stage to ensure that technical, financial, environmental, and regulatory implications are considered together. Such collaboration can reduce uncertainty, improve cost forecasting, and prevent decisions based solely on individual professional judgement.

Another important implication is the need for a structured decision-support mechanism. Practitioners recommended the use of a checklist or multi-criteria assessment tool to compare retrofit and rebuild alternatives across key criteria such as structural safety, cost, project duration, environmental impact, and regulatory compliance. This finding directly informed the development of the Integrated Multi-Criteria Decision Framework proposed in this study. The framework responds to the need for a transparent and practical tool that can support more consistent, evidence-based decisions in the Sri Lankan construction industry.

Finally, participants highlighted the importance of documenting successful retrofit and rebuilding case studies. A stronger evidence base of local project examples would improve professional confidence, support client decision-making, and contribute to the development of national guidelines for sustainable building intervention.

## 4.6 DEVELOPMENT OF THE INTEGRATED MULTI-CRITERIA DECISION FRAMEWORK

The proposed Integrated Multi-Criteria Decision Framework was developed through the systematic triangulation of findings obtained from the literature review, qualitative interviews, and quantitative survey analysis. Existing studies have proposed various decision-support frameworks for retrofit assessment; however, most focus primarily on energy performance, lifecycle cost optimization, or environmental sustainability. The findings of this study demonstrated that retrofit versus rebuild decisions in the Sri Lankan construction industry are influenced by a broader range of factors, including structural safety, affordability, project duration, regulatory constraints, and resource availability. Consequently, a context-specific framework was required to reflect the practical realities faced by local construction professionals.

The framework was developed through a three-stage evidence synthesis process. First, the literature review identified the key decision criteria, barriers, benefits, and best practices reported within previous retrofit and rebuild studies. Second, thematic analysis of interview data revealed the factors most frequently considered by Technical Officers when evaluating retrofit and rebuilding alternatives. Third, the Relative Importance Index (RII) analysis was used to prioritize these factors based on their perceived significance among construction professionals. The final framework therefore represents an empirical synthesis of theoretical knowledge and industry practice rather than a purely conceptual model.

The framework consists of three sequential stages: preliminary assessment, multi-criteria evaluation, and decision selection. The preliminary assessment stage evaluates the

structural feasibility of the existing building. Buildings that exhibit severe deterioration, critical structural defects, or unacceptable safety risks are directed towards rebuilding considerations. Buildings that satisfy minimum structural requirements proceed to the multi-criteria evaluation stage.

The multi-criteria evaluation stage assesses both retrofit and rebuilding alternatives against five key criteria identified through the study findings: structural condition and safety, lifecycle cost, environmental impact, project duration, and regulatory compliance. The relative weighting assigned to each criterion was derived from the RII rankings obtained through the questionnaire survey, thereby ensuring that the framework reflects the priorities of industry practitioners.

*Table 3: Framework criteria, weighting, input requirements and scoring scale*

| Criterion | Default Weight (%) | Scoring Scale (0–10) | Data Source |
|---|---|---|---|
| Structural condition / safety | 30% | 0 = collapse risk / severe deterioration; 5 = moderate repairable defects; 10 = fully sound | NDT assessment, engineer's report |
| Lifecycle cost (including maintenance) | 25% | 0 = >150% of rebuild cost; 5 = 75–150%; 10 = <50% | Quantity surveyor's estimate |
| Environmental impact (carbon + waste) | 15% | 0 = high emissions, large waste; 5 = moderate; 10 = near zero | Lifecycle assessment / waste estimation |
| Project duration | 15% | 0 = longer than rebuild; 5 = same as rebuild; 10 = <50% of rebuild time | Contractor's schedule |
| Regulatory compliance and approval ease | 15% | 0 = impossible to approve; 5 = possible with delays; 10 = fast-track eligible | Local authority consultation |

Each alternative is scored from 0 to 10 against each criterion using the guidance provided in Table 3. The score assigned to each criterion is multiplied by its corresponding weighting, and the weighted scores are aggregated to generate an overall performance score. The framework applies two decision rules. First, retrofit can only be considered where the building achieves a minimum structural feasibility score of five or above. Second, where the total weighted retrofit score equals or exceeds the total weighted rebuild score, retrofit is recommended. Where the rebuild score is higher, or where structural feasibility requirements are not met, rebuilding is recommended.

To illustrate the practical application of the framework, Table 4 presents a sample scoring exercise comparing retrofit and rebuild alternatives. The example demonstrates how the framework converts multiple decision criteria into a transparent and evidence-based recommendation.

*Table 4: Example application of the framework*

| Criterion | Weight | Retrofit Score | Retrofit Weighted Score | Rebuild Score | Rebuild Weighted Score |
|---|---|---|---|---|---|
| Structural condition and safety | 0.30 | 8 | 2.40 | 9 | 2.70 |
| Lifecycle cost | 0.25 | 9 | 2.25 | 5 | 1.25 |
| Environmental impact | 0.15 | 8 | 1.20 | 4 | 0.60 |
| Project duration | 0.15 | 7 | 1.05 | 5 | 0.75 |
| Regulatory compliance | 0.15 | 6 | 0.90 | 8 | 1.20 |
| Total | | | 7.80 | | 6.50 |

The expected output of the framework is a structured recommendation identifying whether retrofit or rebuild represents the most appropriate intervention strategy for a given project. In addition to the final recommendation, the framework enables decision-makers to understand the relative strengths and weaknesses of each alternative across technical, economic, environmental, and regulatory dimensions. Consequently, the framework promotes more transparent, objective, and sustainable decision-making within the Sri Lankan construction industry

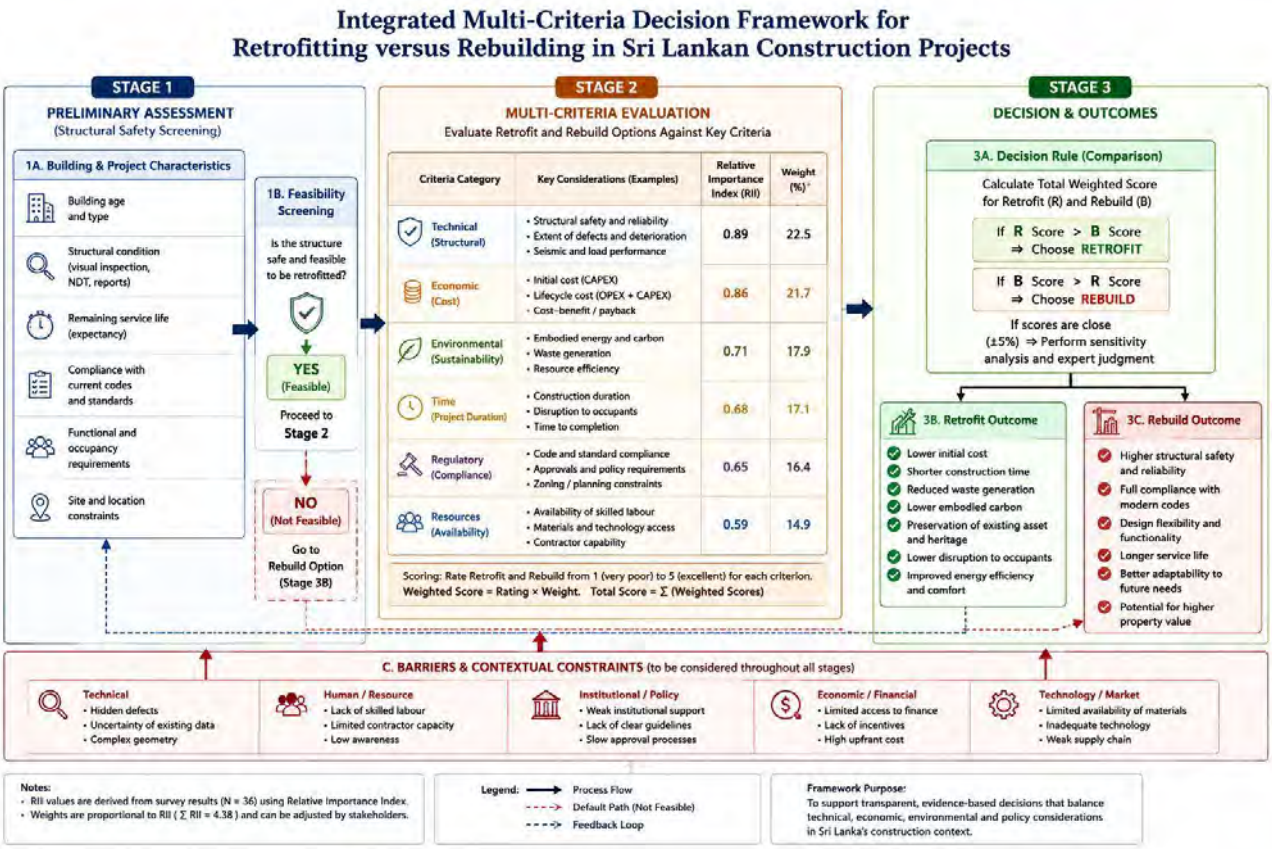



*Figure 1: Decision-making framework*

## 4.7 COMPARISON WITH EXISTING INTERNATIONAL FRAMEWORKS

To evaluate the contribution of the proposed framework, a comparison was undertaken with two established international decision-support models developed by Menassa and Baer (2014) and Steskens et al. (2015). Both frameworks are widely recognized within the retrofit decision-making literature and have contributed significantly to the development of systematic approaches for evaluating building retrofit alternatives. However, both models were developed within high-income contexts characterized by stronger institutional support, advanced technical capabilities, and well-established incentive mechanisms for sustainable construction.

*Table 5: Comparison of the proposed framework with existing international models*

| Feature | Menassa and Baer (2014) | Steskens et al. (2015) | Proposed Framework |
|---|---|---|---|
| Primary Purpose | Retrofit optimisation | Energy-efficient retrofit evaluation | Retrofit versus rebuild decision-making |
| Focus | Energy performance | Energy and environmental performance | Safety, cost, sustainability and feasibility |
| Structural Screening | Not explicit | Limited | Mandatory structural assessment |
| Lifecycle Cost Assessment | Yes | Yes | Yes |
| Environmental Assessment | Yes | Yes | Yes |
| Regulatory Considerations | Limited | Limited | Explicitly included |
| Skilled Labour Considerations | No | No | Reflected through feasibility assessment |
| Developing Country Context | No | No | Yes |
| Input Complexity | High | Moderate to High | Low to Moderate |
| Software Requirements | Advanced simulation tools | Energy modelling tools | Basic project information and professional assessment |

The proposed framework differs from existing international models in several important respects. First, it incorporates a mandatory structural feasibility assessment as a preliminary decision gate. This reflects the findings of the present study, where structural safety emerged as the most influential factor affecting retrofit versus rebuild decisions. Second, the framework assigns greater emphasis to affordability and practical feasibility, recognizing the budget constraints, resource limitations, and regulatory challenges commonly encountered within the Sri Lankan construction sector. Third, the framework has been specifically designed to support direct comparison between retrofit and rebuild alternatives rather than focusing exclusively on retrofit optimization.

Unlike the models developed by Menassa and Baer (2014) and Steskens et al. (2015), the proposed framework can be applied using information typically available during the early stages of project planning, including structural assessments, cost estimates, project schedules, and regulatory requirements. This reduces the need for advanced simulation software and specialist analytical tools, making the framework more accessible to engineers, Technical Officers, architects, quantity surveyors, and project managers operating in resource-constrained environments.

The comparison demonstrates that while existing international frameworks provide valuable methodological foundations, they do not fully address the practical constraints encountered in developing countries such as Sri Lanka. By integrating structural feasibility, affordability, regulatory considerations, and locally derived decision criteria, the proposed framework provides a more context-sensitive and practitioner-oriented decision-support tool for retrofit versus rebuild decisions.

## 5. LIMITATIONS OF THE STUDY

While the study provides valuable insights into retrofit versus rebuild decision-making within the Sri Lankan construction industry, several limitations should be acknowledged. First, the qualitative component was based on interviews with ten Technical Officers. Although thematic saturation was achieved, the relatively small sample size may limit the extent to which the findings fully represent the perspectives and experiences of all construction professionals across Sri Lanka. Future studies could expand the participant pool to include a broader range of stakeholders, such as engineers, architects, quantity surveyors, contractors, and policymakers, from different geographical regions.

Second, the questionnaire survey was primarily distributed through professional networks, resulting in a respondent profile that was concentrated within the Western Province. Consequently, the findings may be influenced by urban bias, potentially underrepresenting the challenges, resource constraints, and decision-making practices prevalent in rural and less-developed regions of the country. Future research should seek a more geographically balanced sample to improve the generalizability of the findings.

Third, the study adopted a cross-sectional research design, capturing industry perceptions and decision-making practices at a single point in time. However, retrofit versus rebuild decisions are influenced by dynamic factors such as construction costs, material prices, labor availability, regulatory changes, technological advancements, and economic conditions. As these factors evolve over time, decision-making priorities may also change. Therefore, longitudinal studies that examine how retrofit and rebuild decisions develop under changing market and policy conditions would provide a more comprehensive understanding of the decision-making process.

Finally, while the proposed framework was developed through the integration of empirical findings and existing literature, it has not yet been validated through application to real-world projects. Future research should focus on testing and refining the framework across different building types and project contexts to evaluate its practical applicability, reliability, and effectiveness as a decision-support tool.

## 6. CONCLUSIONS AND RECOMMENDATIONS

This study examined the status of retrofit versus rebuild decision-making within the Sri Lankan construction industry and developed a context-specific framework to support

more structured decision-making. The findings indicate that structural condition and safety, lifecycle cost, and sustainability are the most influential factors affecting the selection of retrofit or rebuild strategies. While retrofitting is widely recognized for its environmental and economic benefits, concerns relating to hidden defects, limited skilled labor, and weak institutional support continue to constrain its implementation.

The study further revealed that practitioners often rely on professional judgement rather than structured decision-support tools when evaluating retrofit and rebuilding alternatives. To address this gap, an Integrated Multi-Criteria Decision Framework was developed based on literature findings, interview insights, and quantitative prioritization of decision criteria. The framework incorporates structural feasibility, lifecycle cost, environmental impact, project duration, and regulatory compliance to facilitate transparent and evidence-based decision-making.

The findings highlight the need for greater policy support, technical guidance, and capacity building to encourage sustainable retrofit practices within the Sri Lankan construction sector. The proposed framework provides a practical tool for construction professionals and policymakers while contributing to the limited body of knowledge on retrofit versus rebuild decision-making in developing-country contexts. Future research should focus on validating the framework through application to real-world projects and extending its applicability across different building types and geographical regions.

## 7. REFERENCES

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. *Structural Survey, 29*(5), 411–421. https://doi.org/10.1108/02630801111182439

Chen, Y., Wang, Z., & Peng, Z. (2024). A study on carbon emission reduction in the entire process of retrofitting high-rise office buildings based on the extraction of typical models. *Sustainability, 16*(19), 8506. https://doi.org/10.3390/su16198506

Dişli, G., & Ankaralıgil, B. (2023). Circular economy in the heritage conservation sector: An analysis of circularity degree in existing buildings. *Sustainable Energy Technologies and Assessments, 56*, 103126. https://doi.org/10.1016/j.seta.2023.103126

Egbelakin, T., Wilkinson, S., & Ingham, J. (2014). Economic impediments to successful seismic retrofitting decisions. *Structural Survey, 32*(5), 449–466. https://doi.org/10.1108/SS-01-2014-0002

Fasna, M. F. F., & Gunatilake, S. (2020). Overcoming barriers for building energy efficiency retrofits: Insights from hotel retrofits in Sri Lanka. *Built Environment Project and Asset Management, 10*(2), 277–295. https://doi.org/10.1108/BEPAM-01-2019-0010

Ferreira, J., Duarte Pinheiro, M., & de Brito, J. (2015). Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction – A Portuguese benchmarking. *Journal of Building Engineering, 3*, 114–126. https://doi.org/10.1016/j.jobe.2015.07.001

Jagarajan, R., Mohd Asmoni, M. N. A., Mohammed, A. H., Jaafar, M. N., Lee Yim Mei, J., & Baba, M. (2017). Green retrofitting – A review of current status, implementations and challenges. *Renewable and Sustainable Energy Reviews, 67*, 1360–1368. https://doi.org/10.1016/j.rser.2016.09.091

Jayarathne, T. D., De Silva, N., & Samarakoon, W. K. U. R. M. K. P. K. (2024). Adopting smart retrofits: A decision-making model and benchmarking criteria. *Built Environment Project and Asset Management, 14*(3), 366–383. https://doi.org/10.1108/BEPAM-02-2023-0034

Josa, I., & Borrion, A. (2025). Rebuilding or retrofitting? An assessment of social impacts using social life cycle assessment. *Environmental Impact Assessment Review, 112*, 107794. https://doi.org/10.1016/j.eiar.2024.107794

Liu, G., Ye, K., Tan, Y., Huang, Z., & Li, X. (2022). Factors influencing homeowners' housing renovation decision-making: Towards a holistic understanding. *Energy and Buildings, 254*, 111568. https://doi.org/10.1016/j.enbuild.2021.111568

Menassa, C. C., & Baer, B. (2014). A framework to assess the role of stakeholders in sustainable building retrofit decisions. *Sustainable Cities and Society, 10*, 207–221. https://doi.org/10.1016/j.scs.2013.09.002

Peng, Z., Zhao, S., Shen, L., Ma, Y., Zhang, Q., & Deng, W. (2021). Retrofit or rebuild? The future of old residential buildings in urban areas of China based on the analysis of environmental benefits. *International Journal of Low-Carbon Technologies, 16*(4), 1422–1434. https://doi.org/10.1093/ijlct/ctab070

Periyannan, E., Ramachandra, T., & Geekiyanage, D. (2023). Assessment of costs and benefits of green retrofit technologies: Case study of hotel buildings in Sri Lanka. *Journal of Building Engineering, 78*, 107631. https://doi.org/10.1016/j.jobe.2023.107631

Power, A. (2010). Housing and sustainability: Demolition or refurbishment? *Proceedings of the Institution of Civil Engineers – Urban Design and Planning, 163*(4), 205–216. https://doi.org/10.1680/udap.2010.163.4.205

Ranawaka, I., & Mallawaarachchi, H. (2018). A risk-responsive framework for green retrofit projects in Sri Lanka. *Built Environment Project and Asset Management, 8*(5), 477–490. https://doi.org/10.1108/BEPAM-10-2017-0088

Rønning, A., Vold, M., & Nereng, G. (2009). *Refurbishment or replacement of buildings – What is best for the climate?*. Joint Actions on Climate Change, Bonn, Germany. https://scholar.google.com/scholar?q=A.%20R%C3%B8nning%2C%20M.%20Vold%2C%20G.%20Nereng%2C%20Refurbishment%20or%20Replacement%20of%20Buildings-What%20is%20Best%20for%20the%20Climate%3F%2C%20n.d.

Steskens, P., Vanhellemont, Y., Roels, S., & Van Den Bossche, N. (2015). A decision making tool for the energy efficient refurbishment of residential buildings. *Energy Procedia, 78*, 997–1002. https://doi.org/10.1016/j.egypro.2015.11.043

Troian, V., Gots, V. I., Flatt, R. J., & Angst, U. (2024). Rehabilitating instead of rebuilding aged or damaged pre-fabricated concrete buildings for reducing $CO_2$ emissions: The case of Ukraine. *Materials and Structures, 57*(5). 123. https://doi.org/10.1617/s11527-024-02392-0

Sayanthan, S., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Factors influencing the probability of winning a bid in the Sri Lankan construction tendering process. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 768-781. DOI: https://doi.org/10.31705/WCS.2026.57. Available from: https://ciobwcs.com/papers/

# FACTORS INFLUENCING THE PROBABILITY OF WINNING A BID IN THE SRI LANKAN CONSTRUCTION TENDERING PROCESS

**S. Sayanthan[1], K. Thiruchelvam[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Winning construction bids is essential for construction organizations to maintain business continuity, profitability and market competitiveness, particularly in developing economies where competitive bidding is the primary procurement method. In Sri Lanka, contractors operate in a highly competitive environment characterised by cost volatility, resource constraints and market uncertainty. This study aims to identify the critical factors influencing bid winning probability in the Sri Lankan construction industry. A structured two stage quantitative methodology was adopted. Initially, factors identified from the literature were validated through a preliminary survey involving 12 highly experienced industry professionals. Subsequently, a questionnaire survey was conducted among 100 construction practitioners, including quantity surveyors, engineers and architects, to evaluate the relative importance of the validated factors. The collected data were screened using an outlier test and mean score analysis was performed. A cut-off mean value of 4.0 on a five-point Likert scale was used to identify critical factors. The results revealed seven critical factors: financial stability, past performance, availability of resources, technical proposal quality, bidding strategy, expected profitability and market conditions. The findings provide practical guidance for contractors to make informed bid decisions and improve competitiveness, while offering a systematic methodology that can be applied in other developing construction markets.*

***Keywords:*** *Bid Winning; Competitive Bidding; Construction Industry; Contractor Decision Making; Procurement.*

## 1. INTRODUCTION

The construction industry plays a vital role in global economic development by enhancing infrastructure, creating employment and contributing significantly to national GDPs (Pheng & Hou, 2019; Puci et al., 2023; Weerakoon et al., 2023). Construction projects generally progress through several structured phases, including inception, feasibility analysis, design, pre-construction, construction and post construction, with the pre-

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, Sivasaya2001@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

construction stage serving as the formal starting point of project execution (Mohemad et al., 2010).

Bidding is one of the critical processes conducted during pre-construction phase. The bidding process determines the most suitable contractor for awarding the contract (Rashidi et al., 2023; Uduwage et al., 2024; Uduwage et al., 2026). Contractors rely on continuous bidding to ensure business continuity, sustain profitability and reinforce market presence in a competitive environment (Ahmed & El-Adaway, 2024; Ghodoosi et al., 2021; Temu et al., 2025). Competitive bids must balance pricing precision with profit margins, while simultaneously demonstrating technical capability, past experience and credibility to clients (Aznar et al., 2017; Chen et al., 2024; Fawale & Dada, 2017).

Selecting unsuitable bids can lead to significant financial losses because bid preparation requires substantial time, resources and expertise (Hwang & Kim, 2016; Sonmez & Sözgen, 2017). Missing suitable opportunities similarly limits a contractor's growth prospects, weakens long term positioning and reduces the ability to maintain a consistent project pipeline (Aznar et al., 2017; Chen et al., 2024; Oo et al., 2022).

Winning bids is therefore essential for contractors, as it directly influences business continuity, profitability, workforce stability and future market opportunities. Successful bids help strengthen financial security, enhance reputation, promote innovation and foster long-term client relationships (Oo et al., 2022; Temu et al., 2025). In contrast, repeatedly losing bids can create financial strain due to accumulated bid preparation costs, reduce competitiveness, damage market visibility and in severe cases threaten overall business sustainability (Ahmed & El-Adaway, 2024; Chen et al., 2024).

In Sri Lanka's highly competitive construction environment, understanding the factors that influence the likelihood of securing a bid is critically important, as contractors face tightening profit margins, fluctuating material costs, and increasing competition from both local and international firms (Hanák et al., 2021; Whang et al., 2022). These factors directly shape decisions related to pricing, resource allocation, and submission strategies. Therefore, contractors' performance in competitive bidding is significantly affected by how well they understand and respond to the determinants that influence bid success. Although the bidding process is intended to promote fairness, transparency, and healthy competition, many contractors continue to rely on intuition or past experience when estimating their chances of success. This dependence on subjective judgement arises partly because they lack structured knowledge of which factors genuinely influence bid winning.

Existing research in Sri Lanka has examined certain aspects linked to bidding performance, such as price competitiveness, contractor experience, and financial capacity. However, these studies have generally focused on individual variables without providing a comprehensive assessment of the full range of factors that influence the likelihood of winning a bid (Weerakoon et al., 2023).

Unlike previous studies that have focused on individual determinants or general bid/no-bid frameworks in international contexts, this study provides the first empirically validated and ranked list of critical bid-winning factors specific to the Sri Lankan construction industry. By adopting a two-stage quantitative methodology that combines expert validation with a broader industry survey, the study offers both methodological novelty and practical value for contractors operating in competitive developing-country construction markets. Since previous research has not sufficiently addressed the broader

range of factors influencing bid success in Sri Lanka, a significant gap remains in understanding which determinants exert the strongest influence on project acquisition. Addressing this gap is essential, as identifying and prioritising these factors enables contractors to make more rational bid/no-bid decisions, improve the quality of tender submissions, manage resources more effectively, and enhance competitiveness in an increasingly demanding construction market.

The aim of this research is to empirically identify and analyse the critical factors that affect the probability of winning bids in the Sri Lankan construction bidding process, in order to provide a structured understanding that supports more effective and competitive bidding decisions.

This study empirically examines the critical factors influencing the probability of bid winning in Sri Lanka through the following objectives.

1. Identify the factors affecting bid winning in Sri Lankan construction industry.
2. Scrutinize the critical factors that have the highest impact on probability of bid winning.

# 2. LITERATURE REVIEW

## 2.1 BIDDING IN THE CONSTRUCTION PROJECT LIFECYCLE

Construction bidding is a structured procurement process that enables clients to allocate projects through competitive contractor selection (Jiang & Holubava, 2023). It serves as the principal gateway between project planning and execution, directly influencing project cost, quality and scheduling outcomes (Hanák et al., 2021). Among these stages, bidding is concentrated within the pre-construction phase, where strategic decisions regarding procurement method, contractor selection and risk allocation are finalised (Mohemad et al., 2010). These early decisions establish the contractual framework that governs project delivery and significantly affect downstream performance (Abbas et al., 2016).

## 2.2 IMPORTANCE OF WINNING A BID

Construction bidding is the formal procurement mechanism through which contractors compete for project awards based on price, technical capability and compliance with client requirements (Jiang & Holubava, 2023). In this competitive environment, winning a bid is fundamental to a contractor's business viability because project acquisition, revenue generation and long term sustainability rely heavily on securing new work through bid submissions (Temu et al., 2025). In construction markets, particularly in developing economies where competitive bidding is the dominant procurement method, contractors must consistently win bids to maintain operational continuity, retain their workforce and preserve their market presence (Oo et al., 2022).

The decision making process during bid evaluation is not solely determined by price, although lowest price selection remains common in public sector procurement (Ghodoosi et al., 2021). Clients increasingly assess multiple criteria, including a contractor's experience, technical expertise, equipment capacity, past performance, financial stability and ability to deliver quality within time and cost expectations (Hanák et al., 2021). As a

result, a contractor's success depends on a combination of pricing strategy and organisational strengths rather than cost alone (Aznar et al., 2017).

Winning bids brings several advantages, including improved cash flow, better resource utilisation, stronger client relationships and enhanced market reputation. These outcomes contribute directly to business stability and strategic growth. In contrast, failing to win bids can reduce a contractor's project pipeline, weaken financial performance and increase the risk of downsizing or losing skilled personnel. Repeated bid losses also reduce market visibility, lower confidence among clients and create uncertainty in long term planning. Furthermore, each unsuccessful bid carries sunk costs associated with bid preparation, which can accumulate and place financial pressure on the organisation (Ahmed & El-Adaway, 2024).

Research shows that contractors who adopt systematic bid or no-bid decision making processes achieve higher success rates than those who rely solely on intuition or experience based judgement (Ahmed & El-Adaway, 2024). This indicates that the probability of securing a bid is not random. It is influenced by a set of identifiable factors that shape how clients evaluate contractors and decide award priorities (Temu et al., 2025). When these factors are not understood, contractors submit bids with lower chances of success, misallocate resources and expose themselves to unnecessary financial risks.

## 2.3 FACTORS AFFECTING BID WINNING IN THE CONSTRUCTION INDUSTRY

Winning bids is not only a means of winning projects but also a strategic imperative that shapes contractors' survival, growth and long term competitiveness (Hanák et al., 2021). Successful bidding strengthens profitability, optimises resource utilisation and enhances a contractor's reputation by maintaining a consistent project pipeline (Temu et al., 2025). Conversely, repeated bidding failures result in financial instability, resource wastage and reputational damage, which can threaten organizational sustainability (Ghodoosi et al., 2021).

In the Sri Lankan construction context, bid decisions largely rely on traditional project management and financial assessments, where cost estimation accuracy and client relationships play dominant roles (Arifuddin et al., 2025). Recent evidence highlights the increasing importance of risk management practices in improving the quality and reliability of bid submissions (Chen et al., 2024). Globally, however, studies reveal broader determinants such as market competition, client behaviour and technological readiness that influence the probability of winning a bid (Jiang & Holubava, 2023).

Based on the existing literature, Table 1 summarizes the major factors affecting bid winning in construction projects, grouped under five key categories: contractor related, client related, project related, market and external environment related and bid specific factors (Ahmed & El-Adaway, 2024).

*Table 1: Factors influencing bid winning*

| Contractor Related Factors | Project Related Factors |
|---|---|
| • Availability of Resources [1], [2] | • Size of Project [2], [12] |
| • Financial Stability [2], [3], [4] | • Type of Project [12] |
| • Current Workload [2], [3] | • Project Location [1], [4] |
| • Past Performance [1], [5] | • Accessibility of Project Location [1], [4] |
| • Bidding Strategy [6] | • Site Conditions [13], [4] |

| Contractor Related Factors | Project Related Factors |
|---|---|
| • Use of BIM [6], [7]<br>• Integrating Value Engineering Concepts [8]<br>• Joint Venture/Subcontracting [9] | • Procurement Method [3], [9]<br>• Project Delivery Method [8], [9] |
| **Client Related Factors** | **Bid Specific Factors** |
| • Type of Client [2], [10]<br>• Client's Reputation on Payment History [11], [4] | • Bid Preparation Time [1], [12]<br>• Bid Submission Period [1], [12]<br>• Bid Price Deviation from Cost Estimate [14], [15]<br>• Technical Proposal Quality [11], [8]<br>• Expected Profitability [1], [16] |
| **Market & External Environment Factors** | |
| • Market Conditions [13], [4]<br>• Number of Competitors [1], [3]<br>• Funding Source [10], [4] | |
| [1] (Ahmed & El-Adaway, 2024), [2] (Chen et al., 2024), [3] (Muhammed et al., 2022), [4] (Tessema et al., 2022), [5] (Arifuddin et al., 2025), [6] (Hanák et al., 2021), [7] (Kusumarukmi et al., 2018), [8] (Emere et al., 2025), [9] (Memić et al., 2023), [10] (Oo et al., 2022), [11] (Aldossari, 2024), [12] (Leśniak, 2021), [13] (Binshakir et al., 2023), [14] (Ghodoosi et al., 2021), [15] (Jefferies & Schweber, 2022), [16] (Mahamid, 2022) | |

Table 1 synthesizes key findings from the literature on factors influencing the likelihood of securing construction bids. The factors are organised into five distinct categories, which were developed through a thematic review of prior studies. Previous research has similarly grouped determinants of bid performance into contractor related, client related, project related, market related and bid process factors, demonstrating that these categories reflect established patterns in bid/no-bid and bid evaluation literature (Ahmed & El-Adaway, 2024; Aznar et al., 2017; Hanák et al., 2021). During the literature synthesis, similar variables discussed by multiple authors were clustered based on whether they originated from the contractor, client, project, industry environment, or the bidding mechanism itself.

Contractor related factors reflect internal organisational capabilities, including resource availability, financial stability, past performance and technological capacity, all of which directly affect a contractor's ability to submit competitive and compliant bids (Ahmed & El-Adaway, 2024; Chen et al., 2024). Client related factors highlight the role of client characteristics, particularly payment reliability and client type, which influence contractors' strategic interest in bids and their pricing and submission approaches (Aldossari, 2024; Tessema et al., 2022).

Project related factors encompass the inherent characteristics of construction projects, such as size, type, location and delivery method, which determine technical requirements, cost structure and overall bid competitiveness (Binshakir et al., 2023; Leśniak, 2021). Market and external environment factors capture broader industry conditions, including market competition, availability of funding and economic context, which shape contractors' pricing behaviour and competitive positioning during bidding (Ahmed & El-Adaway, 2024; Muhammed et al., 2022). Bid specific factors relate directly to the preparation and submission of bids, including bid preparation time, pricing strategy, expected profitability and technical proposal quality, all of which have a direct influence on bid evaluation outcomes and success rates (Emere et al., 2025; Ghodoosi et al., 2021).

Collectively, these factors demonstrate that winning a bid in construction is influenced by the interaction of contractor capabilities, project attributes, market conditions, client

characteristics and bid preparation quality, highlighting the need for structured and informed approaches to improve bidding effectiveness and bid success.

Understanding the factors that influence winning a bid is therefore essential for contractors to make informed decisions about resource allocation, pricing strategies, risk assessment and project targeting (Aznar et al., 2017). When these factors are clearly identified and prioritised, contractors can optimise their bid/no-bid decisions and avoid submitting bids with low chances of success (Ahmed & El-Adaway, 2024). Clear prioritisation also helps reduce unnecessary bid preparation costs and ensures that resources are directed toward more competitive and strategically aligned opportunities (Sonmez & Sözgen, 2017). Furthermore, recognising the most influential determinants allows contractors to enhance the quality of their bid submissions and strengthen their competitiveness in both public and private sector markets (Chen et al., 2024). Although several studies discuss these determinants internationally, very few have systematically analysed or ranked their relative significance within the Sri Lankan construction context (Weerakoon et al., 2023). This lack of structured evidence highlights the need for research that clarifies which factors matter most, enabling contractors to improve their bidding strategies and increase their likelihood of securing projects (Hanák et al., 2021).

## 3. RESEARCH METHODOLOGY

This study adopts a quantitative research approach supported by an initial expert validation stage to examine and prioritise the critical factors affecting winning a bid in the Sri Lankan construction bidding process. A quantitative approach is appropriate as it enables the statistical evaluation, comparison and ranking of factors based on numerical data obtained from industry professionals, thereby supporting objective decision-making and empirical validation of the research objectives (Nufus, 2023).

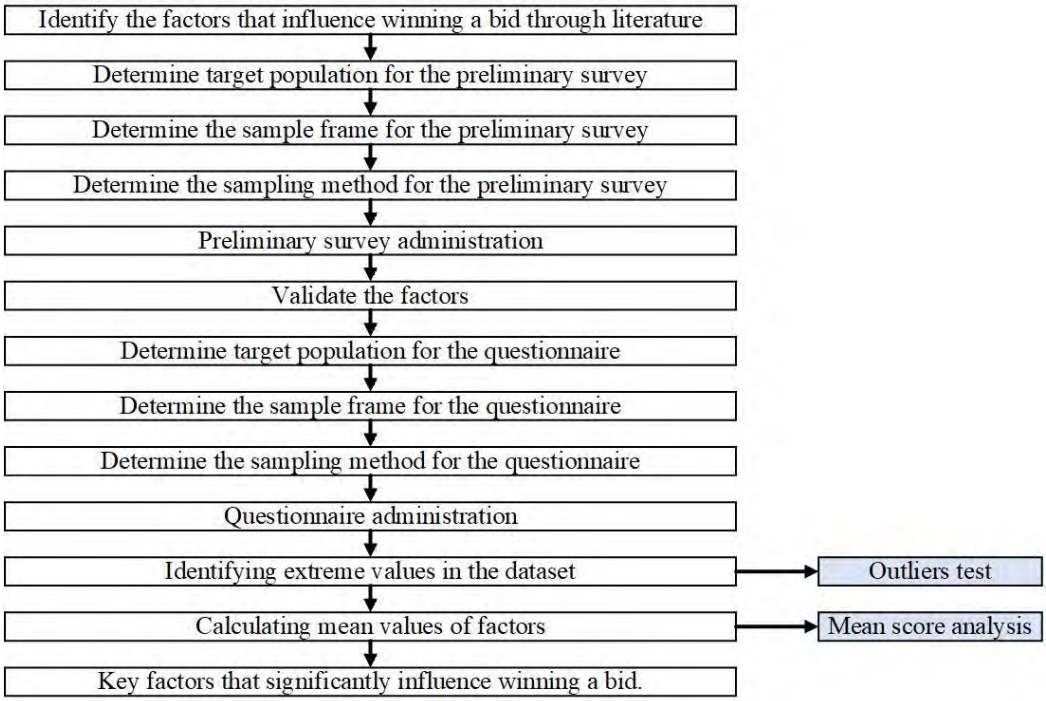



*Figure 1: Research design*

The research was conducted in two stages, as illustrated in Figure 1. In the first stage, an expert-based preliminary survey was conducted to validate whether these factors are applicable to the Sri Lankan construction context. This study focuses on competitive open and selective tendering, which represent the dominant procurement methods used across both public and private sector construction projects in Sri Lanka. Negotiated contracts and other non-competitive procurement forms are outside the scope of this study. In the second stage, a questionnaire survey was administered to statistically evaluate and prioritise the validated factors based on industry perceptions. This design ensured both contextual relevance and statistical robustness of the identified bid winning factors.

These factors formed the basis for the preliminary survey, which was conducted to validate their relevance and applicability to the Sri Lankan construction industry. For the preliminary survey, the target population consisted of highly experienced construction professionals who had direct involvement in bid preparation, evaluation and procurement decision making. A purposive sampling approach was adopted to ensure that only individuals with substantial expertise in bidding practices were included. The sample frame was developed using professional networks and industry affiliations to identify suitable respondents. A total of 12 experts, each possessing more than 15 years of industry experience, were selected. This sample size was considered appropriate because expert validation studies rely on depth of knowledge rather than large numerical representation. The selected experts represented the major professional disciplines in the construction industry, including quantity surveyors, engineers and architects and were drawn from contractor, consultant and client organisations. This ensured a balanced and comprehensive perspective on bidding practices.

During the preliminary survey, respondents were requested to assess the applicability of the factors identified through the literature review and to suggest any additional factors that might influence bid winning within the Sri Lankan context. The feedback obtained from this stage was used to validate, refine and finalise the list of factors to be examined in the subsequent stage of data collection.

The second stage of data collection involved administering a structured questionnaire to a broader group of construction professionals. This stage aimed to evaluate the relative importance of the validated factors using a larger and more diverse sample. The target population for this stage consisted of quantity surveyors, engineers and architects working in contractor, consultant and client organisations across the Sri Lankan construction industry. Only professionals with a minimum of 3 years of industry experience were considered, ensuring that respondents had adequate exposure to bidding procedures and bid preparation activities. Priority was given to professionals who are directly engaged in bid preparation and procurement decision-making processes, including estimating engineers, quantity surveyors responsible for pricing and cost planning, and senior professionals with bid/no-bid decision-making authority. This ensured that the ratings reflected practical, first-hand experience with bidding outcomes.

A purposive sampling technique was again employed to select respondents from recognised industry bodies and professional networks. A sample size of one hundred respondents was adopted for this stage. This sample size was considered sufficient to obtain a reasonable representation of the industry, achieve a reliable response distribution and enable meaningful statistical analysis in construction management research. The questionnaire was designed to collect both demographic and factor related data. The first

part gathered background information such as profession, organisational role and years of experience, while the second part required respondents to rate the importance of each identified factor influencing bid winning using a five-point Likert scale.

Following data collection, the dataset was screened to ensure accuracy, completeness and consistency. An outlier test was conducted to identify and remove extreme values that could disproportionately influence the results. This step enhanced the reliability and robustness of the dataset before the main statistical analysis. After removing outliers, mean score analysis was performed to calculate the average importance rating for each factor. This analysis enabled the identification and ranking of factors based on their perceived influence on bid winning probability. Factors exceeding the predetermined cut-off value were subsequently classified as critical factors affecting bid winning.

### 3.1 MEAN SCORE ANALYSIS AND IDENTIFICATION OF CRITICAL FACTORS

Mean score analysis was employed to evaluate the relative importance of each factor influencing bid winning. Respondents rated each factor using a five-point Likert scale, where higher values indicated greater perceived importance. The mean score for each factor was calculated to determine its overall significance within the dataset.

A cut-off value of 4.0 was adopted to identify critical factors. On a five-point Likert scale, a score of 3 represents a neutral or moderate level of importance, while a score of 4 indicates that a factor is considered important by respondents. Therefore, a threshold of 4.0 represents the transition from moderate importance to a clearly important or influential level. Selecting this value ensures that only factors perceived as important or very important by the majority of respondents are classified as critical.

In addition, the use of a cut-off value of 4.0 aligns with common practice in construction management research, where factors with mean scores at or above this level are considered to have a meaningful influence on project or procurement outcomes. This approach provides a logical and statistically sound basis for distinguishing critical factors from those with lesser impact. Accordingly, factors with mean scores equal to or greater than 4.0 after the outlier test were classified as critical factors affecting bid winning probability, while those below this threshold were excluded from further consideration.

## 4. RESULTS AND DISCUSSION

### 4.1 DEMOGRAPHIC DATA

The results of this study are derived from a two stage data collection process comprising expert validation and a broader industry survey. In the first stage, preliminary data were collected from 12 highly experienced construction professionals. These experts possessed more than 15 years of industry experience, with an average experience of approximately 30 years. Such extensive experience was essential at this stage to ensure that the factors identified through the literature review were critically evaluated by individuals with in depth practical knowledge of bid preparation, bid evaluation and procurement decision making within the Sri Lankan construction industry.

The professional composition of this group consisted of 75% Quantity Surveyors, 16.7% Engineers and 8.3% Architects. In terms of organisational representation, 50% were from consultant organisations, 25% from contractor organisations and 25% from client organisations. All respondents satisfied the minimum academic and professional

qualifications required for recognised practice in the Sri Lankan construction sector. The purpose of this stage was to validate the contextual relevance of the identified factors.

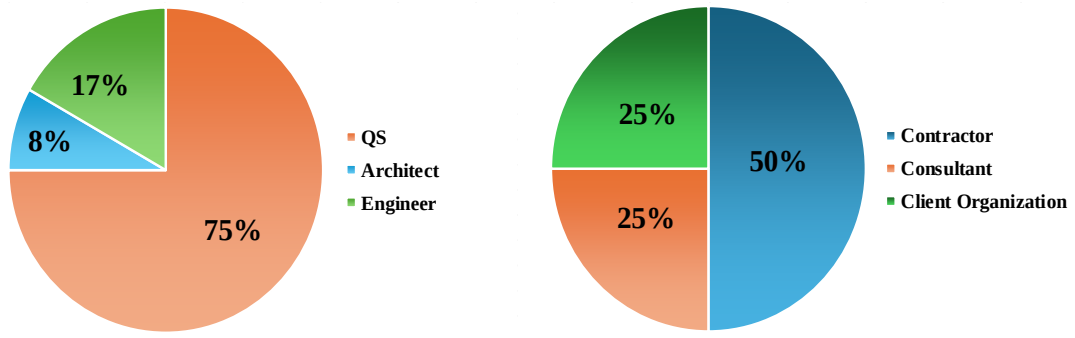



*Figure 2: Respondent's profession & organization type*

In the second stage, questionnaires were distributed to 125 construction professionals who met the minimum requirement of three years of industry experience. A minimum of 3 years of experience was considered necessary to ensure that respondents had sufficient exposure to bidding procedures, bid documentation, pricing strategies and procurement practices. This threshold ensured that participants possessed practical familiarity with bid related decision making rather than purely theoretical knowledge.

Out of the 125 distributed questionnaires, 100 valid responses were received, resulting in a response rate of 80%. A response rate of 51% is generally considered sufficient for business and management related studies. Since the response rate of this study (80%) significantly exceeds the recommended threshold of 51%, it can be considered adequate and satisfactory for reliable statistical analysis in construction management research (Thiruchelvam & Uduwage, 2025).

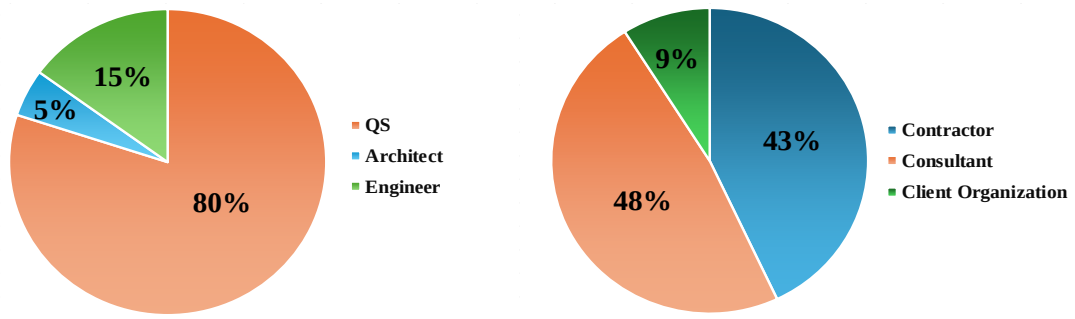



*Figure 3: Respondent's profession & organization type*

The respondents in this stage had an average industry experience of 13.89 years (approximately 14 years), indicating a well experienced sample. The professional distribution comprised 80% Quantity Surveyors, 15% Engineers and 5% other professionals, including project managers, contracts managers, planning engineers, architects and contract experts. In terms of organisational background, 48% of respondents were from consultant organisations, 43% from contractor organisations and 9% from client organisations. This distribution ensured representation across the key stakeholder groups involved in construction bidding, thereby enhancing the reliability and balance of the findings.

## 4.2 DATA SCREENING AND FACTOR SELECTION

Prior to conducting the main statistical analysis, the collected data were screened to ensure completeness, consistency and suitability for analysis. An outlier test was performed using SPSS to identify and address extreme response values that could potentially distort the mean scores and influence the interpretation of results. This procedure strengthened the robustness and reliability of the dataset before proceeding to factor evaluation.

Following data screening, mean score analysis was conducted to determine the relative importance of each of the 26 identified factors influencing bid winning. Respondents rated each factor using a five-point Likert scale and the mean value for each factor was calculated. In line with the methodology, a cut-off mean value of 4.0 was adopted to identify critical factors. This threshold represents the level at which respondents collectively perceive a factor as important or highly important. Therefore, only factors with mean values equal to or greater than 4.0 were classified as critical factors affecting bid winning probability.

Based on this criterion, seven factors were identified as critical. These factors demonstrated strong perceived influence on bid winning within the Sri Lankan construction industry. Table 2 presents the mean values of all 26 factors and highlights those exceeding the adopted cut-off value.

*Table 2: Factors affecting bid winning and their mean values*

| Rank | Factor | Mean Value | Critical Factor (≥4.0) |
|---|---|---|---|
| 1 | Financial Stability | 4.552 | Yes |
| 2 | Past Performance | 4.438 | Yes |
| 3 | Availability of Resources | 4.292 | Yes |
| 4 | Technical Proposal Quality | 4.253 | Yes |
| 5 | Bidding Strategy | 4.196 | Yes |
| 6 | Expected Profitability | 4.050 | Yes |
| 7 | Market Conditions | 4.010 | Yes |
| 8 | Number of Competitors | 3.960 | No |
| 9 | Bid Price Deviation from Cost Estimate | 3.920 | No |
| 10 | Size of Project | 3.875 | No |
| 11 | Accessibility of Project Location | 3.854 | No |
| 12 | Client’s Reputation on Payment History | 3.820 | No |
| 13 | Bid Preparation Time | 3.806 | No |
| 14 | Type of Project | 3.800 | No |
| 15 | Procurement Method | 3.800 | No |
| 16 | Type of Client | 3.790 | No |
| 17 | Current Workload | 3.781 | No |
| 18 | Funding Source | 3.771 | No |
| 19 | Bid Submission Period | 3.750 | No |
| 20 | Project Delivery Method | 3.735 | No |
| 21 | Site Conditions | 3.729 | No |
| 22 | Contract Type | 3.700 | No |
| 23 | Project Location | 3.688 | No |
| 24 | Integrating Value Engineering Concepts | 3.465 | No |
| 25 | Joint Venture or Subcontracting Involvement | 3.406 | No |

| Rank | Factor | Mean Value | Critical Factor (≥4.0) |
|---|---|---|---|
| 26 | Use of BIM or Technology Tools | 3.140 | No |

## 4.3 DISCUSSION OF CRITICAL FACTORS

The analysis identified seven factors with mean values equal to or greater than the cut-off value of 4.0. These were financial stability, past performance, availability of resources, technical proposal quality, bidding strategy, expected profitability and market conditions. These factors are considered critical as respondents collectively perceived them to have a strong influence on bid winning probability.

Financial stability recorded the highest mean value (4.552), indicating that contractors' liquidity, cash flow strength and creditworthiness are decisive in bid evaluations. It is noteworthy that financial stability includes sub-components such as working capital availability, advance payment capacity and plant ownership status, all of which directly affect a contractor's ability to price competitively and secure bids in the Sri Lankan market. This finding is consistent with previous studies that identify financial capacity as a key determinant of contractor selection and bid success (Oo et al., 2022; Tessema et al., 2022). Financial stability also ranked highest in studies conducted in Ethiopia (Tessema et al., 2022) and Taiwan (Chen et al., 2024), indicating that financial capacity is a key determinant of bid success across different contexts.

Past performance (mean 4.438) was the second most critical factor, reflecting the importance of a contractor's track record in terms of quality, timeliness and successful project delivery. Similar findings are reported by Ahmed and El-Adaway (2024) and Ghodoosi et al. (2021), who highlighted the role of historical performance in reducing client risk and improving bid competitiveness. Availability of resources (mean 4.292) indicates the importance of having sufficient labour, equipment and management capacity to execute projects. Technical proposal quality (mean 4.253) reflects the need for clear, compliant and well structured submissions. Bidding strategy (mean 4.196) and expected profitability (mean 4.050) emphasise the strategic nature of bidding decisions, where contractors balance competitiveness with acceptable returns. These factors were similarly highlighted in studies from Australia (Aznar et al., 2017) and the UAE (Aldossari, 2024), confirming their broader relevance across construction markets.

Market conditions (mean 4.010) show that external factors such as competition level and economic climate also affect bid winning (Binshakir et al., 2023; Hanák et al., 2021). However, market conditions ranked lower than in European studies (Hanák et al., 2021; Jiang & Holubava, 2023), possibly due to the relatively stable competitive environment in Sri Lanka. Overall, the results suggest that bid winning probability is influenced by a combination of financial strength, operational capability, strategic decision-making and market dynamics rather than a single factor. The remaining factors did not reach the cut-off value of 4.0, indicating that they were perceived as moderately influential compared to the critical factors. Some of these may represent standard requirements that most contractors already meet, while others may have indirect or context specific impacts that are less decisive in determining bid winning.

## 5. CONCLUSIONS AND RECOMMENDATIONS

For contractors, winning construction bids is crucial as it directly impacts market competitiveness, profitability, and business continuity. Therefore, understanding the key factors influencing bid winning probability is important, especially in competitive environments within developing countries. The aim of this study was to identify and analyse the critical factors that affect the probability of winning bids in the Sri Lankan construction bidding process. A two-stage research methodology was adopted, where factors identified from the literature were first validated by experienced professionals and then evaluated through a questionnaire survey. The collected data were screened using an outlier test and mean score analysis was conducted to determine the most critical factors. The results identified seven critical factors, with financial stability, past performance and availability of resources emerging as the most influential. The findings show that bid success depends not only on price but also on financial strength, technical capability, strategic decisions and market conditions. The study is limited to the Sri Lankan context and to competitive bidding forms; other procurement forms such as negotiated contracts have not been examined. Furthermore, factors such as scope misinterpretation and bid pricing errors, which may counterintuitively increase win probability through under-pricing, were not examined in this study and are recommended for investigation in future research. This study relies primarily on mean score analysis. However, the methodology used in this research can be adopted by other developing countries to identify factors influencing bid winning probability in their own construction industries. It is recommended that contractors improve financial management, maintain strong performance records, ensure adequate resources and adopt strategic bidding practices to enhance their chances of winning bids. Future research could extend this study by employing advanced multivariate techniques such as factor analysis or structural equation modelling (SEM) to explore the interrelationships among the identified critical factors. Longitudinal studies tracking bidding outcomes over time would help validate these findings under dynamic market conditions. The seven critical factors identified in this study can be practically integrated into contractors' bid/no-bid decision-making processes as a structured checklist. By systematically assessing financial stability, resource availability, past performance and strategic alignment prior to bid submission, contractors can make more informed decisions, improve submission quality and enhance their overall competitiveness in the Sri Lankan construction market.

## 6. REFERENCES

Abbas, A., Din, Z. U., & Farooqui, R. (2016). Achieving greater project success & profitability through pre-construction planning: A case-based study. *Procedia Engineering, 145*, 804–811. https://doi.org/10.1016/j.proeng.2016.04.105

Ahmed, M. O., & El-Adaway, I. H. (2024). Exploring the influences on construction bidding decisions: Insights from literature and industry experts. In J. G. Zack & P. S. Gransberg (Eds.), *Construction Research Congress 2024* (pp. 350–360). American Society of Civil Engineers. https://doi.org/10.1061/9780784485286.036

Aldossari, K. M. (2024). Exploring bid/no-bid decision factors of construction contractors for building and infrastructure projects. *Buildings, 14*(10), 3114. https://doi.org/10.3390/buildings14103114

Arifuddin, R., Muharram, M. H., & Abdurrahman, M. A. (2025). Analysis of factors affecting construction project tender winning in small qualification contractors. *Engineering, Technology and Applied Science Research, 15*(1), 20197–20202. https://doi.org/10.48084/etasr.9357

Aznar, B., Pellicer, E., Davis, S., & Ballesteros-Pérez, P. (2017). Factors affecting contractor's bidding success for international infrastructure projects in Australia. *Journal of Civil Engineering and Management, 23*(7), 880–889. https://doi.org/10.3846/13923730.2017.1341955

Binshakir, O., AlGhanim, L., Fathaq, A., AlHarith, A. M., Ahmed, S., & El-Sayegh, S. (2023). Factors affecting the bidding decision in sustainable construction. *Sustainability, 15*(19), 14225. https://doi.org/10.3390/su151914225

Chen, Y. T., Dao, T. H., & Chiu, I. H. (2024). A spherical fuzzy objective weighting framework for factors affecting bidding decisions for construction projects: A case study of Taiwan. *Heliyon, 10*(16), e36420. https://doi.org/10.1016/j.heliyon.2024.e36420

Emere, C. E., Aigbavboa, C. O., & Oguntona, O. A. (2025). Critical project delivery strategies for sustainable building construction in South Africa. *Frontiers in Built Environment, 11*, 1566468. https://doi.org/10.3389/fbuil.2025.1566468

Fawale, T. S., & Dada, J. O. (2017). Impact of contractors' bidding strategies on bid success in the Nigeria construction industry. *International Journal of Built Environment and Sustainability, 4*(1), 23-27. https://doi.org/10.11113/ijbes.v4.n1.156

Ghodoosi, F., Bagchi, A., Hosseini, M. R., Vilutienė, T., & Zeynalian, M. (2021). Enhancement of bid decision-making in construction projects: A reliability analysis approach. *Journal of Civil Engineering and Management, 27*(3), 149–161. https://doi.org/10.3846/jcem.2021.14344

Hanák, T., Drozdová, A., & Marović, I. (2021). Bidding strategy in construction public procurement: A contractor's perspective. *Buildings, 11*(2), 47. https://doi.org/10.3390/buildings11020047

Hwang, J. S., & Kim, Y. S. (2016). A bid decision-making model in the initial bidding phase for overseas construction projects. *KSCE Journal of Civil Engineering, 20*(4), 1189–1200. https://doi.org/10.1007/s12205-015-0760-y

Jefferies, D., & Schweber, L. (2022). Professional judgement: An institutional logic approach to contractor tender pricing. *Buildings and Cities, 3*(1), 518–533. https://doi.org/10.5334/bc.204

Jiang, Y., & Holubava, V. (2023). Risk management and response measures for bidding and tendering in construction projects. *World Science, 3*(81), 1-11. https://doi.org/10.31435/rsglobal_ws/30092023/8042

Kusumarukmi, E. I., Joko, T., & Adi, W. (2018). Public tendering process for construction projects: Problem identifications, analysis, and proposed solutions. *MATEC Web of Conferences, 258*, 02013. https://doi.org/10.1051/matecconf/201925802013

Leśniak, A. (2021). Statistical methods in bidding decision support for construction companies. *Applied Sciences, 11*(13), 5973. https://doi.org/10.3390/app11135973

Mahamid, I. (2022). Critical factors influencing the bid/no-bid decision in the Palestinian construction industry. *Engineering, Technology and Applied Science Research, 12*(1), 8096–8100. https://doi.org/10.48084/etasr.4538

Memić, N., Tadayon, A., Olsson, N. O. E., Wondimu, P. A., Ishtiaque, T. A., & Lædre, O. (2023). Exploring pre-construction activities in infrastructure projects that can benefit from contractor involvement. *Buildings, 13*(10), 2569. https://doi.org/10.3390/buildings13102569

Mohemad, R., Razak Hamdan, A., Othman, Z. A., Maizura, N., & Noor, M. (2010). Decision support systems (DSS) in construction tendering processes. *IJCSI International Journal of Computer Science Issues, 7*(1), 35-45. https://doi.org/10.48550/arXiv.1004.3260

Muhammed, A. O., Muhammed, A. A., Anda Yakubu, H., Suleiman, A., & Adam, A. (2022). Assessment of factors affecting contractors tendering success for construction projects in North-Central Nigeria. *International Journal of Real Estate Studies, 16*(1), 87-99. https://doi.org/10.11113/intrest.v16n1.155

Nufus, Z. (2023). The effect of Rosetta Stone application on student's English reading comprehension. *EDUCATE: Journal of Education and Culture, 1*(03), 192-196. https://pdfs.semanticscholar.org/3f01/0df7dfdeba6578dfbd9d700c2de90710f7bc.pdf

Oo, B. L., Lim, T. H. B., & Runeson, G. (2022). Critical factors affecting contractors' decision to bid: A global perspective. *Buildings, 12*(3), 379. https://doi.org/10.3390/buildings12030379

Pheng, L. S., & Hou, L. S. (2019). The economy and the construction industry. In L. S. Pheng & L. S. Hou (Eds.), *Construction quality and the economy* (pp. 21–54). Springer. https://doi.org/10.1007/978-981-13-5847-0_2

Puci, J., Demi, A., & Kadiu, A. (2023). Impact of macroeconomic variables on the construction sector. *Corporate and Business Strategy Review, 4*(1), 22–30. https://doi.org/10.22495/cbsrv4i1art2

Rashidi, A., Tamošaitienė, J., Ravanshadnia, M., & Sarvari, H. (2023). A scientometric analysis of construction bidding research activities. *Buildings, 13*(1), 220. https://doi.org/10.3390/buildings13010220

Sonmez, R., & Sözgen, B. (2017). A support vector machine method for bid/no bid decision making. *Journal of Civil Engineering and Management, 23*(5), 641–649. https://doi.org/10.3846/13923730.2017.1281836

Temu, J. J., Luvara, V. G. M., & Sospeter, N. G. (2025). The interplay between bidding strategies and tender success rate among small and medium enterprise contractors in Tanzania. *International Journal of Social Science Research and Review, 8*(7), 323–343. https://doi.org/10.47814/ijssrr.v8i7.2706

Tessema, A. T., Alene, G. A., & Wolelaw, N. M. (2022). Assessment of risk factors on construction projects in gondar city, Ethiopia. *Heliyon, 8*(11), e11726. https://doi.org/10.1016/j.heliyon.2022.e11726

Thiruchelvam, K., & Uduwage, D. N. L. S. (2025). Assessing SDG 7 performance: Identifying relevant KPIs for the Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium* (pp. 203–215). https://doi.org/10.31705/WCS.2025.16

Uduwage, D. N. L. S., Panuwatwanich, K., & Waidyasekara, K. G. A. S. (2024). Multicriteria selection practices in public tender evaluation process: The case of Sri Lanka. *Built Environment Project and Asset Management, 15*(3), 733–751. https://doi.org/10.1108/BEPAM-12-2023-0220

Uduwage, D. N. L. S., Perera, B. A. K. S., & Panuwatwanich, K. (2026). Critical factors influencing the contract award criteria in public construction projects: A confirmatory factor analysis approach. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 18*(2), 04526004. https://doi.org/10.1061/JLADAH.LADR-1445

Weerakoon, T. G., Wimalasena, S., & Fedotova, K. (2023). Economic crisis adaptation in Sri Lankan construction industry: Pathway to prosperity. *Baltic Journal of Real Estate Economics and Construction Management, 11*(1), 240–256. https://doi.org/10.2478/bjreecm-2023-0015

Whang, S. W., Donyavi, S., Flanagan, R., & Kim, S. (2022). Balanced approach for tendering practice at the pre-contract stage: The UK practitioner's perspective. *Journal of Civil Engineering and Management, 28*(5), 338–348. https://doi.org/10.3846/jcem.2022.16580

De Silva, M.N.S., Madusanka, H.W.N. and Natasha, K.A.D.M., 2026. FPM sentinel: A data-driven facility performance management dashboard for the Sri Lankan built environment. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 782-795. DOI: https://doi.org/10.31705/WCS.2026.58. Available from: https://ciobwcs.com/papers/

# FPM SENTINEL: A DATA-DRIVEN FACILITY PERFORMANCE MANAGEMENT DASHBOARD FOR THE SRI LANKAN BUILT ENVIRONMENT

**M.N.S. De Silva[1], H.W.N. Madhusanka[2] and K.A.D.M. Natasha[3]**

## *ABSTRACT*

*Facility Performance Management (FPM) is an emerging sub-domain of facility management (FM) concerned with the systematic monitoring and optimisation of built-environment performance across multiple operational dimensions. Despite growing international recognition of its strategic value, Sri Lankan FM practice remains predominantly reactive, with no integrated, data-driven performance monitoring systems established. This paper presents the development and expert validation of FPM Sentinel; a web-based dashboard prototype designed to consolidate multi-dimensional facility performance data into a single, accessible visualisation tool tailored for Sri Lankan FM experts. The prototype is built upon a six-pillar FPM framework comprising Maintenance Management, Energy Management, Resource Utilisation, User and Occupant Comfort, Safety and Compliance, and Aesthetics, with each pillar underpinned by literature-justified Key Performance Indicators (KPIs). Developed using a Design Science Research (DSR) approach and demonstrated through a hypothetical case study facility (F001), the prototype was evaluated by seven Sri Lankan FM experts representing architecture, hospitality, commercial property management, and multi-property FM. Expert review confirmed the conceptual validity of the framework, the contextual relevance of the KPI set, and practical applicability to the local FM context. Evaluation feedback also informed framework refinements, including the addition of a Renewable Energy Utilisation KPI and adjustments to improve accessibility for non-FM users. The FPM Sentinel represents a proof-of-concept response to an identified gap in Sri Lankan FM practice, demonstrating the feasibility of data-driven, multi-dimensional performance monitoring pending validation with live operational data.*

***Keywords:*** *Dashboard Visualisation; Design Science Research; Facility Performance Management; Key Performance Indicators; Sri Lanka.*

## 1 INTRODUCTION

There has been a significant change in the management of built environment, which has evolved to become more data-oriented in terms of performance management as opposed to being more reactive in nature and more of maintenance work. Facility Performance

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, desilvamns.21@uom.lk
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, nandunm@uom.lk
[3] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, miyukin@uom.lk

Management (FPM) has now been perceived as a rational operation that monitors, quantifies, and empowers building performance on various operating facets, therefore, propelling facilities to add real value to occupants and organisations (Liu et al., 2026). With the growing complexity of building systems and the growth of the demands of stakeholders, the ability to centralize the performance information of differing sources to consistent and usable conclusions has become essential in the efficient management of facility management (FM) decision-making (Eckerson, 2012).

The FM practice is however, reactive and fragmented in Sri Lanka. There is a general trend of dispersing building performance data in disconnected systems, such as maintenance records, energy meters, and customer feedback mechanisms, with little to no connection to a unified system of evaluation (Dasandara et al., 2022). As a result, facility managers do not have the means to convert multidimensional performance data into transparent visuals to enable them to detect a trend, set priorities in interventions, as well as justify the strategic value of FM to the stakeholders of the organisation. This has made worse by reported shortcomings in competencies among the local FM workforce as well as lack of internationally-equivalent performance measurement systems adjusted to the Sri Lankan setting (Herath et al., 2019).

To address this gap, this study presents the design, development, and expert assessment of FPM Sentinel, a web-based Facility Performance Management dashboard prototype structured around a six pillar conceptual framework grounded in international FM literature and reviewed by seven locally and internationally experienced FM practitioners. The paper is structured as follows: Section 2 reviews theoretical foundations; Section 3 describes the research methodology; Section 4 presents the FPM Sentinel development; Section 5 reports expert validation findings; Section 6 presents the case study demonstration; Section 7 discusses implications; and Section 8 presents conclusions.

# 2 THEORITICAL BACKGROUND AND CONTEXTUAL GAP

## 2.1 FACILITY PERFORMANCE MANAGEMENT

Facility Performance Management (FPM) is a more specific sub-domain of Facilities Management (FM) that optimistically and in a formalized manner analyses and manages the performance of a facility, especially that of non-core areas of operation. This formal procedure involves monitoring, measuring, and optimising the facility performance to facilitate that buildings are appropriate to organisational goals such as operational efficiency, cost-effectiveness, safety, building occupant comfort, and environmental sustainability (Meng & Minogue, 2011). In FM, the measurement of performance touches upon such essential dimensions as energy efficiency, safety and health, occupant comfort, resources utilisation, and maintenance management, all of which are incorporated into unbiased, multi-dimensional evaluation frameworks (Shin et al., 2023).

The thorough literature review marks six pillars of FPM, including maintenance management, which comprises two categories of the building system maintenance planning and optimisation to prevent failure (Parida et al., 2015); energy management, which encompasses the active monitoring and optimisation of energy use (Fichera et al., 2020); resource utilisation, which concerns active monitoring and optimisation of water, space, and operational resources (Lam et al., 2008); user and occupant comfort

encompassing thermal, visual, acoustic, and respiratory comfort dimensions (Wang et al., 2018); safety and compliance involving systematic management of building safety systems and regulatory adherence (Hassanain et al., 2022); and aesthetics capturing the influence of visual design quality and maintenance condition on occupant satisfaction (Whang et al., 2023).

### 2.2 PERFORMANCE DASHBOARD TECHNOLOGIES

The performance dashboards have become the traditional form of visualisation technology in real-time monitoring of key performance indicators (KPIs), which is a consolidated data-driven visualisation that forms the basis of evidence-based management decisions (Eckerson, 2012). It is known that successful dashboards are a combination of at-a-glance executive-level summary charts and drill-down diagnostic capabilities, thus, allowing both strategic control and targeted intervention (Yigitbasioglu & Velcu, 2012). According to Presthus and Bergum (2015), effective dashboard design consists of six key components: KPI selection, layout clarity, drilling capability, visual principles, technical functionality, and contextual information.

### 2.3 FPM IN THE SRI LANKAN CONTEXT

Facilities Management (FM) in the Sri Lankan construction industry encounters several unique challenges. Despite the diversity of building typologies across residential, commercial, institutional, and industrial sectors, structured approaches to managing building performance remain limited. Empirical data show that FM competence scores in the Sri Lankan market are significantly lower than in more developed FM markets, with notable discrepancies in technical, business management, and people management skills (Herath et al., 2019). This has resulted in decreased quality of FM services in the hotel, hospital, and commercial building sectors due to the absence of proper performance measurement systems (Dasandara et al., 2022). In turn, it has resulted in the evolution of an evident need for a comprehensive, multidimensional FPM and an effective visualisation instrument specific to the Sri Lankan context(Samarakkody & Perera, 2023).

## 3 RESEARCH METHODOLOGY

The research adopted a Design Science Research (DSR) methodology (Gledson et al., 2024; Lechner, 2024), following the seminal DSRM framework of Peffers et al. (2007) (see Table 1), which is most adequate in the context of development and testing of useful artefacts. The artefact, in this case, is the FPM Sentinel dashboard prototype that is aimed at managing the shortcomings of the professional practice identified earlier. DSR has an iterative cycle of problem identification and solution design and artefact development followed by evaluation and thus it can be suitable in applied research on facility management as the main contribution is a functional tool.

*Table 1:Mapping of the study to the Peffers et al. (2007) Design Science Research Methodology (DSRM)*

| DSR Activity | Peffers et al. (2007) Description | Application in This Study | Study Phase |
|---|---|---|---|
| 1. Problem Identification & Motivation | Define the specific research problem and justify the value of a solution | Identified the absence of an integrated, data-driven FPM system in Sri Lanka through a review of local FM practice and international literature. Justified the need for a multi-dimensional performance monitoring tool. | Phase 1 |
| 2. Define Objectives of a Solution | Infer objectives of a solution from the problem definition | Established the objectives of FPM Sentinel: to develop a six-pillar framework covering Maintenance, Energy, Resource Utilisation, Occupant Comfort, Safety & Compliance, and Aesthetics, each supported by literature-justified KPIs. | Phase 1 |
| 3. Design & Development | Create the artefact — construct, model, method, or instantiation | Developed the FPM Sentinel web-based dashboard prototype incorporating the six-pillar FPM framework and 13 KPIs. Built as a single-page web application hosted on Vercel with a four-layer architecture (Presentation, Application Logic, Data Integration, Data Storage). | Phase 2 |
| 4. Demonstration | Demonstrate use of the artefact to solve one or more instances of the problem | Demonstrated the potential functional capabilities of FPM Sentinel using a simulated illustrative dataset for hypothetical facility F001 (150,000 sq. ft., 25-storey commercial building), showcasing the Portfolio Performance Index (PPI), trend analysis, and performance status matrix. | Phase 3 & 4 |
| 5. Evaluation | Observe and measure how well the artefact supports solving the problem | Conducted semi-structured expert validation interviews with seven experienced Sri Lankan FM experts from architecture, hospitality, commercial property management, and multi-property FM. Validated the conceptual framework, KPI relevance, and dashboard usability. Incorporated expert-recommended refinements (e.g., Renewable Energy Utilisation KPI; non-FM user interface adjustments). | Phase 3 |

| DSR Activity | Peffers et al. (2007) Description | Application in This Study | Study Phase |
|---|---|---|---|
| 6. Communication | Communicate the problem, artefact, and its utility to researchers and practitioners | Findings communicated through this conference paper submitted to the 14th World Construction Symposium 2026, contributing to knowledge on data-driven FM practice in developing contexts. | Phase 4 |

The study occurred in four phases. Initially, a systematic literature review was undertaken to develop the six-pillar conceptual framework of FPM, from which two key performance indicators (KPIs) were derived for each pillar based on existing literature, with one additional KPI (Renewable Energy Utilisation) incorporated into the Energy Management pillar following expert validation, resulting in a total of 13 KPIs across the six pillars. Secondly, the prototype of the FPM Sentinel dashboard was deployed as an on-demand web app that is hosted on the Vercel platform, and its functionality was explored with a simulated illustrative dataset. Thirdly, semi-structured expert validation interviews were conducted with seven experienced facility management experts. Finally, the functionality of the dashboard was tested using a hypothetical case-study simulation based on a typical 150,000 sq. ft. commercial area (facility F001) consisting of 25 storeys.

Seven experts were sampled strategically so that they could represent different sectors as well as levels of experience in the field of facility management. Table 2 shows the panel of choice entailed:

*Table 2: Expert profile*

| Expert | Designation | Years of experience |
|---|---|---|
| E1 | Chartered Architect | 40 years |
| E2 | Head of Engineering | 20 years |
| E3 | Senior Property Manager | 25 years |
| E4 | Head of Facilities | 07 years |
| E5 | Facility Engineer | 15 years |
| E6 | Facility Manager | 10 years |
| E7 | Facility Manager | 12 years |

Simulated data used in this study is clearly admitted to be used as a pointer of the functionality of the dashboard, not as an indicator of empirical data of building performance.

# 4 THE FPM SENTINEL DASHBOARD

## 4.1 SYSTEM ARCHITECTURE

The FPM Sentinel has been designed as a custom single-page web app so that the control over interface design, data logic, and visualisation features can be achieved affordably. The dashboard follows a four-layer design: the Presentation Layer is the interactive user interface, the Application Logic Layer includes a JavaScript-based KPI normalisation and

scoring server, the Data Integration Layer includes eight operational data sheets, fully structured and the Data Storage Layer contains a twelve-months' worth of past performance measurements. The overall Portfolio Performance Index (PPI) is calculated as an aggregated weighted station of six pillar scores where every KPI is normalised to a standardised 0-100 before being aggregated. The specific weight values (Maintenance Management 20%, Aesthetics 10%, and intermediate values for remaining pillars) were assigned based on the authors' interpretation of relative operational priority as reflected in the reviewed FM literature; it is acknowledged that this constitutes a limitation, and a formal weighting procedure such as the Analytical Hierarchy Process (AHP) (Vaidya & Kumar, 2006) should be employed in future iterations to derive weights more rigorously. The weight values reflect the relative operational prominence of each pillar as evidenced across the reviewed FM performance measurement literature. Lavy et al. (2010) establish that physical and operational dimensions encompassing maintenance condition, energy, and functional use consistently constitute the core of holistic FM performance assessment frameworks, which informed the higher weights assigned to Maintenance Management (20%), Energy Management (18%), and User and Occupant Comfort (18%) in this study. Aesthetics, while recognised as a valid FM dimension (Dasandara et al., 2022), is consistently positioned as a supplementary rather than primary operational indicator across the FM performance literature (Meng & Minogue, 2011; Lavy et al., 2010), supporting its lower weight of 10%. It is nonetheless acknowledged that differential weighting introduces an element of judgement, and a formal weighting procedure such as the Analytical Hierarchy Process (AHP) (Vaidya & Kumar, 2006) through pairwise comparison by domain experts should be employed in future iterations to derive weights with greater methodological rigour. The PPI is then overlayed onto a letter grade (A-F) and a maturity description of either Optimised, Established, Developing or Ad Hoc.

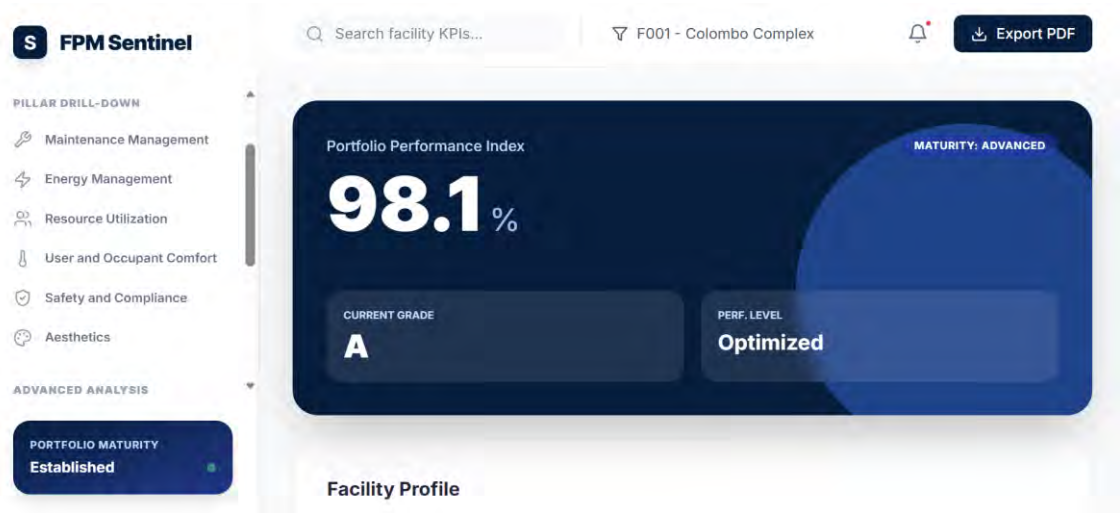



*Figure 1: FPM sentinel landing page*

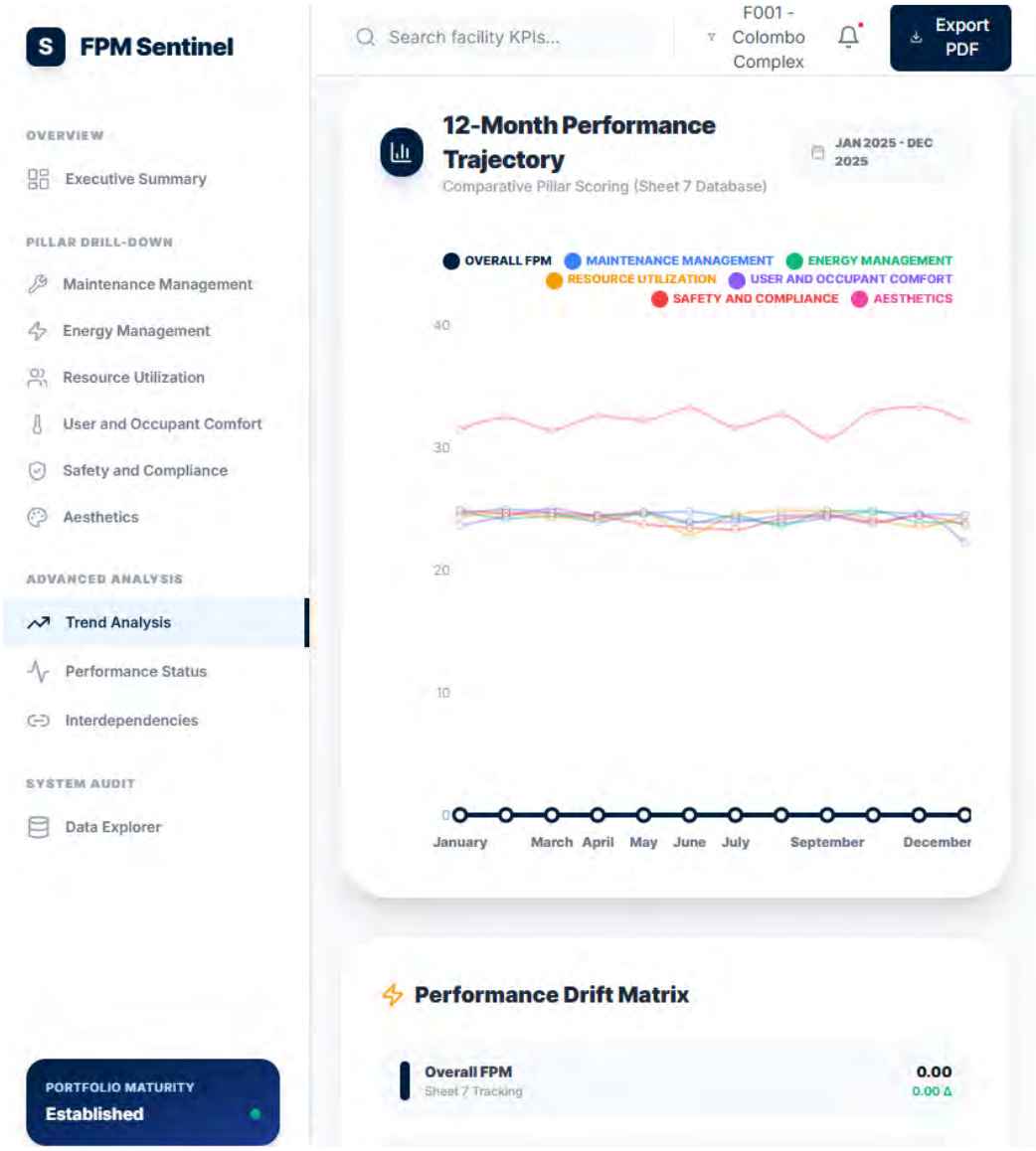



*Figure 2: Advance analysis features*

## 4.2 KPI FRAMEWORK

The KPIs used under each pillar were based on the measurability, availability of data, support in literature, and the dashboard presentation appropriateness. Table 3 presents the final KPI set with associated literature sources.

*Table 3: FPM sentinel KPI framework*

| Pillar | KPI | Formula | Source |
|---|---|---|---|
| Maintenance (P01) | Planned Maintenance % | (Planned / Total Tasks) × 100 | Lavy et al. (2014) |
| | WO Resolution Time | Total WO Time / No. Completed | Ioannidis et al. (2017) |
| Energy (P02) | Energy Use Intensity | Annual Energy (kWh) / GFA (m²) | Chua et al. (2013) |

| Pillar | KPI | Formula | Source |
|---|---|---|---|
| | HVAC Energy % | (HVAC / Total Energy) × 100 | Geekiyanage and Ramachandra (2018) |
| Resource (P03) | Space Utilisation Rate | Frequency (F) × Occupancy (O) | Abdullah et al. (2012) |
| | Water Consumption / m² | Annual Water (L) / GFA (m²) | Bertone et al. (2016) |
| Comfort (P04) | PMV / Thermal Comfort | ISO 7730 / ASHRAE 55 | Fanger (1970) |
| | IAQ / $CO_2$ Concentration | $CO_2$ in ppm (<1000 benchmark) | Aziz et al. (2023) |
| Safety (P05) | Safety Audit Compliance Rate | (Completed / Required) × 100 | Hassanain et al. (2022) |
| | Incident Rate | (Incidents / Total Staff) × 100 | Expert Validation (this study) |
| Aesthetics (P06) | Occupant Aesthetic Satisfaction | Likert scale POE survey (1–5) | Asojo et al. (2021) |
| | Aesthetic Deficiency Rate | (Deficiencies / Areas) × 100 | Preiser (2002) |

### 4.3 INTERFACE AND NAVIGATION

The FPM Sentinel is arranged into three major navigation areas accessible through a fixed left-hand side bar. The Executive Summary shows the total PPI, grade, maturity classification, a hexagonal Pillar Performance Map showing all six pillars at the same time, a Critical Deviations panel indicating KPIs most divergent from to target, and a Facility Profile panel. All of the six individual Pillar Drill-Down pages provide KPI metric cards with current value and trend indicators, 12-month Performance Velocity area chart, a KPI Achievement Variance horizontal bar chart, and KPI Performance Audit panel with discrete KPI trend lines. An Advanced Analysis panel offers cross-pillar Trend Analysis, a Performance Status Matrix that shapes out all KPIs and labels them as On Target, Near Target and Critical At risk and a conceptual System Interdependencies view, which will be empirically developed at a later point. The reflection of System Data Explorer gives complete visibility of the underlying data pipeline over the eight tabbed data sheets.

## 5 KPI RELEVANCE AND CONTEXTUAL APPLICABILITY

The KPI set was found relevant and measurable by experts as shown in Table 4, in general in the context of Sri Lanka. Expert E1 supported the inclusion of Renewable Energy Utilisation into the Energy Management pillar with a reference to the increasing trend in implementing rooftop photovoltaic systems in commercial buildings in Sri Lanka; the suggestion was later implemented into the prototype. Expert E2 confirmed that HVAC energy consumption is the most pragmatic metric that is monitored in the hospitality industry, thus including it. The Safety Audit Compliance Rate was supported by Expert E3 as a substantive general compliance measure; and it is considered practical with regard to the Work Order management subsection. Experts E4 and E5 agreed on the suitability

of the Safety and Compliance KPIs, with Incident Rate being an important outcome-based safety measure that would be relevant in the daily facility management operation.

*Table 4: Expert to KPI mapping*

| Pillar | KPI 1 | KPI 2/ Addition | Experts | Key Validation Finding |
|---|---|---|---|---|
| Maintenance Management | Planned Maintenance Execution Rate | WO Resolution Time | E2, E3, E4, E5 | Both confirmed as most trackable; E3 recommended WO departmental filtering; E5 validated MTBF exclusion |
| Energy Management | Energy Use Intensity | HVAC System Energy %; Renewable Energy Utilisation | E1, E2, E6, E7 | E1's Renewable Energy Utilisation recommendation incorporated; E6 & E7 flagged sector-specific HVAC benchmarks |
| Resource Utilisation | Space Utilisation Rate | Water Consumption Rate | E3, E6 | Both confirmed; E6 suggested Manpower Utilisation as future addition |
| User & Occupant Comfort | PMV / Thermal Comfort | IAQ / $CO_2$ Index | E2, E3, E4 | Confirmed as primary comfort KPIs; comfort complaints identified as leading FM escalation driver |
| Safety & Compliance | Safety Audit Compliance Rate | Incident Rate | E3, E4, E5 | Incident Rate unanimously preferred over Training Completion Rate; SLA-based WO recommended by E7 |
| Aesthetics | Occupant Aesthetic Satisfaction | Aesthetic Deficiency Rate | E1, E3 | Both confirmed; critical for tenant satisfaction and lease renewal |

## 5.1 USABILITY AND ACCESSIBILITY

E3 noted that, whilst the dashboard would be easily understood by facility management experts, some of the KPI definitions may be too difficult to understand by non-FM stakeholders, including property owners or top managers. Thus, E3 recommended that an icon tooltip be added next to every KPI in order to provide a plain-language explanation, which was listed among usability improvements of primary importance for the next development. E2 raised a concern regarding the target user hierarchy, thus highlighting the need to configure access levels in a production implementation, making it a potential development future.

## 5.2 COMMERCIAL VIABILITY

E3 clearly supported the fact that a process-based organisation should be happy to buy and implement the FPM Sentinel in order to streamline FM processes. E2 advised the use of the dashboard as an explanatory instrument that will warrant investment in qualified FM experts and, therefore, support the argument that FPM instruments can make FM a more central aspect of strategic management among Sri Lankan organisations (Dasandara et al., 2022). The E7 proposal in terms of client-definable weightages also adds to the

strength of business viability by allowing the dashboard to adapt itself to unique strategic goals of different clients and construction typologies.

### 5.3 USABILITY, DESIGN, AND CUSTOMISATION

The most noticeable recurrent theme of four experts (E2, E3, E6, and E7) was the ease of use of dashboard by users with dissimilar degrees of FM technical skills. E3 repeated the suggestion of adding 'i' icon tooltips next to every KPI to clarify it in plain language; it has been shown that this is prioritized in the usability enhancements. E7 highlighted the issue, indicating terminologies to be simplified in a manner that all people at any level of operation understand the dashboard without necessarily having to possess an understanding of the FM. E2 stressed the need to have user-access hierarchies configured towards a production deployment. A significant change in design suggested by E7 was the proposal to replace the immutable pillar and KPI weightages with permitting the framework to be set by the clients with their respective weightages as the organisational priorities and types of buildings. This suggestion, which is in line with the multi-criteria decision-analysis methods (Vaidya & Kumar, 2006), would significantly increase the flexibility of the dashboard to work in different deployment settings. Moreover, E7 supported the use of SLA-based work-order categorisation as opposed to department-based, citing the fact that SLAs are more related to FM service-delivery commitments, a substantive operational understanding on the basis of international FM operation.

## 6 CASE STUDY DEMONSTRATION

The FPM Sentinel was tested on a hypothetical building F001, a business complex with the size of 150000 sq. ft. spread on 25 floors with simulated illustrative data, meant to be representative of the typical performance benchmark in commercial buildings. Its dashboard showed an overall Performance Index (PPI) of 98.1%, which was depicted by grade A classification, an optimised level of performance as well as an advanced level of maturity. The performance map in the form of a hexagon indicated the broadly balanced performance across all six dimensions; the User and Occupant Comfort pillar had the lowest aggregate score of 90.5% in contrast to the 97% -100% score in the other five pillars. The Critical Deviations panel declared Lighting Quality Index (actual = 62.59, target = 80) and the Indoor Air Quality Index (actual = 72.1, target = 85) two critical performance indicators (KPIs) for which the target deviations were the highest, and they are both in the "WARNING" status.

Also, the Performance Status Matrix determined 10 of the 13 KPIs were On Target and 3 of the KPIs were also Critical At -Risk with the KPIs all being clustered in the User and Occupant Comfort pillar. The Trend Analysis page stated that User and Occupant Comfort had the highest negative drift over the last 12-months, whereas the Velocity Insights panel provided an automated narrative explanation of changes in performance momentum. Despite the Aesthetics pillar scoring a good aggregate score of 99.0%, the pillar indicated downward trend waves in all three KPIs in the latter half of the year, which illustrates the practical usefulness of the dashboard in alerting on imminent performance risks before the risk develops into a major problem. The case study illustration revealed that the FPM Sentinel can handle, visualise, and interpret multidimensional facility performance information, hence aiding evidence-based facilities management in decision-making.

# 7 DISCUSSION

The FPM Sentinel aims to address two related shortcomings, namely; the absence of an approved multi-dimensional FPM framework applicable to Sri Lanka and the absence of integrated visualisation tools that can turn building performance information into practical management information. The fact that the six-pillar framework received a unanimously positive score among seven experts in different industries and geographically diverse areas, i.e., in relation to Sri Lanka, the Gulf region and international FM practice, testifies to the fact that the framework is based on a real cross-contextual need that is not an exception in the literature (Dasandara et al., 2022; Herath et al., 2019).

The overlap of usability issues between four separate experts (E2, E3, E6, E7) of whom each can independently find it necessary to simplify the terminology provides a consistent indicator of a shared usability concern. When practitioners from different backgrounds independently converge on the same recommendation, this convergence lends indication of a substantive user need as opposed to a fortuitous notice. This intersection is the direct basis of the prioritisation of tooltip implementation as a high-priority development item of any future production version. The E7 suggestion of client weightages of KPI brings to bear a relevant architectural insight that goes not only as far as usability, but also as far as system design. The fact that, a fixed weighting scheme is informed by the literature, does not mean that it will suit the strategic priorities of individual organisations. What would be very beneficial is that a configurable system would go a long way in terms of flexibility and being commercially viable and this is the same kind of literature available on the multi-criteria decision analysis (Vaidya & Kumar, 2006). Similarly, the work-order suggestion of E7, which is based on SLA, is in line with the functional reality of international practice of FM service delivery, whereby the obligations of the contractual performance have more operational significance than the departmental classifications.

The case-study presentation shows how the FPM Sentinel converts disjointed data on KPI measures into a consistent narrative of performance, with User and Occupant Comfort being the least robust pillar, specific shortcomings in IAQ and Lighting Quality being highlighted, and a new aesthetic maintenance risk being noticed. Such diagnostic specificity can be attributed to the position of the literature that the impactful design of dashboards should be able to identify performance issues quickly and assist in making decisions based on evidence (Eckerson, 2012; Presthus & Bergum, 2015). It must be explicitly noted, however, that the reliance on simulated illustrative data constitutes a significant a significant limitation of this study. The hypothetical dataset was designed solely to demonstrate the functional capabilities of the dashboard and is not representative of actual building performance. This limits the generalisability of the results and the strength of validation claims; the framework and tool must be further tested using live operational data from real facilities before broader applicability can be asserted.

# 8 CONCLUSIONS

The research paper outlines how the FPM Sentinel was developed and assessed through expert review, addressing an identified gap in integrated, multi-dimensional FM performance monitoring within Sri Lankan practice. There are three major conclusions of this investigation.

To begin with, the 6-pillar FPM framework, including the Maintenance Management, Energy Management, Resource Utilisation, User and Occupant Comfort, Safety and Compliance, and Aesthetics, provides a structured multi-dimensional conceptual basis for assessing facility performance in the Sri Lankan context. The framework is grounded in international FM literature and assessed by seven experts across diverse industry sectors, demonstrating preliminary conceptual relevance and contextual applicability pending further empirical validation.

Secondly, this framework is brought into practice by the FPM Sentinel as a proof-of-concept dashboard prototype. Expert review indicated that an integrated, multi-dimensional FM performance tool in this nature addresses a recognised gap in the local FM market, with participating practitioners from diverse sectors affirming its practical relevance.

Thirdly, the professional checkpoint process, complemented with international insights provided by Gulf and globally experienced FM experts, produced substantive design recommendations, which entail client-configurable KPI weightages, work-order management via SLAs, simplified terminology, and increased findability of tool tips, and, in general, define and establish a roadmap of development. Future studies must focus on the validation of live-building in operational data, derivation of pillar weight through formal derivation based on AHP, the ability to implement client-configurable weighting to the framework, and apply the framework to the healthcare, education, and residential building domains.

## 9 ACKNOWLEDGEMENTS

The authors wish to thank the seven-facility management experts who participated in the expert validation interviews for their time, expertise, and valuable contributions to this research.

## 10 REFERENCES

Abdullah, S., Ali, H. M., & Sipan, I. (2012). Benchmarking space usage in higher education institutes: Attaining efficient use. *Journal of Techno-Social*, *4*(1), 11–20. https://publisher.uthm.edu.my/ojs/index.php/JTS/article/view/1346

Asojo, A., Vo, H., & Bae, S. (2021). The impact of design interventions on occupant satisfaction: A workplace pre- and post-occupancy evaluation analysis. *Sustainability*, *13*(24), 13571. https://doi.org/10.3390/su132413571

Aziz, N., Adman, M. A., Suhaimi, N. S., Misbari, S., Alias, A. R., Aziz, A. A., & Khan, M. (2023). Indoor air quality (IAQ) and related risk factors for Sick Building Syndrome (SBS) at the office and home: A systematic review. *IOP Conference Series: Earth and Environmental Science*, *1140*(1), 012007. https://doi.org/10.1088/1755-1315/1140/1/012007

Bertone, E., Sahin, O., Richards, R., & Roiko, A. (2016). Extreme events, water quality and health: A participatory Bayesian risk assessment tool for managers of reservoirs. *Journal of Cleaner Production*, *135*, 657–667. https://doi.org/10.1016/j.jclepro.2016.06.158

Chua, K. J., Chou, S. K., Yang, W. M., & Yan, J. (2013). Achieving better energy-efficient air conditioning – A review of technologies and strategies. *Applied Energy*, *104*, 87–104. https://doi.org/10.1016/j.apenergy.2012.10.037

Dasandara, M., Dissanayake, P., & Fernando, D. J. (2022). Key performance indicators for measuring performance of facilities management services in hotel buildings: A study from Sri Lanka. *Facilities*, *40*(5–6), 1–20. https://doi.org/10.1108/F-02-2021-0009

Eckerson, W. W. (Ed.). (2012). *Performance dashboards: Measuring, monitoring, and managing your business*. Wiley. https://doi.org/10.1002/9781119199984

Fanger, P. O. (1970). *Thermal comfort: Analysis and applications in environmental engineering*. Danish Technical Press.

Fichera, A., Volpe, R., & Cutore, E. (2020). Energy performance measurement, monitoring and control for buildings of public organizations: Standardized practises compliant with the ISO 50001 and ISO 50006. *Developments in the Built Environment*, *4*, 100024. https://doi.org/10.1016/j.dibe.2020.100024

Geekiyanage, D., & Ramachandra, T. (2018). A model for estimating cooling energy demand at early design stage of condominiums. *Journal of Building Engineering*, *17*, 43–51. https://doi.org/10.1016/j.jobe.2018.01.011

Gledson, B., Rogage, K., Thompson, A., & Ponton, H. (2024). Reporting on the development of a web-based prototype dashboard for construction design managers, achieved through Design Science Research Methodology (DSRM). *Buildings*, *14*(2), 335. https://doi.org/10.3390/buildings14020335

Hassanain, M. A., Al-Harogi, M., & Ibrahim, A. M. (2022). Fire safety risk assessment of workplace facilities: A case study. *Frontiers in Built Environment*, *8*, 861662. https://doi.org/10.3389/fbuil.2022.861662

Herath, A.G.T.L., Mallawaarachchi, H., & Rathnayake, R.M.D.I.M. (2019). Service consistency improvement of facilities management service providing organisations in Sri Lanka. In Y.G. Sandanayake, S. Gunatilake & A. Waidyasekara (Eds.), *8th World Construction Symposium* (pp. 513–523). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2019.51

Ioannidis, D., Zikos, S., Krinidis, S., Tryferidis, A., Tzovaras, D., & Likothanassis, S. (2017). Occupancy-driven facility management and building performance analysis. *International Journal of Sustainable Development and Planning*, *12*(7), 1155–1167. https://doi.org/10.2495/SDP-V12-N7-1155-1167

Lam, A. C., Kwok, S. K., & Lee, W. B. (2008). A knowledge-based performance measurement system for improving resource utilization. In J. Cordeiro & J. Filipe (Eds.), *International Conference on Enterprise Information Systems* (Vol. 6, pp. 187–192). SciTePress. https://doi.org/10.5220/0001684001870192

Lavy, S., Garcia, J. A., Scinto, P., & Dixit, M. K. (2014). Key performance indicators for facility performance assessment: Simulation of core indicators. *Construction Management and Economics*, *32*(2), 1183–1204. https://doi.org/10.1080/01446193.2014.970208

Lechner, C. (2024). *The use of design science research in the development of a KPI benchmarking dashboard* [Unpublished doctoral dissertation]. Leopold-Franzens-Universität Innsbruck.

Liu, W., Chan, A. P. C., Li, X., & Darko, A. (2026). Automated performance measurement and benchmarking in emergency healthcare facility projects. *Automation in Construction*, *181*, 106630. https://doi.org/10.1016/j.autcon.2025.106630

Meng, X., & Minogue, M. (2011). Performance measurement models in facility management: A comparative study. *Facilities*, *29*(11–12), 472–484. https://doi.org/10.1108/02632771111157141

Parida, A., Kumar, U., Galar, D., & Stenström, C. (2015). Performance measurement and management for maintenance: A literature review. *Journal of Quality in Maintenance Engineering*, *21*(1), 2–33. https://doi.org/10.1108/JQME-10-2013-0067

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, *24*(3), 45–77. https://doi.org/10.2753/MIS0742-1222240302

Preiser, W. (2002). *The evolution of post-occupancy evaluation: Toward building performance and universal design evaluation*. Federal Facilities Council.

Presthus, W., & Bergum, I. (2015). Business intelligence to the people: A case study of dashboard adoption in the health care sector. In *Norsk konferanse for organisasjoners bruk av IT (NOKOBIT)*.

Samarakkody, A., & Perera, B. A. K. S. (2023). Application of soft landings concept in Sri Lanka to narrow the building performance gap, enablers and barriers. *Smart and Sustainable Built Environment*, *12*(1), 156–180. https://doi.org/10.1108/SASBE-03-2021-0052

Shin, H., Son, B., & Park, M. (2023). A balanced performance measurement model for office building facility management. *International Journal of Sustainable Building Technology and Urban Development*, *14*(2), 261–284. https://doi.org/10.22712/susb.20230020

Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, *169*(1), 1–29. https://doi.org/10.1016/j.ejor.2004.04.028

Wang, Z., De Dear, R., Luo, M., Lin, B., He, Y., Ghahramani, A., & Zhu, Y. (2018). Individual difference in thermal comfort: A literature review. *Building and Environment*, *138*, 181–193. https://doi.org/10.1016/j.buildenv.2018.04.040

Whang, S. W., Park, K. S., & Kwon, C. (2023). Influence of aesthetic design elements on residential satisfaction in apartment based on Seoul apartment complex. *Journal of Asian Architecture and Building Engineering*, *23*(4), 1381–1392. https://doi.org/10.1080/13467581.2023.2270006

Yigitbasioglu, O. M., & Velcu, O. (2012). A review of dashboards in performance management: Implications for design and research. *International Journal of Accounting Information Systems*, *13*(1), 41–59. https://doi.org/10.1016/j.accinf.2011.08.00.2

Madushanka, T.H., Soorige, S.D.A. and Madhusanka, H.W.N., 2026. From BIM 6D/7D to operational digital twins: Closing the building energy performance gap in tropical buildings- a mixed-methods study in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 796-813. DOI: https://doi.org/10.31705/WCS.2026.59. Available from: https://ciobwcs.com/papers/

# FROM BIM 6D/7D TO OPERATIONAL DIGITAL TWINS: CLOSING THE BUILDING ENERGY PERFORMANCE GAP IN TROPICAL BUILDINGS- A MIXED-METHODS STUDY IN SRI LANKA

**T.H. Madushanka[1,2] S.D.A. Soorige[3] and H.W.N. Madhusanka[4]**

## *ABSTRACT*

*Buildings and construction are major drivers of global energy demand and energy-related $CO_2$ emissions, yet operational energy use often diverges from design predictions, creating an energy performance gap (EPG). Building Information Modelling (BIM) has expanded toward lifecycle use, including BIM 6D for energy and sustainability analysis and BIM 7D for facilities management. However, many organisations still struggle to translate design intent into operational outcomes because of poor as-built information, BIM–building energy modelling interoperability issues, weak commissioning-to-operations handover, and fragmented building management system data. Operational digital twins (DTs) are increasingly promoted as a means to connect design and operation by linking information models to real-time data, analytics, and feedback loops. This study develops an expert-validated Sri Lanka-specific framework for integrating BIM 6D/7D with operational DTs to reduce the EPG in tropical buildings. An exploratory sequential mixed-methods design was used. Phase 1 combined policy review and semi-structured interviews with 20 Sri Lankan building lifecycle experts. Phase 2 used a two-round Delphi study with 48 panellists to validate and prioritize 20 statements on barriers and critical success factors, analysed using consensus statistics and the Relative Importance Index. The main barriers are unverified as-built BIM/asset data, BIM–BEM interoperability problems, and insufficient commissioning and controls tuning. The top success factors are capturing control sequences and commissioning evidence, publishing energy-focused digital information requirements for BIM-to-operations continuity, and standardizing asset tagging and FM handover templates. The paper proposes a lifecycle digital thread-to-twin framework and implementation roadmap tailored to tropical buildings and developing-country delivery contexts.*

***Keywords:*** *Building Energy Performance Gap; Building Information Modelling (BIM); Operational Digital Twins; Sri Lanka; Tropical Buildings.*

[1] PhD Candidate, Department of Facilities Management, University of Moratuwa, Sri Lanka, madushankath.24@uom.lk
[2] Lecturer, Department of Design Studies, NSBM Green University, Sri Lanka, hashan.m@nsbm.ac.lk
[3] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, sooriged@uom.lk
[4] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka. nandunm@uom.lk

# 1. INTRODUCTION

The building and construction sector is central to global energy and climate outcomes, accounting for around 34% of final energy demand and 37% of energy-related $CO_2$ emissions in 2023 (Ozcan-Deniz & Rodovalho, 2024). Improving operational building performance is therefore a core lever for decarbonisation and energy security. A persistent obstacle is the energy performance gap (EPG), the difference between predicted performance (from compliance calculations or simulations) and measured operational use (Forth & Borrmann, 2024). The EPG undermines confidence in modelling, reduces realised policy and investment benefits, increases operating costs, and, in developing countries with supply constraints and rising cooling demand, contributes to grid stress (Cheng & Das, 2014). Recent work frames the EPG as a lifecycle socio-technical problem arising from modelling assumptions, delivery and installation defects, commissioning and controls practices, maintenance, and occupant-organisation behaviour (Sha & Zhang, 2024), with even well-designed systems drifting into inefficiency over time.

Building Information Modelling (BIM) has expanded beyond geometry to include sustainability and lifecycle information. BIM 6D supports design-stage energy analysis, while BIM 7D targets facilities management (FM), asset registers, and lifecycle O&M. However, BIM 6D/7D outputs often fail to influence operations: simulations are done for approvals and then archived; as-built info is incomplete or late; FM teams revert to spreadsheets; and interoperability issues and poor workflow alignment persist (Kurniawan et al., 2023; Rashwan et al., 2023). Operational digital twins (DTs) are promoted as a bridge between design and operation by linking BIM models with live building management system (BMS)/Internet of Things (IoT) data for monitoring, fault detection and diagnostics (FDD), commissioning, and feedback (Altaf et al., 2024; Choi & Lee, 2023). In this study, an operational DT is more than a BIM-linked dashboard: live data must update the model and support diagnosis, learning, and corrective action; otherwise, it remains a visualisation rather than an operational tool.

This study focuses on Sri Lanka because tropical, cooling-dominated buildings are especially sensitive to heating, ventilation, and air-conditioning (HVAC) operation, humidity control, commissioning quality, and maintenance drift, all of which directly affect the EPG. Although the 2020 Energy Efficiency Building Code addresses large buildings and emphasizes HVAC and controls, lifecycle digitalisation remains uneven because O&M budgets are limited, digital requirements are fragmented, post-occupancy verification is sparse, and analytics capability is patchy. There is no consensus-based, expert-validated framework for operationalising BIM 6D/7D with DTs in tropical, developing-country contexts. Accordingly, the study aims to develop an expert-validated framework for integrating BIM 6D/7D with operational DTs to reduce the EPG in Sri Lankan tropical buildings. The study addresses five research questions: (1) policy and institutional factors for energy efficiency and digitalisation; (2) current BIM 6D/7D practices and their limitations; (3) barriers and enablers to BIM 6D/7D–DT integration across the lifecycle; (4) critical success factors and governance needed to reduce EPG using BIM-enabled DTs; and (5) which factors achieve expert consensus and priority via Delphi. The remainder of the paper reviews the literature, explains the mixed-methods design, presents the qualitative and Delphi findings, discusses Sri Lanka-specific and transferable implications, and concludes with the framework, limitations, and future research.

# 2. LITERATURE REVIEW AND CONCEPTUAL FRAMING

## 2.1 EPG AS A LIFECYCLE PROBLEM

The EPG is commonly defined as the difference between predicted energy use or intensity (e.g., kWh/m²·year) and measured operational energy use. It can be expressed as an absolute difference or ratio:

$$EPG\ ratio = \frac{E\ actual}{E\ predicted}$$

$$EPG\ diff = E\ actual - E\ predicted$$

Recent reviews indicate the EPG is caused by multiple, lifecycle-driven factors, including modelling assumptions (weather, loads, schedules, control strategies, calibration); delivery issues (tolerances, substitutions, installation defects); commissioning and controls (incomplete testing, poorly tuned setpoints/sequences, weak trend checks); operations (maintenance deferral, sensor drift, overrides, organisational practices); and occupant or organisational changes diverging from modelled schedules (Al-Rudainy & Mahjoob, 2024; Qi, 2024). These factors interact: poor commissioning can push systems outside control bounds and increase modelling uncertainty, while strong, ongoing commissioning can limit drift and reduce the EPG even with imperfect models.

## 2.2 BIM 6D AND ENERGY ANALYSIS

BIM-based energy workflows enable early evaluation of design concepts, support performance-informed decisions, and reduce late changes. However, interoperability barriers persist due to geometry translation errors, inconsistent definitions, incomplete metadata, and divergent modelling paradigms between BIM and simulation tools. Exchange requirements are often implicit and lack quality assurance, leading to manual corrections and limited scalability (Sadeghifam et al., 2016). This drives a shift from "export-and-fix" approaches to managed interoperability with contractual rules, test cases, and quality checks at specific stages.

## 2.3 BIM 7D AND FACILITIES MANAGEMENT

The operations phase, the longest lifecycle stage, accounts for the majority of costs and emissions. BIM 7D supports FM by integrating asset data with maintenance workflows. Adoption barriers include incomplete models, limited FM tools and skills, and misaligned BIM and FM/BMS workflows (Ghoneim et al., 2025). The handover issue involves incentives and information: contractors may not invest in high-quality data without contractual and verification requirements, and owners may lack the resources or capabilities to maintain digital assets, leading to "information waste" when BIM models remain unused.

## 2.4 DIGITAL TWINS AND OPERATIONAL ENERGY

Digital twins (DTs) now extend from manufacturing to buildings, serving as virtual counterparts of physical assets through sensing, data integration, and analytics. Built-environment DTs consist of: (i) a physical layer with assets and sensors; (ii) a data layer with BMS/IoT interfaces and databases; (iii) a semantic/modelling layer from BIM models; and (iv) an analytics layer for FDD, optimization, and prediction (Abouelkhier et al., 2025). Energy-focused DTs enable real-time monitoring, fault detection,

commissioning, retrofit simulations, and control optimization. DT value relies on data availability and governance: asset identities, sensing accuracy, and actionable workflows. Without these, DTs risk becoming static visualizations with limited energy impact.

## 2.5 FROM DIGITAL TWIN TO OPERATIONAL DIGITAL TWIN: CLOSING LOOPS

Not all digital twin implementations are the same. Static BIM provides geometry and structured asset information but no live operational feedback. BIM-linked dashboards display live data against spaces or assets, but they do not necessarily diagnose faults or trigger action. In this study, an operational DT closes three loops: a sensing loop that updates the model with time-series data; an inference loop that diagnoses faults or predicts performance; and an action loop that supports or triggers corrective intervention. Closing these loops requires both technical integration and organisational readiness, which is why data quality, governance, and staged maturity are central to the framework.

## 2.6 DIGITAL THREAD, INTEROPERABILITY, AND GOVERNANCE

BIM–DT integration is seen as creating a "digital thread": a traceable info chain linking design, delivery, and operation, allowing data to connect to models of spaces, systems, and assets. ISO 19650 principles guide lifecycle info management, including operations and maintenance (Al-Rudainy & Mahjoob, 2024). ISO-aligned processes (requirements, data environments, roles, approvals) help ensure energy data is retained at handover. Integration demands semantic interoperability: operational systems use point tags and vendor names, whereas BIM models represent hierarchies and spatial relationships. Successful scaling depends on mapping strategies and governance that withstand changes in tools and vendor boundaries.

## 2.7 TROPICAL OPERATIONAL CONTEXT

Tropical buildings focus on cooling in high-humidity environments, increasing latent cooling requirements. Control settings such as setpoints, ventilation, and dehumidification affect energy use. Sri Lanka's building code covers HVAC, insulation, and controls, including measures to prevent condensation in chilled water and ducts (Perera et al., 2022). In tropical buildings, however, the EPG is often amplified by latent loads, sensor drift, ventilation imbalance, unstable chilled-water temperatures, poor dehumidification control, and control overrides after handover. These conditions make commissioning continuity and post-occupancy tuning especially important in hotels, hospitals, universities, and other variable-occupancy buildings. In developing-country settings, these risks are compounded by incomplete asset data, fragmented digital requirements, limited analytics capability, and weak governance, which helps explain why many BIM/DT initiatives fail to close the EPG in practice.

## 2.8 CONCEPTUAL PROPOSITION

Drawing on this literature, the study proposes that EPG reduction in tropical buildings depends on linking BIM 6D energy intent, BIM 7D operational information, and operational DT feedback loops through four conditions: verified asset and as-built data, BIM–BEM interoperability, commissioning-to-operations continuity, and lifecycle governance. Figure 1 later operationalises this conceptual grounding into the Tropical Digital Thread-to-Twin Energy Governance framework.

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN

An exploratory sequential mixed-methods design was used because the topic is complex, under-standardized, and strongly shaped by context and professional practice. Qualitative exploration was first conducted to identify locally relevant barriers and enablers, after which Delphi was used to test expert consensus, prioritize factors, and refine the framework transparently.

## 3.2 PHASE 1: DOCUMENT ANALYSIS

Documents selected to reflect national policies on building energy performance and lifecycle info include (i) Sri Lanka's Energy Efficiency Building Code (2020); (ii) the Sri Lanka Sustainable Energy Authority Act (2007); and (iii) energy policy and guidance emphasizing efficiency and conservation. They were coded for focus on design-stage versus operational verification, accountability mechanisms, and digital requirements or gaps for FM and energy monitoring.

## 3.3 PHASE 1: SEMI-STRUCTURED INTERVIEWS

### 3.3.1 Sampling and Participants

Purposive sampling involved 20 experts across the building lifecycle, including BIM managers/consultants (5), policymakers/regulators (4), facility managers (3), architects (2), MEP/energy engineers (1), energy auditors/ESCOs (2), technology integrators (2), and academics/researchers (1), averaging 14.1 years of experience (Table 1).

### 3.3.2 Data Collection

Interviews followed a semi-structured protocol on EPG manifestations in Sri Lanka's tropical buildings, BIM 6D practices, BIM–BEM workflows, BIM 7D/FM handover, DT awareness and readiness, governance, procurement, and skills. All were anonymized and de-identified, with participants giving informed consent.

### 3.3.3 Qualitative Analysis

Interview transcripts were analysed using thematic analysis through familiarisation, coding, theme development, review, and refinement, and were triangulated with the findings from document analysis. Coding proceeded iteratively until successive interviews yielded no materially new themes and the coding frame stabilized. The resulting themes were then consolidated into lifecycle barriers, enablers, and candidate Delphi statements grouped under technical, process, governance, capability, and financial dimensions.

## 3.4 PHASE 2: DELPHI STUDY

### 3.4.1 Panel Recruitment and Composition

A two-round Delphi study involved 48 panellists with diverse lifecycle roles and experience ranging from 0–5 to 16+ years, spanning early career to senior expertise (Table 2).

### 3.4.2 Delphi Instrument and Rounds

Twenty statements (10 barriers B01–B10 and 10 CSFs CSF01–CSF10) were rated on a 5-point scale (1 = Not important, 5 = Very important). Round 1 collected initial importance ratings. Round 2 provided feedback (group medians and dispersion) and invited panellists to reconsider ratings, supporting convergence without forcing consensus.

### 3.4.3 Analysis and Consensus Criteria

For each statement and round, medians and interquartile ranges (IQR) were summarized to describe the central tendency and dispersion. Agreement was assessed via top-two-box percentages (ratings 4-5) and Relative Importance Index (RII) rankings. Round 2 consensus was IQR ≤ 1 and ≥ 70% ratings in 4–5. Stability across rounds was assessed using median comparisons and Wilcoxon signed-rank tests for responses. Overall concordance was assessed using Kendall's coefficient of concordance (W). Descriptive statistics, Wilcoxon signed-rank tests, Kendall's W, and RII calculations were performed using SPSS and R.

## 3.5 TRUSTWORTHINESS AND ETHICS

Qualitative trustworthiness was enhanced through triangulation of documents and stakeholder perspectives, along with an audit trail of coding decisions. Delphi validity was supported by a diverse panel, controlled feedback, and stability checks. The study adhered to ethical standards with informed consent, anonymization, and secure data management. The findings support analytical rather than statistical generalization and do not constitute direct empirical validation of energy savings in operating buildings. Tables 1 and 2 summarize interview participants by role and Delphi panel composition.

*Table 1: Interview participant profile (n=20)*

| Role category | n | % |
|---|---|---|
| BIM Manager/Consultant | 5 | 25.0 |
| Policy/Regulator | 4 | 20.0 |
| Facility Manager/Operator | 3 | 15.0 |
| Architect | 2 | 10.0 |
| Energy Auditor/ESCO | 2 | 10.0 |
| Tech Integrator | 2 | 10.0 |
| Academic/Research | 1 | 5.0 |
| MEP/Energy Engineer | 1 | 5.0 |

*Table 2: Delphi panel profile (n=48)*

| Role group | n | % |
|---|---|---|
| **Energy Auditor/ESCO** | 13 | 27.1 |
| **BIM Manager/Consultant** | 7 | 14.6 |
| Architect | 7 | 14.6 |
| MEP/Energy Engineer | 6 | 12.5 |
| Facility Manager/Operator | 5 | 10.4 |

| Role group | n | % |
|---|---|---|
| Policy/Regulator | 4 | 8.3 |
| Academic/Research | 4 | 8.3 |
| Tech Integrator | 2 | 4.2 |

# 4. RESULTS

## 4.1 DOCUMENT ANALYSIS: POLICY AND REGULATORY SIGNALS FOR LIFECYCLE ENERGY PERFORMANCE

Sri Lanka's policy views energy efficiency as a national priority, providing a technical basis for design standards. The 2020 Energy Efficiency Building Code covers the building envelope, HVAC, lighting, water heating, and related services, focusing on design compliance, including enforcement and calculations such as ETTV/RTTV for large buildings. However, it emphasizes design and installation over operational verification and performance tracking. Operational energy practices lack strong institutional support, creating gaps that lifecycle digital tools such as BIM 7D, operational digital twins, and continuous commissioning could help fill. National policies also recognize energy efficiency and conservation as strategic, with buildings as a major sector. While aligned with priorities, delivery mechanisms and data governance remain fragmented.

## 4.2 INTERVIEW FINDINGS: SOCIO-TECHNICAL THEMES AFFECTING BIM–DT ADOPTION FOR EPG CLOSURE

Table 3 summarises the five socio-technical themes most frequently identified across the interviews, which are then discussed in turn. The most cited were as-built model quality (40%), skills/training needs (35%), and commissioning, controls tuning, sensor readiness, data governance, and BMS vendor silos (each 30%). This shows EPG closure is limited by information continuity and operational capability.

**Theme 1: Commissioning and controls are central EPG drivers in tropical buildings.**

Participants noted that operational setpoints, schedules, and control sequences often differ from design assumptions after handover. Small deviations in control logic, such as simultaneous heating/cooling, high outside-air rates, or supply-air temperature resets, can cause significant energy penalties in cooling-dominated buildings. A common comment was: "Our biggest energy wastage is after handover controls are not tuned, sensors drift, and nobody owns continuous commissioning."

**Theme 2: As-built information and asset data are unreliable, limiting DT feasibility.**

As-built BIM models are often incomplete or outdated, affecting digital twin (DT) efforts that rely on accurate asset data. A common view was: "As-built BIM is delivered but rarely verified or updated; FM teams can't rely on it."

**Theme 3: Data fragmentation and vendor silos limit operational integration.**

Participants highlighted that BMS data are often locked in proprietary vendor systems, and sensor/meter data are inconsistent across buildings. This makes each integration a custom project and constrains scalability: "BMS data is in vendor silos; integrating it with BIM and FM systems is still a custom project every time."

**Theme 4: Skills and organizational capability gaps constrain lifecycle digitalization.**

Even where BIM models exist, FM teams may lack tools, training, or mandates to maintain model fidelity. Respondents highlighted the need for cross-disciplinary skills: BIM, data management, controls/commissioning, and analytics literacy.

**Theme 5: Governance and procurement are missing backbones.**

Interviewees said procurement docs rarely specify energy-related digital deliverables, data ownership, or responsibilities for the "single source of truth." A tech integrator summarized: "Digital twin projects fail without clear governance, who owns the data, maintains the model, and acts on analytics?"

## 4.3 DELPHI RESULTS: VALIDATED AND PRIORITIZED FACTORS

Table 4 presents the highest-ranked Round 2 barriers and CSFs that informed the framework design principles; overall ratings were high (median = 4), with 8 of 20 statements meeting consensus thresholds (IQR ≤ 1, ≥ 70% top-two-box). Kendall's W showed modest but significant agreement (Round 1 W ≈ 0.176; Round 2 W ≈ 0.170; $p < 0.001$), reflecting typical Delphi study patterns where item-level consensus is more informative than full convergence.

### 4.3.1 Top-Ranked Barriers

The top barrier was the lack of verified as-built BIM and asset data (B02; median=5, IQR=1; RII=0.93). Next were interoperability issues between BIM and BEM tools (B01; median=4, IQR=1; 97.9% top-two-box; RII=0.89). The third was insufficient commissioning and controls tuning (B03; median=4, IQR=1; RII=0.87). These align with qualitative themes.

### 4.3.2 Top-Ranked Critical Success Factors

The key success factors included capturing control sequences and commissioning evidence in operations, publishing energy digital information requirements, standardizing asset tagging and FM handover templates, and using DT pilots and quick wins to drive implementation. These factors received high rankings (medians around 4-5, RII~0.86-0.89).

### 4.3.3 Stability Across Rounds

Several items, such as policy incentives for verification (CSF10) and BIM 7D integration with FM (CSF09), showed greater central tendency after controlled feedback, indicating improved recognition of governance and systems integration. Overall, top items remained stable, aligning with Phase 1 findings.

*Table 3: Frequency of interview themes (n=20; top themes shown)*

| Theme | Count | % of interviews |
|---|---|---|
| As-built model quality | 8 | 40.0 |
| Skills/training needed | 7 | 35.0 |
| Sensor readiness | 6 | 30.0 |
| Commissioning/controls tuning | 6 | 30.0 |
| Data governance & ownership | 6 | 30.0 |

| Theme | Count | % of interviews |
|---|---|---|
| BMS vendor silos | 6 | 30.0 |
| Tropical cooling loads | 5 | 25.0 |
| Procurement specs | 5 | 25.0 |
| Post-occupancy verification | 4 | 20.0 |
| BIM–BEM interoperability | 4 | 20.0 |

*Table 4: Delphi round 2 top-ranked barriers and CSFs (importance)*

| Type | Code | Statement (abridged) | Median | IQR | RII |
|---|---|---|---|---|---|
| Barrier | B02 | As-built BIM models are not updated/verified, limiting operational energy use. | 5.0 | 1.0 | 0.93 |
| Barrier | B01 | BIM-to-BEM interoperability issues reduce confidence in energy predictions. | 4.0 | 1.0 | 0.89 |
| Barrier | B03 | Insufficient commissioning and controls tuning drive the energy performance gap. | 4.0 | 1.0 | 0.87 |
| Barrier | B10 | Cybersecurity and privacy concerns hinder the operation of connected systems. | 4.0 | 2.0 | 0.76 |
| Barrier | B06 | Procurement rarely specifies energy-focused BIM deliverables and handover needs. | 4.0 | 1.0 | 0.72 |
| CSF | CSF03 | Capture and transfer control sequences and commissioning evidence at handover. | 5.0 | 1.0 | 0.89 |
| CSF | CSF01 | Publish energy digital information requirements for BIM 6D/7D deliverables. | 4.5 | 1.0 | 0.89 |
| CSF | CSF02 | Standardize asset tagging and FM handover templates for BIM 7D. | 4.0 | 1.0 | 0.86 |
| CSF | CSF04 | Start with DT quick wins (fault detection, scheduling, chiller optimization). | 4.0 | 1.0 | 0.86 |
| CSF | CSF06 | Define data ownership, access, and update responsibility across the lifecycle. | 4.0 | 1.0 | 0.78 |

## 4.4 INTERPRETING THE DELPHI PRIORITIES AS AN IMPLEMENTATION LOGIC

The ranked items suggest a multi-stage implementation logic. The highest-priority barriers, built-in data quality, BIM–BEM interoperability, and commissioning/controls form the foundation of any operational DT, as they determine if operational data can be reliably mapped to assets and deviations interpreted against an agreed baseline. Mid-ranked barriers, procurement, finance, culture, and data integration indicate that scaling beyond pilots requires contractual and organizational change once initial data trust and value are established. Lower-ranked factors, such as cybersecurity and privacy, are necessary design considerations but not immediate bottlenecks, aligning with a staged approach where early pilots focus on proving value while embedding security and governance from the start.

## 4.5 DELPHI-VALIDATED FRAMEWORK: FROM BIM 6D/7D TO AN OPERATIONAL DIGITAL TWIN FOR EPG CLOSURE

This study presents the Tropical Digital Thread-to-Twin Energy Governance framework (TDT2-EG), based on Phase 1 themes and Phase 2 Delphi priorities. It operationalizes BIM 6D/7D info via an operational DT, reducing EPG by linking design intent with operational reality. The lifecycle model has three layers: (L1) Governance and info management, covering roles, data ownership, cybersecurity, and ISO 19650 processes; (L2) Digital thread deliverables, key digital artifacts from design to operations; (L3) Operational twin services, including data pipelines, analytics, and decision workflows for monitoring, fault detection, and optimization. Figure 1 shows the framework across four lifecycle stages: Design (BIM 6D), Delivery (verification), Commissioning & soft landings, and Operations (BIM 7D + operational DT).

### 4.5.1 Core Design Principles Derived from Delphi Priorities

The framework includes Delphi-based design principles:

**P1.** Use as-built verification as a data quality gate before DT analytics (B02).
**P2.** Ensure BIM–BEM interoperability through agreed formats and validation (B01).
**P3.** Digitally capture commissioning and control knowledge (B03; CSF03).
**P4.** Formalize energy data requirements (E-DIR) for datasets, responsibilities, and updates (B06; CSF01; CSF06).
**P5.** Standardize asset-tagging and handover templates for operations (B02; CSF02).
**P6.** Focus on quick DT wins such as fault detection and scheduling to justify investment and build capability (CSF04).

### 4.5.2 Energy Digital Information Requirements (E-DIR)

E-DIR is proposed as the contractual and governance mechanism that specifies the minimum set of energy-relevant digital deliverables throughout the lifecycle. Unlike generic BIM execution plans, E-DIR is energy-outcome oriented: it defines which data are required to enable post-occupancy verification and continuous optimization. Table 5 provides an illustrative E-DIR structure. The E-DIR should be attached to procurement and handover requirements and should define: (i) energy intent assumptions and modelling inputs; (ii) asset metadata, tags, and relationships; (iii) commissioning and controls deliverables; (iv) metering and sensing requirements; and (v) data governance rules.

### 4.5.3 Digital Thread Deliverables Across the Lifecycle

The digital thread is operationalized through explicit deliverables and quality gates at each lifecycle stage:

**Design:** Develop an “energy intent model” that details the zoning strategy, schedules, loads, setpoints, and control logic, and documents assumptions in a structured narrative. Define rules for BIM–BEM interoperability exchange.

**Delivery:** Implement as-built verification and asset tagging to capture equipment identifiers, capacities, and key parameters, and reconcile them with design intent.

**Commissioning:** Capture testing evidence, logs, calibration certificates, control sequences, and setpoints to turn commissioning knowledge into reusable digital assets.

**Operations:** Maintain an asset registry linked to CMMS, establish secure data pipelines from BMS/IoT, and use analytics to support continuous commissioning and optimization.

#### 4.5.4 Operational Twin Services for EPG Closure

Once digital thread prerequisites are met, the operational DT supports a closed-loop EPG reduction cycle:

**Measure**: Ingest and validate time-series data (energy, temperatures, flows, pressures, humidity, occupancy proxies) and map to assets/spaces.

**Diagnose**: Perform automated FDD and detect performance drift relative to design intent and commissioning baselines.

**Decide**: Recommend corrective actions (setpoint correction, schedule optimization, maintenance work orders) and prioritize by energy impact and comfort risk.

**Act**: Implement changes through operators, FM workflows, or supervisory control.

**Verify** and learn to perform measurement & verification (M&V) of savings and feed learning back to standards, energy models, and future project E-DIR templates.

In tropical buildings, the analytics library should explicitly address cooling and humidity issues, such as AHU overventilation, excessive reheat, chilled-water temperature drift, condenser degradation, valve leaks, sensor bias, and dehumidification problems.

#### 4.5.5 Implementation Maturity Pathway

To support staged adoption in resource-constrained contexts, the framework defines an operational DT maturity pathway:

**Level 0 - Disconnected:** BIM models and BMS data exist but aren't linked; energy modelling is only for design compliance.

**Level 1 - Visibility:** Establish metering, sensing, and dashboards linked to assets and zones.

**Level 2 - Diagnostics:** Implement rules-based and data-driven FDD and continuous commissioning workflows.

**Level 3 - Prediction:** Develop calibrated models for scenario analysis, maintenance forecasting, and anomaly detection prediction.

**Level 4 - Optimization:** Implement predictive control and optimization loops with formal M&V and governance.

The Delphi results indicate that Sri Lanka's near-term value peaks when projects focus on Level 1-2 capabilities, visibility, and diagnostics, backed by commissioning continuity and reliable as-built information.

#### 4.5.6 Stakeholder Responsibilities (RACI logic)

A practical framework must allocate responsibilities across stakeholders:

**Designers/energy modellers**: Accountable for the energy intent model and assumptions, and for defining E-DIR inputs.

**Contractors and commissioning agents**: Responsible for as-built updates, asset tagging, and evidence-based commissioning deliverables.

**Owners/FM teams**: Accountable for operational KPIs, data governance decisions, and ongoing model maintenance.

**BMS/IoT vendors and integrators**: Responsible for secure data pipelines, point mapping, and analytics integration.

**Regulators and public clients**: Enable adoption through procurement templates and incentives for post-occupancy verification. This allocation of responsibilities directly addresses governance gaps identified in interviews and supports lifecycle continuity.

Figure 1 consolidates the preceding Delphi-derived design principles, digital thread deliverables, maturity pathway, and stakeholder responsibilities into a single lifecycle framework. The framework should be read from left to right across the four lifecycle stages, design, delivery, commissioning and soft landings, and operations. It shows that EPG reduction depends not only on introducing an operational digital twin at the operations stage, but also on creating verified energy-relevant information, control knowledge, and governance rules earlier in the project lifecycle.

To operationalise the framework, Table 5 translates the lifecycle logic in Figure 1 into minimum Energy Digital Information Requirements (E-DIR), verification gates, and primary ownership responsibilities. This prevents the framework from remaining conceptual and clarifies what information must be produced, checked, and transferred before BIM 6D/7D can support operational digital twin services.

*Table 5: Illustrative Energy Digital Information Requirements (E-DIR) structure for BIM 6D/7D–DT integration*

| Lifecycle stage | Minimum digital deliverables (energy-relevant) | Quality gate/verification | Primary owner (RACI: A/R) |
|---|---|---|---|
| **Design (6D)** | Energy intent model; zoning & schedules; setpoint logic; BEM inputs; interoperability mapping rules; metering & sensing plan. | Model QA/QC; traceability of assumptions; BIM–BEM exchange test case. | Design lead/energy modeller |
| **Construction/delivery** | As-built model update; asset tags; equipment metadata; O&M manuals; commissioning plan; sensor installation records. | As-built reconciliation; asset tag audit; spot checks of key capacities and locations. | Main contractor / BIM manager |
| **Commissioning & soft landings** | Functional test records; trend logs; calibration certificates; control sequences; setpoint baselines; handover training logs. | Commissioning sign-off; controls sequence verification; baseline acceptance test. | Commissioning agent/controls engineer |
| **Operations (7D + DT)** | Asset registry linked to CMMS; point naming and mapping; data pipeline to time-series DB; dashboards; FDD rules; continuous commissioning workflow. | Data quality monitoring; KPI reporting; M&V verification of interventions. | Owner/FM + DT operator |

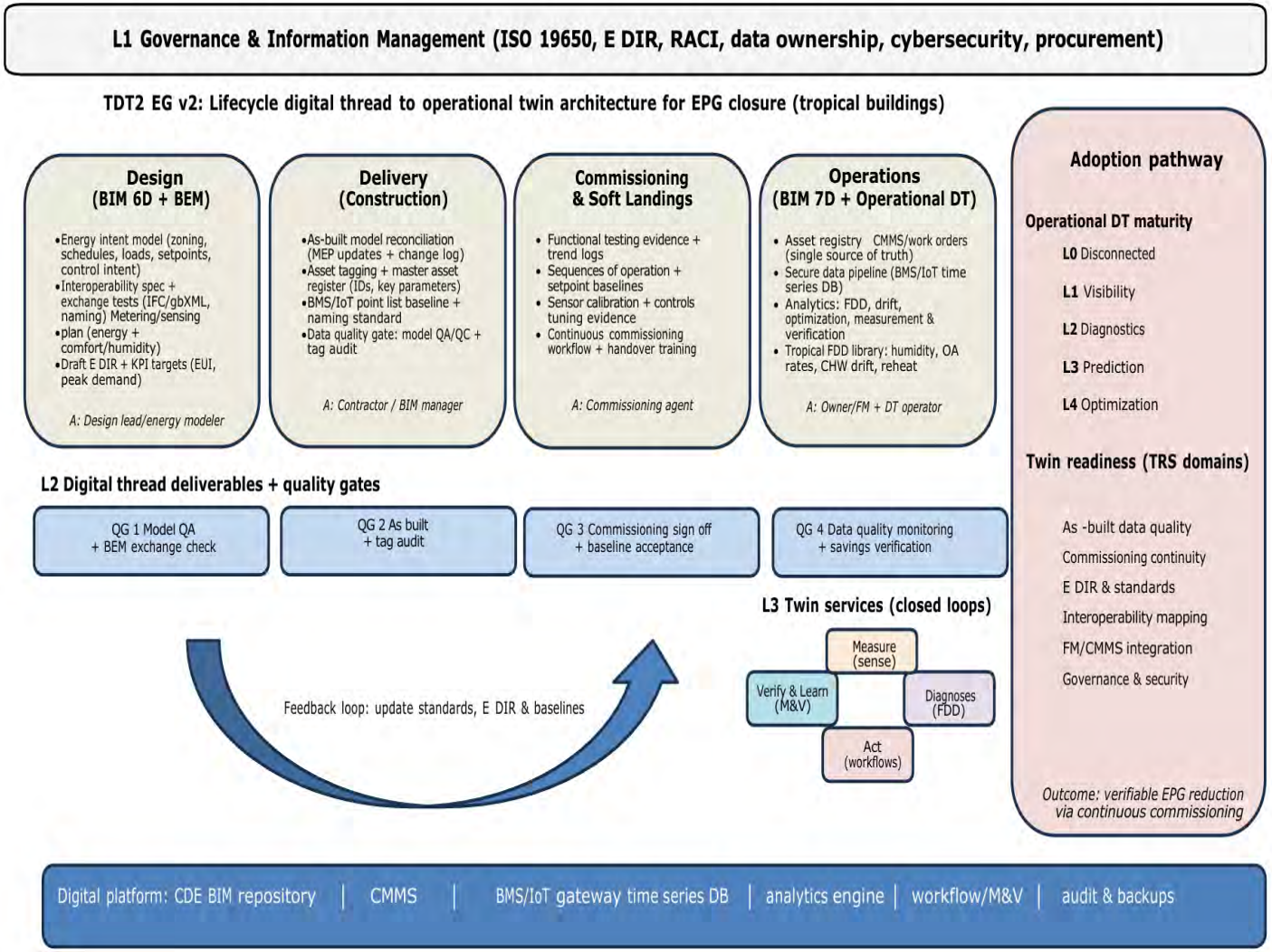



*Figure 1: BIM 6D/7D to operational digital twin integration framework (TDT2-EG)*

Table 5 shows that the E-DIR functions as the practical bridge between the conceptual framework and implementation. It links each lifecycle stage to specific energy-relevant deliverables and verification activities, thereby addressing the highest-ranked Delphi barriers, unverified as-built data, BIM-BEM interoperability issues, and weak commissioning continuity. By assigning ownership of the design, construction, commissioning, and FM to the actors, the table also clarifies how information accountability should shift from project delivery to operations.

### 4.5.7 Twin-Readiness Scorecard (TRS)

To support decision-makers, the study proposes a Twin-readiness scorecard (TRS) that assesses whether a project/building is ready to progress from BIM 6D/7D toward an operational DT and identifies which prerequisites should be prioritized. The TRS uses six readiness domains derived from Delphi priorities and assigns weights based on normalized RII values. Each domain is scored on a 1-5 scale (1 = not ready, 5 = fully ready). The overall TRS is calculated as:

$$TRS = \frac{\sum(Wi \times Scorei)}{5} \quad (01)$$

where Wi are weights summing to 100. The TRS can be interpreted as: <50 'not ready'; 50–70 'pilot-ready'; 70–85 'scale-ready'; and >85 'optimization-ready'. Table 6 lists the domains, weights, and diagnostic prompts.

*Table 6: Twin-readiness scorecard (TRS) domains and Delphi-derived weights (illustrative)*

| Readiness domain | Weight (%) | What "ready" looks like (diagnostic prompts) | Evidence artifacts (examples) |
|---|---|---|---|
| Data quality & as-built verification | 18.1 | Verified as-built model, asset tags reconciled, model QA completed, changes controlled. | As-built QA report; asset tag register; reconciliation log |
| Commissioning & controls continuity | 17.1 | Documented control sequences, test records, baselines, trend logs, and calibration certificates are available. | Commissioning report; sequences of operation; trend logs; calibration certificates |
| Standards & Energy Digital Information Requirements (E-DIR) | 17.3 | E-DIR agreed contractually; minimum data set defined; update responsibilities and cadence specified. | E-DIR document; BIM execution plan addendum; information delivery schedule |
| Interoperability & toolchain mapping | 16.5 | Agreed formats and mapping rules; test case shows data transfer is lossless or acceptable; naming conventions are defined. | Exchange test case; mapping specification; naming/ID standard |
| Handover & FM system integration | 16.0 | BIM 7D aligned with CMMS/BMS workflows; work order linkage; operators trained; data maintained post-handover. | COBie/asset export, CMMS integration, training records |
| Data governance, security & ownership | 15.0 | Data ownership and access defined; cybersecurity baseline implemented; audit and backup procedures in place. | Data governance charter; access matrix; security baseline checklist |

### 4.5.8 Operational Performance Indicators and Verification

To ensure that a DT contributes to EPG closure rather than merely monitoring, the framework recommends a minimal set of KPIs and a verification cycle. KPIs should be defined at three levels:

i. **Building-level**: energy use intensity (EUI), peak demand, and carbon intensity (if grid emission factors are available).
ii. **System-level**: chiller plant efficiency (kW/ton), cooling tower approach, AHU fan power per airflow, and ventilation rates.
iii. **Zone-level**: temperature and humidity compliance, comfort complaints, and schedule adherence.

Verification should follow a continuous cycle: detect-diagnose-act-verify, with monthly reviews and quarterly retuning, supported by automated FDD alerts and work-order tracking in FM systems. This approach is vital in tropical buildings where humidity and cooling can drift rapidly due to fouling, sensor bias, or control overrides.

# 5. DISCUSSION

## 5.1 SYNTHESIS OF FINDINGS

This study advances BIM-DT research by showing that, in Sri Lanka, the EPG is shaped less by the absence of modelling tools than by weak lifecycle continuity between design, delivery, commissioning, and operations. This finding is consistent with Zheng et al. (2024), who argue that the EPG is driven not only by simulation uncertainty but also by poor communication and management of lifecycle information. However, the present study extends this literature by identifying, through Delphi consensus, the specific information failures that matter most in a tropical developing-country context: unverified as-built BIM and asset data, BIM-BEM interoperability limitations, and insufficient commissioning and controls tuning.

The findings also align with Forth and Borrmann (2024), who show that BIM-based energy simulations depend on the availability and enrichment of reliable semantic information. While their work focuses mainly on improving BIM-based energy simulation inputs, the present study shows that semantic and asset-data reliability must continue beyond design-stage modelling into commissioning, handover, and FM. This is why the proposed E-DIR, asset-tagging requirements, and as-built verification gates are positioned as prerequisites for operational DT deployment rather than as optional handover documentation.

The Delphi results further correspond with recent digital twin studies that emphasise operational monitoring, anomaly detection, optimisation, predictive maintenance, and scenario simulation as core building-DT applications (Cespedes-Cubides & Jradi, 2024). Nevertheless, this study adds a more cautious implementation logic for Sri Lanka: most buildings should first target Level 1-2 DT capabilities, namely visibility, metering, dashboards, fault detection, and continuous commissioning, before moving toward predictive optimisation. This differs from technology-led DT narratives by showing that operational value depends on verified data, commissioning evidence, and FM workflow integration before advanced analytics can be trusted.

The emphasis on controls and commissioning also supports recent BIM-DT control literature. Hauer et al. (2024) identify building controls and fault detection as major areas for DT development, while Zech et al. (2025) position commissioning as a critical interface between design intent and operational performance. The present study reinforces these findings in a tropical setting, where control sequences, humidity management, sensor drift, chilled-water temperature control, and post-handover overrides can rapidly widen the EPG. Therefore, the contribution of this study is not simply to

confirm that BIM and DTs can improve energy performance, but to show which lifecycle governance conditions must be in place for such improvements to be achievable in Sri Lankan tropical buildings.

### 5.2 IMPLICATIONS FOR POLICY AND PROCUREMENT

For Sri Lanka, existing design-stage requirements should be supported by operational verification mechanisms. Rather than creating new compliance regimes, it's practical to embed E-DIR and post-occupancy verification in public procurement for large buildings. This aligns with energy efficiency goals and builds market capacity. Procurement should specify as-built verification, asset tagging, commissioning evidence, cybersecurity for connected systems, and post-handover maintenance of the digital thread. These measures address governance and procurement gaps identified by interviewees.

### 5.3 IMPLICATIONS FOR RESEARCH

The findings point to research opportunities in three areas: (i) semantic interoperability between BIM schemas and operational ontologies to support scalable point mapping; (ii) methods for continuous commissioning and FDD tailored to tropical HVAC and humidity control; and (iii) socio-technical governance models for operational DTs, including cybersecurity, data ownership, and incentives for long-term information maintenance.

## 6. PRACTICAL IMPLICATIONS AND ROADMAP FOR SRI LANKA

Drawing on the Delphi-ranked CSFs, a practical near-term roadmap for Sri Lanka is to publish an E-DIR template for major buildings; implement 3–5 Level 1–2 pilot projects focused on metering, dashboards, FDD, and soft-landings support; standardize asset tagging and handover templates aligned with computerized maintenance management system (CMMS)/BMS workflows; add procurement clauses for as-built verification, commissioning evidence, and cybersecurity baselines; and progressively embed DT-readiness and post-occupancy verification requirements into major public projects. This staged approach prioritizes capacity building, governance, and early operational value before wider institutionalization.

## 7. LIMITATIONS AND FUTURE RESEARCH

This study is limited by its Sri Lanka-specific qualitative and Delphi samples and by its reliance on expert judgement rather than measured energy outcomes from implemented digital twins. The findings, therefore, support analytical rather than statistical generalization. Future research should test the framework through longitudinal building case studies, quantify EPG reduction, and examine cost-benefit, semantic interoperability, and data governance issues across different ownership and procurement models.

## 8. CONCLUSIONS

This paper presents an expert-validated Sri Lanka-specific framework for integrating BIM 6D/7D with operational digital twins to reduce the EPG in tropical buildings. Using interviews (n = 20) and a two-round Delphi study (n = 48), it identifies unreliable as-built data, BIM–BEM interoperability issues, and weak commissioning continuity as the main

barriers, and highlights control-sequence capture, energy digital information requirements, asset tagging, and workflow alignment as the priority enablers. The study contributes a lifecycle Tropical Digital Thread-to-Twin Energy Governance framework, an E-DIR mechanism, and a twin-readiness scorecard to guide staged adoption. While developed for Sri Lanka, the framework offers analytical lessons for other tropical, developing-country contexts where data quality, commissioning, and lifecycle governance constrain operational performance.

# 9. REFERENCES

Abouelkhier, N., Rauf, A., Luyten, L., & Shafiq, M. T. (2025). Mitigating early-phase miscommunication between architects and structural engineers: A systematic review and framework linking BIM/VR strategies to communication barriers. *Architectural Engineering and Design Management*, 1–23. https://doi.org/10.1080/17452007.2025.2586665

Al-Rudainy, A. S. A., & Mahjoob, A. M. R. (2024). Using building information modelling to optimise design quality of natural lighting in Iraqi school buildings. *Organization, Technology and Management in Construction*, *16*(1), 52-62. https://doi.org/10.2478/otmcj-2024-0004

Altaf, M., Alalaoul, W. S., Musarat, M. A., Abdelaziz, A. A., & Thaheem, M. J. (2024). Optimization of energy and life cycle costs via building envelope: a BIM approach. *Environment, Development and Sustainability*, *26*(3), 7105-7128.

Cespedes-Cubides, A. S., & Jradi, M. (2024). A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Informatics*, *7*, Article 11. https://doi.org/10.1186/s42162-024-00313-7

Cheng, J. C. P., & Das, M. (2014). A BIM-based web service framework for green building energy simulation and code checking. *Journal of Information Technology in Construction*, *19*, 150–168. http://www.itcon.org/2014/8

Choi, J., & Lee, S. (2023). A Suggestion of the Alternatives Evaluation Method through IFC-Based Building Energy Performance Analysis. *Sustainability*, *15*(3), 1797. https://doi.org/10.3390/su15031797

Forth, K., & Borrmann, A. (2024). Semantic enrichment for BIM-based building energy performance simulations using semantic textual similarity and fine-tuning multilingual LLM. *Journal Of Building Engineering*, *95*. https://doi.org/10.1016/j.jobe.2024.110312

Ghoneim, M. M., Halabya, A., Moussa, O. M., & Hassan, A. A. (2025). An empirical assessment of material waste drivers and sustainability strategies in Egypt's construction sector. *Discover Sustainability*, *6*(1), 30, Article 1154. https://doi.org/10.1007/s43621-025-01976-2

Hauer, M., Hammes, S., Zech, P., Geisler-Moroder, D., Plörer, D., Miller, J., van Karsbergen, V., & Pfluger, R. (2024). Integrating digital twins with BIM for enhanced building control strategies: A systematic literature review focusing on daylight and artificial lighting systems. *Buildings*, *14*(3), 805. https://doi.org/10.3390/buildings14030805

Kurniawan, T. B., Dewi, D. A., Usman, F., & Fadly, F. (2023). Towards Energy Analysis and Efficiency for Sustainable Buildings. *Emerging Science Journal*, *7*(6), 2226-2238. https://doi.org/10.28991/ESJ-2023-07-06-022

Ozcan-Deniz, G., & Rodovalho, S. (2024). Towards carbon-neutral construction: Integrating BIM and energy analysis for sustainable design decision-making. *International Journal of Architectural Computing*. https://doi.org/10.1177/14780771241310213

Perera, U. D. S., Kulatunga, U., Abdeen, F. N., Sepasgozar, S. M. E., & Tennakoon, M. (2022). Application of building information modelling for fire hazard management in high-rise buildings: An investigation in Sri Lanka. *Intelligent Buildings International*, 14(2), 207–221. https://doi.org/10.1080/17508975.2021.1874858

Qi, C. (2024). Simulation of indoor thermal energy cycle in green building VR design based on BIM and computer virtual vision. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-024-14826-8

Rashwan, Y. G. M., & Mostafa, A. O. M. S. (2023). Top trends and challenges of building information modeling (BIM) to enhance the performance of building designs' energy consumption, and the reality of its practice in the Saudi local market - Riyadh city as a model. *Journal of Architecture and Planning – King Saud University*, 35(1), 1–41. https://doi.org/10.33948/JAP-KSU-35-1-1

Sadeghifam, A. N., Marsono, A. K., Kiani, I., Isikdag, U., Bavafa, A. A., & Tabatabaee, S. (2016). Energy analysis of wall materials using building information modeling (BIM) of public buildings in tropical climate countries. *Jurnal Teknologi*, *78*(10), 35-41. https://doi.org/10.11113/jt.v78.7591

Sha, X., & Zhang, X. (2024). High-rise building steel structure monitoring and energy efficiency optimization based on BIM and strain sensor vibration signal processing. *EAI Endorsed Transactions on Energy Web*, *11*, 1-10. https://doi.org/10.4108/EW.6560

Zech, P., Hammes, S., Goldin, E., Geisler-Moroder, D., Breu, R., & Pfluger, R. (2025). From BIM to digital twin: A transformation process through advanced control modeling and automated commissioning using daylight and artificial lighting as examples. Energy and Buildings, 329, 115184. https://doi.org/10.1016/j.enbuild.2024.115184

Zheng, Z., Zhou, J., Zhu, J., Yang, Y., Xu, F., & Liu, H. (2024). Review of the building energy performance gap from simulation and building lifecycle perspectives: Magnitude, causes and solutions. *Developments in the Built Environment*, *17*, 100345. https://doi.org/10.1016/j.dibe.2024.100345

Lokuge, A., De Silva, G.H.S.P. and Vinoshan, S., 2026. From inertia to integration: Evaluating the challenges and enablers of BIM in the infrastructure sectors of Sri Lanka and the Middle East. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 814-827. DOI: https://doi.org/10.31705/WCS.2026.60. Available from: https://ciobwcs.com/papers/

# FROM INERTIA TO INTEGRATION: EVALUATING THE CHALLENGES AND ENABLERS OF BIM IN THE INFRASTRUCTURE SECTORS OF SRI LANKA AND THE MIDDLE EAST

**Angel Lokuge[1], G.H.S.P. De Silva[2] and S.Vinoshan[3]**

## *ABSTRACT*

*The development of infrastructure using Building Information Modelling (BIM) in Sri Lanka and the Middle East poses its own unique set of challenges, notwithstanding the international recognition that BIM is a game-changing technology in construction. The presence of geographically context-specific technological, organisational, and cultural barriers has hindered consistent BIM implementation. This study was conducted to investigate the challenges and enablers associated with BIM adoption in infrastructure projects across these contexts. The study used a quantitative approach, employing a questionnaire among industry experts comprising engineers, architects, and quantity surveyors involved in the development of BIM infrastructure projects in Sri Lanka and the Middle East region. The collected data were analysed using the descriptive statistical tools, including percentages, weighted average and means, on a 5-point Likert scale to identify critical implementation challenges and enabling factors. The findings revealed that issues such as a lack of qualified professionals, high initial investment, policy gaps, and limited stakeholder awareness were the dominant barriers in both contexts. The study also highlighted key enablers including government mandates, educational initiatives, and improved interoperability through standardised protocols. While the Middle East benefits from structured policies and investment in digital infrastructure, Sri Lanka's progress is driven by academic initiatives and pilot projects. This research may assist industry professionals in identifying the challenges and improving BIM implementation in the construction landscape.*

***Keywords:*** *Building Information Modelling; Challenges; Digital Construction; Enablers; Infrastructure Development; Middle East; Sri Lanka.*

## 1. INTRODUCTION

Building Information Modelling (BIM) is a collaborative virtual platform (Wang, 2024) that supports decision-making throughout the building lifecycle (Singh et al., 2021). Today, BIM is used not only for building projects but also for infrastructure projects

[1] Academic Instructor, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, angel.o@sliit.lk
[2] Senior Lecturer, Department of Quantity Surveying, Sri Lanka Institute of Information Technology, Sri Lanka, priyanwada.d@sliit.lk
[3] Student, Liverpool John Moores University (LJMU) (UK), Sri Lanka, vinoshan549@gmail.com

worldwide. With respect to infrastructure projects, many researchers have pointed out the significance of BIM application in infrastructure due to its complexity and the scale of such projects, highlighting the importance of incorporating innovative and effective technologies to ensure the project meets the set time targets, budget and the quality of the final product (Venkatachalam & Ko, 2017).

Many countries, such as the United Kingdom, the United States, Singapore, and Australia, have incorporated BIM into their plans and policies for developing and implementing infrastructure, improving coordination, reducing rework, and enhancing asset management (AbuMoeilak et al., 2023). Among all the countries implementing BIM, the UAE is known as one of the leading adopters, with an uptake of 77%. It is promoted by the country's sustainable policies and regulatory directives (Fasasi, 2024). While the construction industry in some countries, such as the UAE, Australia, and the UK, mandates promoting BIM to its fullest, Sri Lanka is still in its infancy in implementing BIM due to poor policy frameworks, insufficient strategic direction, and a lack of industry-wide awareness (Moghayedi et al., 2025). Examining these two specifics, differing geographic contexts enable a comparative understanding of how each influencing factor affects the BIM adoption at two levels. It will also provide insights to support improvements in BIM implementation strategies in emerging construction industries, such as in Sri Lanka. Therefore, the Middle East and Sri Lanka were selected as the focus of this study, especially given their contrasting levels of BIM maturity, policy support, and industry readiness. Furthermore, considering the data collection and sample selection, these two contexts were deemed to be the most reliable for this research.

Economic barriers, resistance to change, insufficient training, a divided project team, and poor contract arrangements, especially in developing countries, are among the challenges facing BIM adoption (Barnes & Davies, 2014). However, the success stories of government leadership, stakeholder cooperation, and the relationship between the education system and industry in countries such as Australia, China, and the UAE highlight the importance of such efforts (Ahmed, 2018). BIM is not only a technological breakthrough but also a strategic facilitator of the modernisation of the construction industry and of national development objectives (Hamma-adama & Kouider, 2019). The study will thus critically examine the key factors affecting the implementation of BIM in infrastructure projects in both Sri Lanka and the Middle East to inform future policy, training, and investment decisions aligned with national priorities.

Thus, the study aimed to explore the critical factors influencing the implementation of BIM in infrastructure projects across Sri Lanka and the Middle East. Accordingly, to achieve the aim of the research, the Authors carried out a comprehensive literature review to identify the challenges and enablers of BIM in Infrastructure Projects, thereby investigate the implementation challenges of BIM in infrastructure projects in these two contexts (Sri Lanka and the Middle East Contexts) and finally examine the enablers of the implementation of BIM in infrastructure projects in Sri Lanka and the Middle East Contexts.

## 2. LITERATURE REVIEW

According to ISO 29481-1:2016, standard BIM in infrastructure is the utilisation of a standardised digital format to depict the physical and operational characteristics of individual infrastructure assets, including roads, bridges, and public utilities, over their

lifetimes (Ejekwu et al., 2025). BIM facilitates digital collaboration through the shared data, coordinated task development, and integrated planning across multidisciplinary teams and organisations, leading to a consistent understanding of roles, duties, and project goals. Infrastructure BIM applications do not require the same approach as building projects, as infrastructure projects involve large spatial scales, intricate structures, and multiple contractors (Marzouk & Othman, 2020). In contrast to the vertical development of buildings, which is subject to standard procedures, infrastructure projects involve horizontal development over large territories, which presupposes a complex grid and alterations to the terrain (Zak & Vitasek, 2019).

## 2.1 EVOLUTION AND ADOPTION OF BIM IN INFRASTRUCTURE PROJECTS

BIM is an important industrial revolution in which a collaborative framework replaces the traditional segmented workflow, and it has evolved over the years into a full-fledged digital platform (Jeon et al., 2025; Newton et al., 2023). The adoption of BIM in infrastructure initiatives continues to rise because of sustainability objectives, which result in a minimum 30% decrease in construction waste, a 20–25% reduction in energy usage, and a near 20% reduction in carbon emissions from optimized designs and effective resource management practices (Letendre & Mitra, 2018).

## 2.2 CHALLENGES AND ENABLERS OF BIM IMPLEMENTATION IN INFRASTRUCTURE PROJECTS

### 2.2.1 Technological Challenges and Enablers

BIM software adoption in infrastructure development requires acquisition of highly advanced software personnel training programs, sourcing skilled personnel with digital competencies and hardware upgrades which are significant financial challenges especially for small to medium sized enterprises with limited financial resources (Sood & Laishram, 2024). The late adoption of BIM at the initial stages also owes to the limited benefits of investing in BIM in situations where little or no push for BIM adoption exists (Ngoc et al., 2023). Resistance from Organisational and personal fronts to embracing new technology is another significant obstacle. There is a challenge in sourcing skilled personnel with digital competencies to facilitate this adoption process (Ajirotutu et al., 2024; Hijazi & Omar, 2017). Due to the various software packages, each with its own set of tools, which often limit in information sharing and handover processes across data environments, interoperability has remained a barrier (Broo & Schooling, 2023; Nuttens et al., 2018). Given these challenges, the BIM adoption in the infrastructure sector demands domain-specific software applications that are easy to use and highly interoperable with standards such as IFC, LandsXML, and ISO 19650. In addition, there is also a need to ensure the availability of classification standards to facilitate information sharing and collaboration in the development process (Laitinen et al., 2024; Moradi & Sormunen, 2023; Rotimi et al., 2025; Wijeratne et al., 2024).

### 2.2.2 Organisational and Managerial Challenges and Enablers

The successful application is hindered in contexts where the government lacks clear BIM guidelines and supporting policies, resulting in the unsystematic and incomplete implementation (Bradley et al., 2016; Liao & Teo, 2018). The barriers to change in traditional organisational frameworks, insulated project culture, inadequate communication standards, and lack of coordination among stakeholders also hinder the

implementation of BIM within current project delivery frameworks and cooperation (Hetemi et al., 2020). Factors such as leadership commitment and the roles of client or government bodies are crucial to ensuring the successful execution of BIM in infrastructure projects through a strategic direction at the executive level (Alankarage et al., 2024). The public-sector requirements, integrated into the procurement procedures, stimulate organisations to invest in resources, internal policies, and digital capacities, and specific training promotes professional skills and contributes to the implementation of projects in a more data-driven and collaborative manner, but inappropriate BIM-specific training and reskilled pathways are one of the greatest challenges, especially in the environment of the recent digital transformation (Marsov et al., 2025; Singh & Kumar, 2023).

### 2.2.3 Cultural and Behavioural Challenges and Enablers

Culture and behavioural issues are major obstacles to successful BIM implementation in infrastructure projects, including insufficient stakeholder knowledge of BIM capabilities, unrealistic expectations about BIM value, and resistance to implementation (Murguia et al., 2021). Lack of trust, information hiding, and communication asymmetry, caused by digital illiteracy and traditional ways of doing things, would impede collaboration and restrict innovation with the help of BIM (Bradley et al., 2016; Brewer & Gajendran, 2012). The key to overcoming these obstacles is specific education, training programs in the industry, and the spread of successful BIM case studies to develop the confidence of the stakeholders, show their business value, and facilitate open communication and planning coordination among the project teams (Nguyen et al., 2022; Soltani et al., 2025).

### 2.2.4 Economic and Regulatory Challenges and Enablers

The high cost of BIM technology implementation creates significant uncertainty among stakeholders regarding return on investment; thus, financial barriers and doubts about the long-term economic value were identified as significant barriers to its use (Nielsen et al., 2024). The reasons behind the slow adoption of BIM also include outdated construction policies, the absence of digital standards, and ineffective regulatory policies, meaning that BIM adoption in infrastructure projects only gains ground where economic incentives and coordinated policy orientations exist (Farouk & Rahman, 2023). The lack of resistance and stakeholder trust can be achieved through focused education, training programs in the industry, and the popularization of successful BIM cases that show time efficiency and financial cost savings, and effective BIM implementation is possible when the communication channels are open, the planning activities are coordinated, and the Organisational cultures are organized to work collaboratively (Nguyen et al., 2022; Soltani et al., 2025).

## 2.3 BIM IMPLEMENTATION IN SRI LANKA AND THE MIDDLE EAST

Road and urban development remain the top priority in the Sri Lankan infrastructure sector, and BIM implementation is still at the grassroots level, with universities and market leaders leading the development of the technology rather than the government (Chathuranga et al., 2025; Ruzieh, 2025b). Despite the well-known benefits of increased accuracy and lean construction to be provided by BIM technology, insufficient financial incentives, cultural resistance, and limited technical skills are identified as obstacles to its adoption in Sri Lanka (Oduoza et al., 2023). On the other hand, the Middle East is actively developing, with intensive spending by states and sovereign wealth funds; as such,

developed economies such as the UAE and Qatar require BIM for large-scale projects, including the 2022 FIFA World Cup (Ruzieh, 2025a; Zahin, 2024). However, there are improvements in these contexts, problems related to fragmented policies, start-up costs, and the lack of local professionals persist (Nnaji et al., 2025). In comparison, Middle Eastern adoption is driven by governmental regulatory systems and national visions and Sri Lankan development is supported by educational integration and pilot projects to demonstrate value in an environment dominated by customary modes of project delivery (Aamri et al., 2025; Gurumayum, 2025).

## 3. RESEARCH METHOD

The authors conducted a comprehensive literature review of the challenges and enablers of BIM in infrastructure projects, drawing on journal articles, conference papers, and industry reports. With the understanding that the different contexts of the construction industry carry different challenges in BIM adoption, and to enable the collection of standardised data and support comparative analysis across different contexts, based on the literature findings, a questionnaire survey was administered to investigate the context-based challenges of Sri Lanka and the Middle East (UAE). A quantitative method was chosen to evaluate and compare the barriers and facilitators of BIM implementation among industry professionals. Quantitative research is employed to test patterns across a large population and generate findings that can be generalized to a broader context (Lim, 2025), Quantitative techniques enable one to gather standardized information and analyse statistics, which makes it appropriate to measure and prioritize the most important factors (Huyler & McGill, 2019; Lim, 2025).

This study focused on gathering data from construction professionals with relevant knowledge and practical experience in BIM implementation. Therefore, the questionnaire was administered to professionals with BIM experience, such as Engineers, Architects, and Quantity Surveyors, through purposive sampling, who had a proper understanding to offer. Diversity among professionals, organizations and regions was a focus in sampling, to help make the data more valuable. Furthermore, the sample was drawn from both public and private sectors in Sri Lanka and Middle Eastern countries, ensuring a balanced representation. Although the sample size was comparatively low in number it was considered adequate for the objectives of this study due to the targeted nature of the respondent group. Of the questionnaires distributed, the analysis considered only 52 that the professionals fully completed; the incomplete questionnaires were disregarded in the study. The collected data were then analysed using descriptive statistical tools, such as percentages, counts, weighted averages, and means, on a 5-point Likert scale, as shown in Table 1.

*Table 1: Likert scale for the level of criticality of challenges of Implementation of BIM.*

| Value | Range | Scale |
|---|---|---|
| 1 | 1.00-1.08 | Low |
| 2 | 1.81-2.60 | Very low |
| 3 | 2.61-3.40 | Moderate |
| 4 | 3.41-4.20 | High |
| 5 | 4.21-5.00 | Very high |

In the Likert scale, authors assumed that the distance between “very high" and "high” is the same the distance between “high” and “moderate”. This equal interval assumption allows the calculation of means and the use of parametric statistical techniques (Norman, 2010). Weighted average for each selected factor was calculated using the equation expressed below to conduct the final comparison. The number of responses for each scale point was multiplied by its corresponding Likert value. Thereafter, the result was divided by the total number of responses.

$$WA = \frac{\sum(f \times w)}{N} \qquad (01)$$

where, WA = weighted average, $f$ = frequency of responses for each scale point,

$w$ = weight assigned to each response category, and $N$ = Total number of responses.

# 4. FINDINGS AND DISCUSSION

## 4.1 DEMOGRAPHIC DATA

Ultimately, the 52 valid responses mentioned above were obtained from a diverse range of construction industry professionals as it shown in Table 2 below. Furthermore, these respondents possessed varying levels of professional experience while some of them had exposure to both Sri Lankan and the Middle Eastern contexts.

*Table 2: Demographic details of Respondents*

| | | Profession | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quantity Surveyor | | | Architect | | | Engineer | | | Project Manager | | | Contractor | | | Sustainability Consultant | | |
| | | SL | UAE | Both | SL | UAE | Both | SL | UAE | Both | SL | UAE | Both | SL | UAE | Both | SL | UAE | Both |
| Experiences | < 5 years | 10 | | | | | | 6 | 1 | | 3 | | | 1 | | | 1 | | |
| | 6-10 years | | | | 1 | 5 | | | | 1 | | 1 | 2 | | | | | 1 | |
| | 11-15 years | | | | | 2 | | | 2 | | | 2 | | | | | | | |
| | 16-20 years | | | | | 2 | 2 | 1 | | | | | | 1 | | | | 1 | 1 |
| | > 20 years | | 1 | | | | | 1 | | 1 | | | | | | | 1 | 1 | |

The demographic profile of the respondents in this research shows that they are balanced in terms of contextual distribution and experience levels. 50% of the respondents have experience in Sri Lanka, while 36.5% have experience from the Middle East. In addition, this data collection was more fruitful: 13.5% of respondents gained experience in both contexts, a significant finding. In terms of experience, the sample is dominated by younger professionals: 42.3% have less than 5 years of experience, while 21.2% have between 6-10 years of experience. Well-experienced professionals are those with 11-15 years of experience (11.5%), followed by those with 16-20 years of experience (15.4%) according to the percentages. 9.6% of overall sample hand more than 20 years of experience. Therefore, with a well-balanced and diverse sample, the study is well positioned to examine the key factors that affect and challenge the BIM implementation in both the contexts.

## 4.2 IMPACT OF TECHNICAL CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

The technical challenges affecting BIM implementation in Middle Eastern infrastructure projects include poor interoperability, integrating BIM, high initial costs, and difficulty

linking BIM processes, each marked "very high" by over 44% of respondents. Interoperability had the highest average level of effect (4.30%), while inconsistent data formats had the lowest (3.78%). On the other hand, the majority among the Sri Lankan experts rated the issues shown in Table 3 as either "high" or "Very High". The highest impact score was given to inconsistent data formats, rated at 3.70, while poor interoperability received the lowest impact score of 3.19. Overall, the findings emphasise that data and integration issues are major technical barriers to BIM adoption in Sri Lanka. Table 3 below illustrates the overall impact of technical challenges in both the contexts.

*Table 3: Weighted average impact of technical challenges*

| | **Poor Interoperability** | **High Initial Cost** | **Risk of Data Loss** | **Difficult to integrate BIM** | **Inconsistent Data Format** | **Inability to efficiently link BIM** |
|---|---|---|---|---|---|---|
| Middle East | **4.30** | 3.93 | 3.89 | 4.00 | 3.78 | 3.93 |
| Sri Lanka | 3.19 | 3.44 | 3.41 | 3.67 | **3.70** | 3.48 |

The significance of interoperability and data sharing difficulties is evident from the work by Bradley et al. (2016), who also considered information integration difficulties as major hurdles for the adoption of BIM technology. This indicates that interoperability problems continue to persist in various project environments. The data indicated that the impact of each factor may differ across contexts or countries. This may mainly be due to resource availability, the state of the country's development, and cultural differences. Furthermore, unlike in other countries, Sri Lanka has not advanced in adopting BIM or in developing BIM object libraries, which led the system to end up with inconsistent data formats; the lack of proper institutional insurance for digital assets led companies to lose confidence in the face of data loss; and the highly fragmented nature of the local industry, that may be among the reasons for these results (Thushyanthan, 2019).

### 4.3 IMPACT OF HUMAN RESOURCE & SKILL CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

In Middle Eastern infrastructure projects, many respondents reported a lack of recognition, language and communication barriers, and the misconception that BIM is merely 3D modelling, all of significantly impact the implementation of BIM in these projects. Among these causes, lack of recognition had the highest average impact, followed by language barriers (3.89) and BIM misunderstanding (3.85). The shortage of BIM trainers had the lowest impact (3.52), as shown in Table 4. Overall, the findings highlight that awareness, communication, and understanding are major human-related barriers to BIM adoption. The reason may be the multinational workforce on projects in the Middle East, which also leads to communication issues. Moreover, BIM requires high collaboration, and this communication barrier, compounded by a workforce that speaks multiple languages, can lead to information loss in the Middle East.

In Sri Lanka, over 52% of professionals confirmed that the most critical issues with very high impact are a lack of recognition, BIM being misunderstood as just 3D modelling, and a shortage of BIM trainers. The reason for that is unfamiliarity with the technology, as Sri Lanka is still in the early stages of adopting these new technologies and lacks institutional recognition (Arachchige et al., 2025). It is noteworthy that the lack of recognition was identified as the highest impacting factor in both contexts.

*Table 4: Weighted average impact of human & skill challenge*

| | Lack of Qualified Professionals | Shortage of BIM trainers | Limited BIM education | Delays from untrained staff | BIM misunderstand as just a 3D modelling | Language & Communication Barriers | Lack of Recognition |
|---|---|---|---|---|---|---|---|
| Middle East | 3.67 | 3.52 | 3.81 | 3.78 | 3.85 | 3.89 | **4.07** |
| Sri Lanka | 3.12 | 3.44 | 3.60 | 3.40 | 3.96 | 3.60 | **4.76** |

## 4.4 IMPACT OF ORGANISATIONAL & PROCESS CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

Table 5 shows that both selected geographic contexts face the highest impact from issues related to transferring BIM from the design stage to construction sites, with a weighted average impact in the Middle East of 3.93 and 3.80 in Sri Lanka. It shows that integrating BIM workflow is also a common issue regardless of the context. At the same time, low contractor involvement ranked the lowest impact (3.56) among respondents from the Middle East. Overall, it is evident that inefficiencies in processes and coordination, and resistance to change, constitute major organisational and procedural barriers to BIM adoption. Among the other factors considered within the Sri Lankan context, issues of poor coordination (3.72) ranked higher than resistance to (3.60). At the same time, delays in clash detection and inflexible delivery systems (3.56) also ranked high.

*Table 5: Weighted average impact of organisational & process challenge*

| | Poor Model coordination | Resistance to Change | Delay in Clash Detection | Issues in transferring BIM from design | Inflexibility of the delivery system | Low Contractor involvement |
|---|---|---|---|---|---|---|
| Middle East | 3.67 | 3.70 | 3.81 | **3.93** | 3.70 | 3.56 |
| Sri Lanka | 3.72 | 3.60 | 3.56 | **3.80** | 3.56 | 3.40 |

In the Middle East industry Construction industry, contractors play a major role in BIM implementation, given the complexity and size of the projects undertaken (Abdullah et al., 2024). BIM must form a part of their operational processes as well. The high criticality of BIM transfer from design could also be explained by differences in design and construction modes, where current design priorities lie in visual appeal and spatial analysis rather than it does in constructability. In conclusion, coordination gaps, poor process integration, and industry practices are major factors in BIM adoption challenges in Sri Lanka. These factors may be attributed to the industry's perception of BIM while designers still rely on 2D drafting rather than BIM-based information delivery. Furthermore, only a handful of industry professionals and Organisations possess the BIM management capabilities.

## 4.5 IMPACT OF CULTURAL & AWARENESS CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

Table 6 shows, cultural resistance to collaboration (3.81) and lack of awareness (3.74) as the most significant cultural and awareness-related challenges affecting BIM implementation in the Middle East context. More than 37% respondents indicated that awareness issues have a very high impact. On the contrary, the impact of the lack of

understanding was relatively lower, at 3.44 on a weighted average. Therefore, these results indicate that, despite existing BIM awareness in the region, collaborative BIM application and lifecycle integration remain limited. The reason behind this observation could be the workforce's diversity of cultures and nationalities, and even though awareness of BIM is relatively high, understanding of it is relatively low (Mehran, 2016). Furthermore, BIM implementation is made mandatory rather than optional.

*Table 6: Weighted average impact of cultural & awareness challenge*

| | Lack of understanding | Lack of awareness | Cultural Resistance to Collaboration | Misconception about the BIM full life cycle value |
|---|---|---|---|---|
| Middle East | 3.44 | 3.74 | **3.81** | 3.50 |
| Sri Lanka | 3.73 | **3.92** | 3.87 | 3.83 |

In Sri Lanka, cultural resistance to collaboration (3.87) and lack of awareness (3.92) was also identified as factors with a higher impact, with over 44% of the sample indicating a very high impact level for the BIM misconception. These findings demonstrate a low level of understanding of BIM among professionals, and resistance to moving from a conventional process to a more digitalised, technical platform has significantly hindered its implementation in Sri Lanka. The main reasons for this situation are the lack of professionals with knowledge of BIM, legal and institutional awareness, the absence of a national policy for BIM, and the continuation of traditional procurement practices, which result in poor collaboration (Ajirotutu et al., 2024; Hijazi & Omar, 2017).

## 4.6 IMPACT OF POLICY & REGULATORY CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

The policy and regulatory challenges include outdated procurement practices with an average value of 3.92, and lack of government-led BIM strategies (3.83) according to the figures shown in Table 7, with nearly half of the population rating them as having “very high.” Impact. Meanwhile, even the poor contractual frameworks and the absence of national BIM standards (3.81) were also highlighted in the UAE context. Hence, these results reinforce the importance of clear policies, updated procurement practices, and even government leadership support for BIM adoption in such developed contexts. Similarly, the Sri Lankan context also experiences the same factors, among them conventional procurement practices that are outdated and instability of Government policies, which have been rated as “High” impact. However, the absence of national standards has been rated as a moderate issue. Overall, the highest impact score among the factors affecting BIM adoption in Sri Lanka was the absence of government-led strategies, rated 3.88. Following this was the policy instability.

*Table 7: Weighted average impact of policy & regulatory challenge*

| | Absence of National BIM standards | Outdated Procurement Practices | Poor Contractual Framework | Lack of government-led BIM strategies | Policy instability disrupting |
|---|---|---|---|---|---|
| Middle East | 3.81 | **3.92** | 3.71 | 3.83 | 3.77 |
| Sri Lanka | 3.44 | 3.64 | 3.48 | **3.88** | 3.76 |

However, the findings imply that, in the absence of proper policies, stable regulations, and government leadership, the implementation of BIM remains fragmented. This

suggest and support the previous researchers' conclusions reported from various contexts (Farouk & Rahman, 2023). Furthermore, the persistence of traditional procurement methods and an ineffective contractual environment discourage stakeholders from embracing the BIM process.

## 4.7 IMPACT OF FINANCIAL & MARKET CHALLENGES ON IMPLEMENTING BIM IN INFRASTRUCTURE PROJECTS

*Table 8: Weighted average impact of financial & market challenge*

| | **Budget Constraints** | **Uncertainty of ROI** | **Lack of an incentives program** | **Absence of Client** |
|---|---|---|---|---|
| Middle East | 3.44 | 3.64 | 3.48 | 3.76 |
| Sri Lanka | 3.52 | 3.36 | 3.72 | 3.56 |

The findings in the Table 8 indicated that both contexts are suffering from financial and market challenges, as they are marked as high impact: budget constraints, uncertainty about ROI, lack of an incentive program, and absence of a Client. These records demonstrate the importance of securing client commitment; introducing incentives and proactive measures to address financial uncertainties is mandated. Also, it emphasises the importance of a motivational mechanism for BIM implementation in both contexts. Most importantly, the findings are consistent with the results obtained by previous research which established that implementation cost is one of the major barriers to implementation, especially in the construction industry of developing countries (Nielsen et al., 2024; Sood & Laishram, 2024).

## 4.8 ENABLERS FOR BIM IMPLEMENTATION IN INFRASTRUCTURE PROJECTS

Based on stakeholder perspectives, several measures can boost BIM implementation in infrastructure projects within Sri Lanka and the Middle East. At the outset, governments should establish mandatory BIM standards for public projects. Policies to help new technologies cover specific expenses, such as tax exemptions, adoption grants, or subsidies, should be supported in developing countries, where paying for the newest technologies is a major barrier. Clear stakeholder responsibility outlining, proper legal foundations, and a BIM-integrated procurement process can lessen uncertainties. Institute contextual accreditation and licensing for BIM users, ensuring their skills are recognised worldwide, and include BIM mandates in the bidding process, regardless of whether the private or public sector, or even public-private partnerships, are the better enablers. Simultaneously, building national BIM knowledge centres and providing access to open-source information ensures that manufacturers and constructors can learn the latest practices and continue to grow. They should encourage users to adopt Common Data Environments (CDEs) to enable swift cross-field collaboration and reduce design issues. Liaisons between BIM task forces in Sri Lanka and Middle Eastern countries can help ensure BIM standardisation is right and share knowledge. Besides, governments and organisations should support demonstration projects to highlight BIM's advantages, identify unforeseen problems, and enhance understanding of its use. Organising annual innovation contests and BIM-infrastructure challenges encourages universities and drives the creation of solutions tailored to local needs. Moreover, aligning BIM policies with the country's digital transformation and smart city objectives will ensure long-term capabilities for communication and maximum importance. There is also a major

requirement to regularly organise activities that educate government officials, clients, and decision-makers, aiming to ensure their role in making BIM a standard practice in infrastructure policy and building.

## 5. CONCLUSIONS

This study investigated the fundamentals that have a vital impact on the implementation of BIM in infrastructure projects in Sri Lanka and the Middle East by using a structured questionnaire to identify key challenges and enablers. The findings demonstrate that BIM implementation barriers are both interconnected and multidimensional. The study revealed high start-up expenses, the absence of national BIM standards, a shortage of technical skills, stringent government requirements, cultural resistance, and a misunderstanding of BIM as a 3D tool as major barriers to BIM adoption. Sri Lanka lacks regulatory systems and monetary rewards, whereas the Middle East suffers from a lack of policy cohesion. However, nations such as the UAE and initiatives like Saudi Vision 2030 are making strides towards this by introducing compulsory policies. Therefore, successful BIM implementation requires not only technological readiness but also policy support, organisational transformation, and more. Leadership commitment, improved training, and the introduction of BIM into procurement activities through grassroots university efforts in Sri Lanka could serve as enablers. Nevertheless, its narrow geographic scope, a sample of 52 respondents, and the use of online surveys limited the study's external validity, as they did not allow for qualitative coverage or assessment of long-term consequences. However, as the final output, this research contributes to existing knowledge by providing a comparative understanding of the BIM implementation challenges and enablers across both developing and developed countries. Further research could delve deeper into this gap through other approaches, such as mixed-methods, and extend the analysis to obtain deeper insight into organisational behaviours, policy implementation processes, and the long-term impacts of BIM implementation across different contexts.

## 6. RECOMMENDATIONS

The study recommends that the Government mandate BIM in Sri Lanka, at least for public-private partnership projects. Also, introducing financial incentives and tax concessions for BIM-enabled projects can help expand awareness and adoption of BIM in both contexts, enabling many professionals to experience and understand its benefits. Most importantly, construction-related regulatory bodies may increase their efforts to promote BIM in professional development programmes and conduct related workshops, which may also raise awareness among professionals and other stakeholders in the construction landscape. Involvement of academia and industry, as well as Government sponsorship, may provide a platform for sharing resources and promoting BIM awareness through adaptation of international BIM protocols. Future researchers may explore the challenges more effectively using mixed method approach and larger comparative sample sizes. From a pragmatic point of view, the results of this study can help policymakers and industry player enhance BIM standards and strategies for implementation.

## 7. ACKNOWLEDGEMENTS

The authors would like to express their sincere heartfelt gratitude to the Department of Quantity Surveying, Sri Lanka Institute of Information Technology (SLIIT), for their

support and meaningful contribution to the research. They played a very important role in guiding and providing resources for the completion of the research.

# 8. REFERENCES

Aamri, A. M. S. A., Evdorides, H., & Baniotopoulos, C. (2025). Barriers and opportunities for the adoption of building information modelling in the design of buildings: Case study of Oman. *Sustainability, 17*(8). https://doi.org/10.3390/su17083510

Abdullah, M., Salem, M., Said, S., & Tantawy, M. (2024). BIM adoption in MENA's construction industry: A contractor's perspective. *Civil Engineering Journal, 10*, 2661–2676. https://doi.org/10.28991/CEJ-2024-010-08-015

AbuMoeilak, L., Alquraidi, A., AlZarooni, A., & Beheiry, S. (2023). Critical success factors for building information modeling implementation as a sustainable construction practice in the UAE. *Buildings, 13*, 1406. https://doi.org/10.3390/buildings13061406

Ahmed, S. (2018). Barriers to implementation of building information modeling (BIM) to the construction industry: A review. *Journal of Civil Engineering and Construction, 7*(2), 107–113. https://doi.org/10.32732/jcec.2018.7.2.107

Ajirotutu, R.O., Adeyemi, A.B., Gil-Ozoudeh, I., Ohakawa, T.C., Iwuanyanwu, O., & Garba, B.M.P. (2024). Exploring the intersection of building information modeling (BIM) and artificial intelligence in modern infrastructure projects. *International Journal of Science and Research Archive, 13*(2), 2414–2427. https://doi.org/10.30574/ijsra.2024.13.2.2421

Alankarage, S., Chileshe, N., Samaraweera, A., Rameezdeen, R., & Edwards, D. J. (2024). Diagnosing organizational BIM culture: A Qualitative case study using Schein's Model. *Journal of Management in Engineering, 40*(3). https://doi.org/10.1061/jmenea.meeng-5672

Arachchige, U., Madushanka, H., Ashly, I., & Mendis, G. (2025). Implementing BIM for economic sustainability: Addressing adoption challenges in Sri Lanka's residential construction sector. *Journal of Research Technology & Engineering, 6*(4) 1–16.

Barnes, P., & Davies, N. (2014). *BIM in principle and in practice*. ICE Publishing

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and contractor perspective. *Automation in Construction, 71*, 139–152. https://doi.org/10.1016/j.autcon.2016.08.019

Brewer, G., & Gajendran, T. (2012). Attitudes, behaviours and the transmission of cultural traits: Impacts on ICT/BIM use in a project team. *Construction Innovation, 12*(2), 198–215. https://doi.org/10.1108/14714171211215949

Broo, D. G., & Schooling, J. (2023). Digital twins in infrastructure: Definitions, current practices, challenges and strategies. *International Journal of Construction Management, 23*(7), 1254–1263. https://doi.org/10.1080/15623599.2021.1966980

Chathuranga, N., Thajdeen, F., & Siriwardana, C. (2025). A Conceptual framework for enhancing construction safety in Sri Lanka through digital technology implementation. *Buildings, 15*(8), 1223. https://doi.org/10.3390/buildings15081223

Ejekwu, T.B. et al. (2025). Engineering infrastructure and national development: The need for cost control, *PM World Journal, 14*(2), 1-17.

Farouk, A. M., & Rahman, R. A. (2023). Integrated applications of building information modelling in project cost management: A systematic review. *Journal of Engineering, Design and Technology, 23*(1), 287–305. https://doi.org/10.1108/JEDT-10-2022-0538

Fasasi, M. (2024). Challenges and opportunities in implementing building information modelling (BIM) in the UAE construction sector: A project management perspective. *Journal of Materials Engineering, Structures and Computation, 3*(1), 12-22. https://doi.org/10.5281/zenodo.10891148

Gurumayum, S. (2025). Understanding the causes of project delays and cost overruns in construction: A Comprehensive analysis across literature, surveys, and case studies. *Journal of Civil and Construction Engineering, 11*(1), 74–94. https://shorturl.at/nRdiF

Hamma-Adama, M., & Kouider, T. (2019). Comparative analysis of BIM adoption efforts by developed countries as precedent for new adopter countries. *Current Journal of Applied Science and Technology*, 1–15. https://doi.org/10.9734/cjast/2019/v36i230224

Hetemi, E., Ordieres-Meré, J., & Nuur, C. (2020). An institutional approach to digitalization in sustainability-oriented infrastructure projects: The limits of the building information model. *Sustainability*, *12*(9), 3893. https://doi.org/10.3390/su12093893

Hijazi, A. A., & Omar, H. A. (2017). Level of detail specifications, standards and file-format challenges in infrastructure projects for BIM level three. *WIT Transactions on the Built Environment*, *1*, 143–154. https://doi.org/10.2495/bim170141

Jeon, Y., Tran, D. Q., Vo, K. T. D., Jeon, J., Park, M., & Park, S. (2025). Neural radiance fields for construction site scene representation and progress evaluation with BIM. *Automation in Construction*, *172*, 106013. https://doi.org/10.1016/j.autcon.2025.106013

Laitinen, K., Luhtala, M., Örmä, M., & Vaismaa, K. (2024). Productivity development enablers in the infrastructure sector: Capability maturity model integration approach. *Built Environment Project and Asset Management*, *14*(2), 201–227. https://doi.org/10.1108/BEPAM-07-2022-0095

Liao, L., & Ai Lin Teo, E. (2018). Organisational change perspective on people management in BIM implementation in building projects. *Journal of Management in Engineering*, *34*(3), 04018008. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000604

Lim, W. M. (2025). What is quantitative research? An overview and guidelines. *Australasian Marketing Journal*, *33*(3), 325–348. https://doi.org/10.1177/14413582241264622

Marsov, A., Lædre, O., Andersen, B., & Olsson, N. O. E. (2025). Opportunity management enablers in construction projects: A systematic literature review. *Production Planning & Control*, *36*(10), 1380–1394. https://doi.org/10.1080/09537287.2024.2362861

Marzouk, M., & Othman, A. (2020). Planning utility infrastructure requirements for smart cities using the integration between BIM and GIS. *Sustainable Cities and Society*, *57*, 102120. https://doi.org/10.1016/j.scs.2020.102120

Mehran, D. (2016). Exploring the adoption of BIM in the UAE construction industry for AEC firms. *Procedia Engineering*, *145*, 1110–1118. https://doi.org/10.1016/j.proeng.2016.04.144

Moradi, S., & Sormunen, P. (2023). Integrating lean construction with BIM and sustainability: A comparative study of challenges, enablers, techniques, and benefits. *Construction Innovation*, *24*(7), 188–203. https://doi.org/10.1108/CI-02-2023-0023

Moghayedi, A., Silva, K.V., & Nawarathna, A. (2025). *Evaluating the impact of building information modelling on Sri Lankan highway construction projects*. International Sustainable Ecological Engineering Design for Society (SEEDS) Conference 2025, Loughborough University, Loughborough, United Kingdom. https://hdl.handle.net/10779/leedsbeckett.30399739.v1

Murguia, D., Demian, P., & Soetanto, R. (2021). The role of the industry's cultural-cognitive elements on actors' intention to adopt BIM: An empirical study in Peru. *Engineering, Construction and Architectural Management*, *30*(3), 1183–1200. https://doi.org/10.1108/ECAM-08-2021-0743

Newton, S., Carnemolla, P., & Darcy, S. (2023). Building information modelling and related technologies applied to the post occupancy evaluation of accessible bathrooms for people with disability. *Smart and Sustainable Built Environment*, *14*(1), 237–253. https://doi.org/10.1108/SASBE-04-2023-0075

Ngoc, N. M., Son, T. T., & Vu, M. (2023). Advantages and challenges of applying BIM in urban technical infrastructure projects. *E3S Web of Conferences*, *403*, 04001. https://doi.org/10.1051/e3sconf/202340304001

Nguyen, T.N., Do, S. T, Nguyen, V.T., & Nguyen, T.A. (2022). Interrelationships among enabling factors for BIM adoption in construction enterprises. *Engineering, Construction and Architectural Management*, *31*(2), 891–918. https://doi.org/10.1108/ECAM-05-2022-0465

Nielsen, O. A., Miceli, G., Filho, A. D. S. F., & Pellanda, P. C. (2024). A review of global efforts in BIM adoption for road infrastructure. *Infrastructures*, *9*(8), 126. https://doi.org/10.3390/infrastructures9080126

Norman, G. (2010). Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education*, *15*(5), 625–632. https://doi.org/10.1007/s10459-010-9222-y

Nnaji, E. T., Okafor, C. N., Ezeani, O. C., & Umeh, I. C. (2025). Review of lean construction practices for enhancing project delivery in Anambra State, Nigeria. *Ayden Journal of Engineering and Applied Sciences*, *13*(2), 9–21. https://doi.org/10.5281/zenodo.15470148

Nuttens, T., De Breuck, V., Cattoor, R., Decock, K., & Hemeryck, I. (2018). Using BIM models for the design of large rail infrastructure projects: Key factors for a successful implementation. *International Journal of Sustainable Development and Planning, 13*(01), 73–83. https://doi.org/10.2495/SDP-V13-N1-73-83

Oduoza, C. F., Alamri, R., & Oloke, D. (2023). Best practice for safety management – case of major oil processing country in the Middle East. *Engineering, Construction and Architectural Management, 32*(3), 1857–1874. https://doi.org/10.1108/ECAM-02-2023-0126

Rotimi, F. E., Silva, C., Ramanayaka, C. E. D., & Rotimi, J. O. B. (2025). Digital technology knowledge transfer enablers amongst end-users in architecture, engineering, and construction organisations: New Zealand insights. *Buildings, 15*(5), 772. https://doi.org/10.3390/buildings15050772

Ruzieh, A. S. (2025a). Advancing Middle East Construction Sustainability: A framework for addressing logistics challenges through solutions and critical success factors. *Sustainability, 17*(2), 533. https://doi.org/10.3390/su17020533

Ruzieh, A. S. (2025b). Mitigation Matrix for improving Material Management Sustainability within Construction in the Middle East. *Sustainability, 17*(2), 490. https://doi.org/10.3390/su17020490

Singh, A. K., & Kumar, V. R. P. (2023). Analyzing the barriers for blockchain-enabled BIM adoption in facility management using best-worst method approach. *Built Environment Project and Asset Management, 14*(2), 164–183. https://doi.org/10.1108/BEPAM-04-2023-0080

Singh, S., Chinyio, E., & Suresh, S. (2021). The key enablers, techniques and benefits of managing stakeholders within BIM supported projects. *Journal of Engineering, Design and Technology, 21*(2), 469–485. https://doi.org/10.1108/JEDT-04-2021-0203

Soltani, S., Abbasnejad, B., Gu, N., Yu, R., & Maxwell, D. (2025). A multi-faceted analysis of enablers and barriers of industrialised building: Global insights for the Australian context. *Buildings, 15*(2), 214. https://doi.org/10.3390/buildings15020214

Sood, R., & Laishram, B. (2024). Challenges in implementation of 7D-BIM for infrastructure asset management: A systematic review. *Construction Economics and Building, 24*(3), 95–117. https://doi.org/10.5130/AJCEB.v24i3.8738

Thushyanthan, S. (2019). Adoption and Implementation of Building Information Modelling (BIM) Application into Sri Lankan Construction Industry. *KDU IRC 2019*. https://ir.kdu.ac.lk/handle/345/2231

Venkatachalam, S., & Ko, S.B. (2017). Design of power and area efficient approximate multipliers. *IEEE Transactions on Very Large-Scale Integration (VLSI) Systems, 25*(5), 1782–1786. https://doi.org/10.1109/TVLSI.2016.2643639

Wang, K. (2024). Mapping the global knowledge landscape of digital transformation in the AEC industry: A scientometric analysis. *Engineering, Construction and Architectural Management, 32*(10), 6445–6479. https://doi.org/10.1108/ECAM-11-2023-1174

Wijeratne, P. U., Gunarathna, C., Yang, R. J., Wu, P., Hampson, K., & Shemery, A. (2024). BIM enabler for facilities management: A review of 33 cases. *International Journal of Construction Management, 24*(3), 251–260. https://doi.org/10.1080/15623599.2023.2222962

Zahin, N. (2024). *Digital innovation roadmap for construction industry: Bridging the gap for future*. [Master's Thesis]. University of Kentucky. https://doi.org/10.13023/etd.2024.526

Zak, J., & Vitasek, S. (2019). BIM and data standard for effective investment in infrastructure, *18th International Scientific Conference Engineering for Rural Development, Jelgava*. https://doi.org/10.22616/erdev2019.18.n504

Malvila, T.M.A.Y.B., Bandara, R.M.H.R. and Thayaparan, M., 2026. From reactive reporting to regenerative control: Rethinking construction progress monitoring in Sri Lanka through IoT enabled real-time practices. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 828-841. DOI: https://doi.org/10.31705/WCS.2026.61. Available from: https://ciobwcs.com/papers/

# FROM REACTIVE REPORTING TO REGENERATIVE CONTROL: RETHINKING CONSTRUCTION PROGRESS MONITORING IN SRI LANKA THROUGH IOT ENABLED REAL-TIME PRACTICES

**T.M.A.Y.B. Malvila[1], R.M.H.R. Bandara[2] and M. Thayaparan[3]**

## *ABSTRACT*

*Construction progress monitoring remains a critical yet underperforming function in the Sri Lankan construction industry, where continued reliance on manual and semi-digital methods results in reactive reporting systems that do not align with the continuous feedback mechanisms required for regenerative construction. This study examines current progress monitoring practices in Sri Lanka and explores how IoT-enabled real-time monitoring can support a transition from reactive reporting toward regenerative control. A qualitative research approach was adopted, using semi-structured interviews with sixteen experts from the construction and information technology sectors. The collected data were analysed using qualitative content analysis based on predefined thematic categories derived from the literature. The findings indicate that progress monitoring remains largely manual, while IoT adoption is limited to fragmented applications including drone photogrammetry, RFID-based labour tracking, and barcode-based material monitoring. Major barriers include high investment costs, unreliable connectivity, limited digital literacy, and the absence of clear regulatory frameworks. The findings further reveal that these barriers are closely connected to broader structural realities within the Sri Lankan construction industry, particularly government-dominated procurement systems, economic instability, and limited institutional readiness for digital transformation. Nevertheless, considerable opportunities exist for IoT to support proactive resource management, reduce rework, and enable continuous optimisation in line with regenerative construction principles. The study contributes empirical evidence from a developing country context and reframes IoT-enabled monitoring as a socio-technical mechanism for regenerative control rather than merely automated reporting.*

***Keywords:*** *Construction Progress Monitoring; Internet of Things (IoT); Real-time Monitoring; Regenerative Control.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, malvilatmyb.21@uom.lk
[2] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, bandararmhr.20@uom.lk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk

# 1. INTRODUCTION

The construction industry plays a significant role in the global economy, making a substantial contribution to the Gross Domestic Product (GDP) and generating extensive employment opportunities, particular in developing countries including Sri Lanka (Silva et al., 2025). Construction projects are inherently complex, requiring the coordination of multiple stakeholders, substantial resources, and intricate scheduling process. The time, cost, and quality control of a project lifecycle are important during the construction progress monitoring (Shamsollahi et al., 2022). Regenerative construction extends beyond traditional sustainability by focusing on adaptive systems that continuously optimise resource use while minimising long-term environmental impacts. Therefore, accurate progress monitoring is essential to support adaptive decision-making and continuous system improvement (Sertyesilisik, 2016).

Despite global technological advancements, construction progress monitoring still relies heavily on traditional manual methods including site inspections, daily progress reports, and scheduled site visits (Rehman et al., 2023). These time-consuming data collection procedure and periodic assessments are becoming increasingly inadequate for the complex demands of modern projects (Omar, 2018). Manual reporting often results in delayed communication, subjective assessments, and overlaps in data collection which slow down corrective actions (Rehman et al., 2023; Shamsollahi et al., 2022). In a regenerative context, where continuous resource optimization and minimal environmental impact are key objectives, delayed and reactive reporting systems become highly detrimental, as these practices often lead to increased rework, material waste, and cost overruns (Pal et al., 2023).

To bridge the gap between reactive reporting and proactive control, industry 4.0 technologies, particularly the Internet of Things (IoT), have emerged as important transformative enabler (Naji et al., 2024). The concept of the IoT, first introduced by Kevin Ashton in 1999, refers to a network of sensors, devices and software that can collect and exchange data automatically without human intervention (Ashton, 2009). In construction IoT applications supports a shift from periodic oversight to continuous project control by enabling real-time progress tracking, predictive maintenance, and more efficient resource management across all project phases (Khan et al., 2024).

While global studies highlight the advantages of IoT in construction monitoring (Kim et al., 2025), developing economies continue to experience a significant gap between technological potential and practical implementation. The Sri Lankan construction industry remains relatively slow in adopting digital technologies due to low digital infrastructure, insufficient technical expertise, economic instability, fragmented subcontracting systems, financial constraints, and resistance to organisational transparency (Sendanayake et al., 2024). Current literature highlights a notable gap: the role of IoT-enabled real-time progress monitoring as an operational mechanism for regenerative construction within developing economies remains insufficiently explored. Existing studies largely focus on technical performance and automation capabilities in developed contexts, with limited attention given to the socio-economic, institutional, and procurement realities that shape technology adoption in financially constrained construction environments.

Therefore, this paper investigates current construction progress monitoring in Sri Lanka and examines how IoT-enabled real-time monitoring can support a transition from

reactive reporting to regenerative control. Although numerous studies highlight the technical capabilities of IoT for automated monitoring, limited empirical research has explored how these technologies can transform traditional progress monitoring practices to support regenerative construction principles in developing economies. Furthermore, limited studies have critically examined how government procurement systems, financial instability, institutional culture, and regulatory environments influence the feasibility of IoT-enabled regenerative control in developing construction industries such as Sri Lank.

# 2. LITERATURE REVIEW

## 2.1 TRADITIONAL CONSTRUCTION PROGRESS MONITORING PRACTICES

Construction progress monitoring serves as a fundamental project management function aimed at tracking task completion and optimizing resource allocation over time (Rehman et al., 2023). Traditionally, document-based, labour-intensive task procedures including handwritten site reports, physical site visits, and photographic evidence have been relied on in this required process (Rehman et al., 2023). To evaluate performance, project managers typically utilize foundational visual tools including Gantt charts, s-curve, and milestone schedules to compare planned baselines against actual site execution (Suvvari & Saxena, 2024). Furthermore, Earned Value Management (EVM) is often incorporated into traditional project management practices to provide a quantitative evaluation of scope, cost, and schedule performance (Alvarez et al., 2022).

Despite their long-standing use, these conventional techniques rely largely on human observation and manual data collection, resulting in significant delays in identifying operational deviations (Gamil et al., 2023). This time-consuming nature of manual data collection places a considerable burden on site supervisors and produces subjective reporting that ultimately compromise data reliability (Gamil et al., 2023). Because the data collection and communication processes are periodic rather than continuous, a significant time lag arises between actual site events and the distribution of progress updates (Samsami, 2024). These delayed reporting mechanisms also make the project management teams unable to institute proactive interventions, resulting in issues being addressed only after escalation (Omar, 2018). As modern infrastructure initiatives increase in scale and complexity, the inefficiencies of these static, paper-based systems become increasingly difficult to mitigate (Khan et al., 2024). The dynamic and highly competitive nature of modern construction demands a level of operational agility that static reporting methods are unable to provide (Alaloul et al., 2022).

When used independently, traditional monitoring methods are rarely connected to digital scheduling or cost control systems, leading to fragmented project management (Dilaksha et al., 2024). The lack of geometric accuracy and the difficulty in directly comparing actual site conditions with planned models further reduce the reliability of visual estimations (Dilaksha et al., 2024). Traditional monitoring approaches rely heavily on manual observation and periodic reporting, which creates significant delays between site activities and management awareness. Ultimately, traditional monitoring is incompatible with regenerative construction goals, which demand continuous optimization and dynamic responsiveness to environmental constraints(Rehman et al., 2023).

## 2.2 REAL-TIME PROGRESS MONITORING AND IOT IN CONSTRUCTION

To address the profound limitations of manual tracking, the construction sector is transitioning toward real-time progress monitoring through the integration of digital, automated frameworks (Qureshi et al., 2023). This transformation is largely driven by the IoT, which links physical site elements with digital systems to create intelligent, data-driven environments (Qureshi et al., 2023). The deployment of wireless sensor networks (WSNs) forms the fundamental perception layer that monitors site conditions automatically transmit data (Hudda & Haribabu, 2025). Modern automated monitoring integrates diverse sensor technologies, including Ultra-Wideband (UWB) and Bluetooth Low Energy (BLE) for precise indoor localisation, and Radio Frequency Identification (RFID) tags placed on construction materials to monitor delivery and installation progress without manual input (Aziz & Koo, 2025).

The real value of these integration lies in their ability to maintain continuous data flows rather than simply adoption technology (Kozlovska et al., 2021). Continuous data capture from distributed IoT networks eliminates the information latency that traditionally hinders project coordination and decision-making (Musarat et al., 2024). Automated status updates generated by these systems enable site planners to compare actual work progress with 4D scheduling models more efficiently (Liu et al., 2025).

Consequently, this continuous feedback loop enables the early detection of discrepancies allowing supervisors to identify minor deviations long before they manifest as critical path delays (Radman et al., 2025). Edge computing further enhances this functionality by processing sensor data directly at the source, thereby reducing bandwidth strain and delivering near real-time alerts to site personnel (Musarat et al., 2024). Furthermore, machine learning algorithms are increasingly applied to this sensor data to convert raw site information into predictive insights on potential cost overruns and schedule delays (Marengo, 2024). These technologies enable continuous visibility of construction activities, allowing project managers to identify deviations earlier than traditional monitoring methods (Musarat et al., 2024).

## 2.3 PROGRESS MONITORING AS AN ENABLER OF REGENERATIVE CONSTRUCTION

The concept of regenerative construction extends beyond basic sustainability by actively focusing on systems that renew resources and minimize long-term ecological impacts throughout the building lifecycle (Alqahtani et al., 2024). Unlike conventional sustainability approaches that primarily focus on reducing negative environmental impacts, regenerative construction seeks to create adaptive systems capable of restoring ecological balance, optimising long-term resource efficiency, and generating continuous environmental and operational value throughout the project lifecycle (Oyefusi et al., 2024). Therefore, achieving regenerative construction objectives requires project execution to become more data-driven, adaptive, and supported by continuous feedback mechanisms (Maqbool et al., 2023). Real-time progress monitoring plays a key role in enabling this shift by providing accurate and timely information that helps improve material use and labour efficiency on construction sites (Althoey et al., 2024). Automated tracking of materials via IoT directly improves supply chain visibility, which is a critical factor in reducing unnecessary material waste and preventing over-ordering on complex projects (Liu et al., 2025).

Promoting circular economy practices on construction sites requires clear and real-time visibility of reusable materials to reduce unnecessary waste and support resource recovery processes (Liu et al., 2025). Furthermore, continuous monitoring facilitates better resource utilization by allowing managers to analyse live usage data and instantly divert idle equipment to areas with higher operational demand (Soleymani et al., 2022). This level of site visibility supports adaptive planning, allowing construction teams to adjust short-term schedules quickly in response to unexpected disruptions (Radman et al., 2025). By combining real-time environmental sensors with progress tracking, quality control becomes a proactive process, helping to reduce defective work and minimize the need for carbon-intensive rework (Hong & Guo, 2025).

Reducing rework directly lowers overall environmental impact by avoiding the repeated use of raw materials, heavy machinery fuel, and human effort (Munianday et al., 2024). Using IoT telematics to implement predictive maintenance for heavy machinery helps prevent unexpected breakdowns, allowing construction activities to proceed more efficiently and sustainably (Althoey et al., 2024). Additionally, monitoring temporary works and site energy consumption via smart metering allows for precise demand profiling, ensuring that power usage is minimized without hindering daily productivity (Hong & Guo, 2025).

Integrating lean logistic with IoT data streams supports regenerative practices by reducing site bottlenecks and enabling smoother coordination between different trade contractors (Liu et al., 2025). Consequently, the economic benefit of reducing delays and waste intersect perfectly with environmental responsibility, creating a strong case for adopting digital technologies (Ghosh et al., 2021). Regenerative construction therefore depends heavily on real-time visibility, continuous learning, and adaptive decision-making processes capable of responding dynamically to changing site conditions (Sertyesilisik, 2016). Within this context, IoT-enabled monitoring systems can operationalise regenerative principles by enabling continuous feedback loops, proactive interventions, predictive resource allocation, and minimisation of waste generation throughout the project lifecycle (Mahmud, 2025). Although global applications demonstrate significant benefits, considerable economic, technical, and cultural barriers still hinder the integration of this advanced system in many regions (Massoud et al., 2025). Developing economies face unique challenges, including fragmented supply chain and unreliable digital infrastructure, which make the smooth adoption of these regenerative technologies more difficult (Waqar et al., 2024).

In addition to these technical constraints, institutional factors such as limited regulatory frameworks, fragmented procurement systems, financial instability, and low organisational readiness further influence the feasibility of regenerative digital transformation within developing construction contexts. Despite the recognised potential of real-time monitoring technologies, limited empirical studies have examined how such systems can operationalise regenerative construction principles in developing construction contexts.

## 3. METHODOLOGY

This study adopted an exploratory qualitative research design to investigate the transition from reactive reporting to regenerative control through IoT-enabled real-time progress monitoring in Sri Lankan construction industry. A qualitative survey strategy was

selected to systematically capture exploratory insights from professionals, as qualitative methods help researchers explore real situation, understand professional perspectives, and develop theoretical insights (Oranga & Matere, 2023). Data collection commenced with a literature review to build the strong theoretical foundation for the study (Snyder, 2019), followed by semi-structured interviews were chosen due to their flexibility, allowing for the collection of in-depth and detailed information, linking broader patterns to individual experiences (Littig, 2009). To ensure relevance and expertise, a non-probability sampling method, incorporating snowball sampling, was used to make the selection of respondents more effective, as it enables the selection of participants with relevant knowledge and experience (Vehovar et al., 2016). The sample comprised 16 experts, 8 from information technology (IT) sector and 8 from the construction industry, ensuring a balanced perspective between technological capabilities and site-level realities. The investigation specifically focused on current progress monitoring practices, the baseline awareness and use of IoT, perceived implementation challenges, and the potential opportunities for achieving regenerative outcomes. Interviews were conducted until data saturation was reached and no new themes or insights emerged. Each interview lasted approximately 30–45 minutes. Data saturation was assessed through continuous comparison of interview responses and coding patterns across both construction and IT professionals. Saturation was considered achieved when later interviews produced repetitive insights with no substantially new codes or perspectives emerging across the predefined thematic categories (Saunders et al., 2017). Finally, the collected qualitative data were analysed using directed qualitative content analysis informed by predefined thematic categories adapted from existing literature and interpreted using coding principles proposed by Braun and Clarke (2006) to identify meaningful patterns in the text. The analytical framework was deductively structured around four predefined themes identified from the literature review: current progress monitoring practices, challenges, opportunities, and regenerative implications while still allowing iterative interpretation of emerging expert insights during the coding process. This approach enabled the synthesis of multidisciplinary perspectives into cohesive and practice-focused conclusions.

*Table 1: Profile of the experts*

| Expert Code | Sector | Designation | Experience |
|---|---|---|---|
| E1 | Construction | Civil Engineer | 22 years |
| E2 | Construction | Quantity Surveyor | 4 years |
| E3 | Construction | Planning Engineer | 14 years |
| E4 | Construction | Project Manager | 24 years |
| E5 | Construction | Technical Officer | 7 years |
| E6 | Construction | Civil Engineer | 28 years |
| E7 | Construction | Civil Engineer | 11 years |
| E8 | Construction | Planning Engineer | 6 years |
| E9 | IT | IoT Engineer | 11 years |
| E10 | IT | IoT Engineer | 8 years |
| E11 | IT | Electronic Engineer | 5 years |
| E12 | IT | Software Engineer | 14 years |
| E13 | IT | Software Engineer | 6 years |

| Expert Code | Sector | Designation | Experience |
|---|---|---|---|
| E14 | IT | Telecommunication Engineer | 5 years |
| E15 | IT | IoT Engineer | 9 years |
| E16 | IT | Network Engineer | 15 years |

# 4. FINDINGS

## 4.1 CURRENT PROGRESS MONITORING PRACTICES IN SRI LANKA

Construction progress monitoring in Sri Lanka largely continues to rely on manual and semi-digital methods, with only selective adoption of advanced tools confined to a few organisations. The most widely practiced progress monitoring approaches are still based on traditional site documentation and regular reporting. Daily site visits and Daily Progress Reports (DPR) were identified by E1, E3, E4, E5, and E6 as standard practice, indicating that physical presence and manual recording remain the dominant means of capturing progress on Sri Lankan construction sites. Expert E1 confirmed that *"Site engineers and technical officers record daily work quantities in daily progress reports"*, illustrating the labour-intensive nature of this data collection process. Photographic documentation of completed works and inspection-based verification of major construction activities further reinforce the reliance on human observation as the primary means of progress assurance. Progress monitoring through periodic meetings was also confirmed by E1, E3, E4, and E7. Expert E7 elaborated that *"In most of the projects I have been involved in, progress monitoring is also reviewed during periodic progress meetings where the team discusses completed work, delays, and the activities planned for the next period"*.

A secondary layer of semi-digital practices, mainly involving spreadsheet applications and scheduling software, was commonly observed among the experts. Excel-based reporting and monitoring emerged as the most adopted digital practice, highlighted by E1, E2, E3, E4, E5, E6, E7, and E8, where site records are transferred into spreadsheet files for tracking and reporting purposes. Expert E8 provided a detailed account of this workflow, noting that *"I send out blank Excel templates to the site execution team every Thursday. They fill in the percentage completion for each activity and send it back to me on Friday. Over the weekend, I cleaned that data and input it into P6 to update the schedule".* Expert E5 further noted that *"some companies use shared Excel files or Google Sheets where daily quantities are entered instead of maintaining only paper records"*. Schedule-based monitoring using Microsoft Project or Primavera P6 was confirmed by E1, E3, E4, E6, and E8, with E3 elaborating that *"we usually develop detailed schedules using Primavera or MS Project, including activity sequencing, resource allocation, and milestones".*

More advanced digital monitoring tools were also identified, although their use was limited to a smaller number of organisations. Dashboard-based systems were reported by E2, E4, and E8, while ERP-based monitoring platforms were mentioned by E1 and E2. E2 stated *"In some advanced companies, progress is monitored through mobile applications that directly update a centralised ERP system"*. E4 reinforced this. Drone-based aerial monitoring of construction progress was identified by E2, E3, E5, and E6 as an emerging practice. Despite these emerging applications, E1 emphasized the overall situation by stating that *"progress monitoring in Sri Lanka remains a semi-digital*

*process, heavily dependent on human reporting and documentation"*. These findings indicate that construction progress monitoring in Sri Lanka remains largely reactive, with limited capability to detect deviations in real time.

## 4.2 LEVEL OF IOT ADOPTION FOR REAL-TIME PROGRESS MONITORING

IoT adoption within Sri Lankan construction remains low to moderate, with existing applications largely confined to planning support, safety monitoring, and asset tracking rather than real-time progress control. The most identified IoT-related devices were used for workforce and safety management. E2 and E7 mentioned the use of fingerprint scanners and site-wide CCTV systems. E7 noted that *"We use fingerprint scanners for our direct labour attendance, so we know exactly how many of our own guys are on site"*. These systems can be considered IoT-based because they collect and transmit real-time workforce data through connected digital devices. E6 described the use of weekly drone photogrammetry surveys for earthwork verification. RFID-based labour monitoring systems were cited by E2 and E6. Expert E6 noted that *"some projects have begun experimenting with RFID-based labour monitoring systems, where RFID tags attached to workers' helmets"*, are used to track workforce activity, indicating early experimentation with automated technologies.

The most structured IoT implementation identified was reported by E2, who deployed a barcode-based tracking system in which *"Each precast module had a barcode, and progress was tracked using sensors and mobile applications integrated into a central ERP system"*, demonstrating that sensor-driven automated data capture is technically feasible within the local context but remains confined to isolated project applications. E8 confirmed that *"The visualization is digital, but the data feed is totally manual"*, indicating that although some digital tools are used, real-time IoT-based progress monitoring is still largely absent in Sri Lankan construction projects. While several emerging digital tools were identified, their implementation remains fragmented and insufficient to establish a fully automated monitoring system. These findings suggest that Sri Lanka is positioned at an early experimental stage of IoT adoption, where isolated applications exist but systemic, project-wide deployment has yet to emerge. Understanding why this gap persists requires examining the barriers that constrain broader implementation.

## 4.3 BARRIERS TO IOT IMPLEMENTATION

The implementation of IoT-enabled real-time progress monitoring in Sri Lanka is constrained by several interconnected barriers spanning financial, technical, infrastructural, and cultural dimensions. The high cost of investment was among the most prominent, with Expert E6 noting that *"Convincing a board of directors to spend millions of rupees on sensors when they are struggling to secure letters of credit for steel is very difficult"*, a concern reinforced by E3 who confirmed that *"Many organisations hesitate to invest in technology without immediate visible returns"*. Poor network connectivity was equally critical, with E7 warning that *"In a concrete high-rise under construction, getting a stable internet signal is very difficult because concrete walls block the signal"*. A similar challenge was also noted by E2, who experienced that reliable internet connectivity was unavailable even on the upper floors of a 30-storey project. Resistance to change extended into deliberate avoidance of transparency, as E8 observed that *"Some project managers prefer the manual system because it allows them to adjust the numbers*

*and conceal small delays"*, while E6 highlighted that *"A lot of imported IoT devices are not built for Sri Lankan site conditions and will break within a week"*. Limited awareness at decision-maker level further compounds adoption, with E10 noting that *"Many organisations hesitate because they are not sure how quickly IoT adoption will generate measurable benefits"*. These challenges, collectively confirmed across both construction and IT professionals, are comprehensively summarised in the following table.

*Table 2: Barriers to IoT implementation for real-time progress monitoring in Sri Lanka*

| Barrier | Experts Who Agreed |
|---|---|
| High initial investment and financial constraints | E1, E2, E3, E4, E6, E9, E10, E11, E14, E15, E16 |
| Limited technical knowledge and expertise among construction professionals | E1, E2, E3, E4, E5, E9, E10, E15 |
| Resistance to change and conservative industry culture | E1, E2, E3, E4, E5, E6, E7, E8, E9 |
| Poor or unreliable internet connectivity on construction sites | E1, E2, E3, E7, E9, E10, E11, E13, E14, E15, E16 |
| Difficulty integrating IoT with management existing systems | E3, E4, E8, E12 |
| Data privacy and cybersecurity concerns | E8, E12, E13, E14 |
| Lack of clear industry standards and guidelines for IoT adoption | E3, E9, E12, E14, E16 |
| Limited awareness of the practical benefits of IoT technologies | E1, E3, E9, E14, E15 |
| Device durability and harsh site conditions | E5, E6, E9, E11, E15 |

## 4.4 OPPORTUNITIES FOR REGENERATIVE CONTROL

Collectively, these barriers reveal that the challenge of IoT adoption in Sri Lanka is not merely technical but is deeply embedded in the financial constraints, cultural resistance, and institutional gaps that characterise the broader construction environment. Despite these constraints, the experts also identified a range of practical opportunities through which IoT-enabled monitoring could begin to support regenerative construction outcomes. IoT-enabled real-time monitoring can help move the Sri Lankan construction industry from reactive reporting to regenerative control by supporting continuous feedback, better decision-making, improved resource management, and waste reduction. E3 highlighted this potential by stating that *"IoT allows automatic data capture, which can directly support planning and decision-making",* indicating a shift from periodic, manual updates toward more continuous and system-driven monitoring. Moreover, Expert E1 confirmed that *"When deviations from the plan are identified early, corrective actions can be taken before costs increase"*, highlighting how real-time data creates the feedback loops essential to regenerative control rather than reactive intervention.

A key opportunity highlighted by several experts was the potential to reduce resource waste and idle time by enabling real-time visibility of labour, materials, and equipment on site. Expert E6 explained that *"If I can see on a dashboard that the cement trucks haven't left the plant, I can instantly reassign my masonry gang to another task before the day is wasted"*. Similarly, E7 noted that tracking material consumption can prevent over-ordering and reduce waste, while E2 added that RFID-based material tracking *"Reduces wastage and prevents disputes regarding material quantities"*, further linking automated monitoring to measurable reductions in unnecessary resource consumption.

Furthermore, IoT offers significant opportunities for proactive quality control, central to minimising the rework that regenerative construction seeks to eliminate. Expert E5 noted that *"Sensors can monitor curing conditions in real time, helping us decide when to remove formwork or proceed with the next activity safely"*, while E6 reinforced this by describing how embedded concrete temperature sensors allow formwork to be stripped the moment required strength is reached, *"Rather than waiting a conservative 7 or 14 days just to be safe"*. These capabilities collectively represent the transition from a reactive, document-driven industry toward a regenerative, data-driven construction ecosystem.

## 5. DISCUSSION

The findings of this study show that construction progress monitoring in Sri Lanka is still largely reactive, relying heavily on manual data collection, periodic reporting, and human judgement. As identified in both the literature review and expert interviews, progress monitoring practices remain dependent on daily site inspections, spreadsheet-based reporting, and periodic progress meetings. These findings are consistent with Rehman et al. (2023) and Samsami (2024), who highlighted that traditional monitoring systems create delays between actual site events and management awareness. Such delays limit the ability to implement proactive interventions and contribute to rework, material waste, resource inefficiencies, and schedule overruns, all of which contradict regenerative construction principles that depend on continuous optimisation and adaptive decision-making.

According to the literature review and expert findings, IoT technologies offer a clear pathway to transform this reactive monitoring system into a more adaptive and regenerative process through sensor-driven data capture, RFID tracking, drone photogrammetry, and BIM-integrated monitoring platforms. However, the findings indicate that IoT implementation within Sri Lankan construction projects remains fragmented and limited to isolated applications including barcode-based material tracking, drone-assisted earthwork verification, and RFID-based labour monitoring. These findings suggest that Sri Lanka currently remains at an early experimental stage of IoT adoption where digital technologies are used selectively rather than systematically integrated into project-wide progress monitoring frameworks.

The study further reveals that barriers to IoT implementation are not purely technological but strongly connected to broader structural and institutional realities within the Sri Lankan construction industry. Key challenges identified by the experts include high initial investment costs, poor internet connectivity, limited technical expertise, resistance to organisational transparency, and harsh site conditions affecting device durability. These findings align with previous studies conducted within developing economies, which emphasise that financial instability, inadequate infrastructure, and fragmented industry practices significantly hinder Industry 4.0 adoption (Waqar et al., 2024). Importantly, the findings indicate that digital transformation in construction should be understood as a socio-technical and institutional challenge rather than simply a technological transition.

The dominance of government-funded projects within Sri Lanka further shapes the feasibility of IoT implementation. The government functions not only as the primary regulator but also as the largest client and procurement authority within the construction

sector. Consequently, decisions regarding digital adoption are heavily influenced by procurement systems, contract conditions, reimbursement structures, and regulatory requirements established through public projects. Several experts highlighted that contractors facing financial hardship are unlikely to independently invest in expensive IoT infrastructure without client-driven requirements or financial support mechanisms. Therefore, large-scale adoption is unlikely unless procurement reforms, reimbursable digital implementation costs, and government-supported pilot initiatives are introduced.

Despite these constraints, the findings demonstrate considerable opportunities for IoT-enabled monitoring to support regenerative construction outcomes. Experts identified that real-time visibility of labour, materials, and equipment can improve resource allocation, reduce idle time, minimise material waste, and support proactive quality control. These findings support the argument of Liu et al. (2025) that continuous monitoring enhances operational efficiency and enables more adaptive construction management practices. Furthermore, IoT-enabled feedback systems allow early identification of deviations and facilitate corrective action before delays escalate into major operational and environmental inefficiencies. Consequently, this study contributes to the emerging regenerative construction discourse by demonstrating how IoT-enabled real-time monitoring can function as an operational mechanism for continuous feedback, adaptive decision-making, and resource optimisation within developing construction contexts.

## 6. CONCLUSIONS

This study examined current construction progress monitoring practices in Sri Lanka and explored how IoT-enabled real-time monitoring can support a transition from reactive reporting toward regenerative control. The findings reveal that construction progress monitoring within Sri Lanka remains heavily dependent on manual and semi-digital methods including daily site inspections, spreadsheet-based reporting, and periodic progress meetings. These traditional practices continue to create delays in information flow, subjective assessments, fragmented communication, and limited ability to implement proactive interventions. Such limitations are fundamentally incompatible with regenerative construction principles, which require continuous feedback, adaptive decision-making, and resource optimisation throughout the project lifecycle.

The study further identified that IoT adoption within Sri Lankan construction projects remains limited and fragmented, with only selective applications such as RFID-based labour tracking, drone photogrammetry, barcode-based material tracking, and ERP-integrated monitoring systems being implemented in isolated cases. Although the experts acknowledged the significant potential of IoT technologies to improve real-time visibility, reduce waste, minimise rework, and enhance operational efficiency, implementation is constrained by several interconnected barriers. These include high investment costs, unreliable internet connectivity, limited digital literacy, resistance to organisational transparency, lack of interoperability standards, cybersecurity concerns, and poor institutional readiness. The findings additionally highlight that these barriers are deeply embedded within the broader structural realities of the Sri Lankan construction industry, particularly government-dominated procurement systems, financial instability, and fragmented subcontracting practices.

The study recommends that future digital transformation initiatives should move beyond isolated technological experimentation and focus on collaborative implementation

strategies supported by procurement reforms, public sector pilot projects, reimbursable digital implementation mechanisms, and stronger institutional support. Greater emphasis should also be placed on improving digital literacy, cybersecurity governance, interoperability standards, and regulatory frameworks to support sustainable IoT integration within the construction sector.

This study contributes to knowledge by extending the emerging discourse on regenerative construction through the conceptualisation of IoT-enabled real-time progress monitoring as a regenerative control mechanism rather than merely an automated reporting tool. Furthermore, the study contributes empirical evidence from a developing country context that remains underrepresented within existing Industry 4.0 and construction digitalisation literature, highlighting the importance of socio-technical, institutional, and economic realities in shaping the feasibility of regenerative digital transformation.

## 7. REFERENCES

Alaloul, W. S., Musarat, M. A., Rabbani, M. B. A., Altaf, M., Alzubi, K. M., & Salaheen, M. Al. (2022). Assessment of economic sustainability in the construction sector: Evidence from three developed countries (the USA, China, and the UK). *Sustainability*, *14*(10). https://doi.org/10.3390/su14106326

Alqahtani, F. M., Abas, M., Alkahtani, M., Hayat, M., & Farrukh, A. (2024). Enhancing sustainable safety practices in construction: Insights from cultural and socio-economic analysis. *Sustainability*, *16*(12). https://doi.org/10.3390/su16125103

Althoey, F., Waqar, A., Alsulamy, S. H., Khan, A. M., Alshehri, A., Falqi, I. I., Abuhussain, M., & Abuhussain, M. A. (2024). Influence of IoT implementation on resource management in construction. *Heliyon*, *10*(15). https://doi.org/10.1016/j.heliyon.2024.e32193

Alvarez, L. M., Risco, A. A., Arcentales, S. D. A., Sekar, M. C., & Yanez, J. A. (2022). A systematic review of earned value management methods for monitoring and control of project schedule performance: An AHP approach. *Sustainability*, *14*(22). https://doi.org/10.3390/su142215259

Ashton, K. (2009, June 22). That "internet of things" thing. *RFID Journal*. https://www.rfidjournal.com/articles/view?4986

Aziz, T., & Koo, I. (2025). A comprehensive review of indoor localization techniques and applications in various sectors. *Applied Sciences*, *15*(3). https://doi.org/10.3390/app15031544

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Dilaksha, S., Ranadewa, K. A. T. O., Weerasooriya, D., Parameswaran, A., & Weerakoon, P. (2024). Comparative analysis of challenges in manual and automated construction progress monitoring in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, & H. Chandanie (Eds.), *Proceedings of the 12th World Construction Symposium* (pp. 379–394). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2024.30

Gamil, Y., Alhajlah, H., & Kassem, M. A. (2023). Automated project progress monitoring in construction projects: A review of current applications and trends. *Lecture Notes in Networks and Systems*, *584 LNNS*, 274–293. https://doi.org/10.1007/978-3-031-25274-7_23

Ghosh, A., Edwards, D. J., & Hosseini, M. R. (2021). Patterns and trends in internet of things (IoT) research: Future applications in the construction industry. *Engineering, Construction and Architectural Management*, *28*(2), 457–481. https://doi.org/10.1108/ECAM-04-2020-0271

Hong, Y., & Guo, F. (2025). A framework of BIM-IoT application in construction projects through multiple case study approach. *Journal of Building Design and Environment*. https://doi.org/10.70401/jbde.2025.0004

Hudda, S., & Haribabu, K. (2025). A review on WSN based resource constrained smart IoT systems. *Discover Internet of Things*, *5*(1). https://doi.org/10.1007/s43926-025-00152-2

Khan, A. M., Alrasheed, K. A., Waqar, A., Almujibah, H., & Benjeddou, O. (2024). Internet of things (IoT) for safety and efficiency in construction building site operations. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-78931-0

Kim, J.-Y., Kang, S., Cho, J., Jeong, S., Kim, S., Sung, Y., Lee, B., & Kim, G.-H. (2025). Implementation of integrated smart construction monitoring system based on point cloud data and IoT technique. *Sensors*, *25*(13). https://doi.org/10.3390/s25133997

Kozlovska, M., Klosova, D., & Strukova, Z. (2021). Impact of industry 4.0 platform on the formation of construction 4.0 concept: A literature review. *Sustainability, 13(5), 1–15.* https://doi.org/10.3390/su13052683

Littig, B. (2009). Interviewing the elite interviewing experts: Is there a difference? *Interviewing Experts. London: Palgrave Macmillan UK*, 98–113. https://doi.org/10.1057/9780230244276_5

Liu, X., Antwi-Afari, M. F., Li, J., Zhang, Y., & Manu, P. (2025). BIM, IoT, and GIS integration in construction resource monitoring. *Automation in Construction*, *174*. https://doi.org/10.1016/j.autcon.2025.106149

Mahmud, D. (2025). An IOT-enabled decision support system for circular economy business models: A review of economic efficiency and sustainability outcomes. *American Journal of Scholarly Research and Innovation*, *04*(01), 250–286. https://doi.org/10.63125/28kdxg31

Maqbool, R., Saiba, M. R., & Ashfaq, S. (2023). Emerging industry 4.0 and Internet of Things (IoT) technologies in the Ghanaian construction industry: Sustainability, implementation challenges, and benefits. *Environmental Science and Pollution Research*, *30*(13), 37076–37091. https://doi.org/10.1007/s11356-022-24764-1

Marengo, A. (2024). Navigating the nexus of AI and IoT: A comprehensive review of data analytics and privacy paradigms. *Internet of Things*, *27*, 101318. https://doi.org/10.1016/j.iot.2024.101318

Massoud, M., Kineber, A., Elshaboury, N., Abunada, Z., Arashpour, M., Alatroush, M., Mostafa, S., & Alhusban, M. (2025). Identifying and assessing the internet of things implementation barriers for sustainable building projects: SEM-ANN approach. *KSCE Journal of Civil Engineering*, 100310. https://doi.org/10.1016/j.kscej.2025.100310

Munianday, P., Sarawak, M., Rahman, R. A., Abdullah, A. S., & Esa, M. (2024). A comprehensive analysis of the importance of investigating the impact of construction 4.0 skills on project performance. *Journal of Information Technology in Construction*, *29*, 686–721. https://doi.org/10.36680/j.itcon.2024.031

Musarat, M. A., Khan, A. M., Alaloul, W. S., Blas, N., & Ayub, S. (2024). Automated monitoring innovations for efficient and safe construction practices. *Results in Engineering*, *22*. https://doi.org/10.1016/j.rineng.2024.102057

Naji, K. K., Gunduz, M., Alhenzab, F. H., Al-Hababi, H., & Al-Qahtani, A. H. (2024). A systematic review of the digital transformation of the building construction industry. *IEEE Access*, *12*, 31461–31487. https://doi.org/10.1109/ACCESS.2024.3365934

Omar, H. S. A. (2018). Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities. *Computers in Industry*, *98*. https://doi.org/10.1016/j.compind.2018.03.012

Oranga, J., & Matere, A. (2023). Qualitative research: Essence, types and advantages. *Open Access Library Journal*, *10*(12), 1–9. https://doi.org/10.4236/oalib.1111001

Oyefusi, O. N., Enegbuma, W. I., Brown, A., & Olanrewaju, O. I. (2024). Development of a novel performance evaluation framework for implementing regenerative practices in construction. *Environmental Impact Assessment Review*, *107*, 107549. https://doi.org/10.1016/j.eiar.2024.107549

Pal, A., Lin, J. J., Hsieh, S.-H., & Golparvar-Fard, M. (2023). Automated vision-based construction progress monitoring in built environment through digital twin. *Developments in the Built Environment*, *16*, 100247. https://doi.org/10.1016/j.dibe.2023.100247

Qureshi, A. H., Alaloul, W. S., Wing, W. K., Saad, S., Ammad, S., & Altaf, M. (2023). Characteristics-based framework of effective automated monitoring parameters in construction projects. *Arabian Journal for Science and Engineering*, *48*(4), 4731–4749. https://doi.org/10.1007/s13369-022-07172-y

Radman, K., Jelodar, M. B., & Lovreglio, R. (2025). Realcons: A digital framework for construction reporting accuracy and early delay detection. *Journal of Information Technology in Construction*, *30*, 745–777. https://doi.org/10.36680/j.itcon.2025.031

Rehman, M. S. U., Shafiq, M. T., Ullah, F., & Ahmed, K. G. (2023). A critical appraisal of traditional methods of construction progress monitoring. *Built Environment Project and Asset Management*, *13*(6). https://doi.org/10.1108/BEPAM-02-2023-0040

Samsami, R. (2024). A systematic review of automated construction inspection and progress monitoring (ACIPM): Applications, challenges, and future directions. *CivilEng*, *5*(1), 265–287. https://doi.org/10.3390/civileng5010014

Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., Burroughs, H., & Jinks, C. (2017). Saturation in qualitative research: Exploring its conceptualization and operationalization. *Quality & Quantity*, *52*(4), 1893–1907. https://doi.org/10.1007/s11135-017-0574-8

Sendanayake, H., Nawarathna, A., & Fernando, N. (2024). Exploring opportunities and challenges in integrating Industry 4.0 for advancements in the Sri Lankan construction sector. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, & H. Chandanie (Eds.), *Proceedings of the 12th World Construction Symposium* (pp. 470–480). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2024.37

Sertyesilisik, B. (2016). A preliminary study on the regenerative construction project management concept for enhancing sustainability performance of the construction industry. *International Journal of Construction Management*, *17*(4), 293–309. https://doi.org/10.1080/15623599.2016.1222665

Shamsollahi, D., Moselhi, O., & Khorasani, K. (2022). Construction progress monitoring and reporting using computer vision techniques- a review. *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, *39*, 467–474. https://doi.org/10.22260/ISARC2022/0064

Silva, N. De, Rajakaruna, R. W. D. W. C. A. B., & Bandara, K. A. T. N. (2025). Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors. *Building Resilience*, 158–169.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Soleymani, M., Bonyani, M., & Attarzadeh, M. (2022). Autonomous resource management in construction companies using deep reinforcement learning based on IoT. *ArXiv Preprint*. https://doi.org/10.48550/arXiv.2208.08087

Suvvari, S. K., & Saxena, V. D. (2024). Innovative Approaches to project scheduling: Techniques and tools. *Innovative Research Thoughts*, *10*(2), 133–143. https://doi.org/10.36676/irt.v10.i2.1481

Vehovar, V., Toepoel, V., & Steinmetz, S. (2016). Nonprobability sampling. *The Sage Handbook of Survey Methods*, *1*, 329–345. https://doi.org/10.4135/9781473957893.n22

Waqar, A., Shafiq, N., Othman, I., Alsulamy, S. H., Alshehri, A. M., & Falqi, I. I. (2024). Deterrents to the IoT for smart buildings and infrastructure development: A partial least square modeling approach. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e31035

Sivakumar, A., Staal, A. and Piri, I., 2026. From strategy to practice: Implementing sustainable procurement in construction SMEs - A systematic review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 842-854. DOI: https://doi.org/10.31705/WCS.2026.62. Available from: https://ciobwcs.com/papers/

# FROM STRATEGY TO PRACTICE: IMPLEMENTING SUSTAINABLE PROCUREMENT IN CONSTRUCTION SMES– A SYSTEMATIC REVIEW

**Abiramy Sivakumar[1], Anne Staal[2] and Imelda Piri[3]**

## *ABSTRACT*

*Sustainable procurement (SP) has become a critical mechanism for improving environmental, social, and economic performance in the construction sector, thereby contributing to achieve UN-SDG goals (SGD12). However, SP implementation within construction SMEs is rarely examined in existing studies, indicating a significant gap in the literature. This study addresses this gap through a systematic literature review of 47 peer-reviewed articles. The review applies inductive and deductive content analysis to identify the most prominent SP implementation strategies that help SMEs to foster sustainability. The findings reveal a total of 12 implementation strategies. Among them stakeholder collaboration, awareness and knowledge enhancement, and top management support are the strategies most frequently highlighted in the literature, while project-specific measures and the use of project power structures remain underexamined. The study contributes to theory by articulating the strategies in practicing sustainability tailored to construction SMEs context and to practice by identifying actionable recommendations for addressing financial and capability constraints. SMEs and policy makers in construction can use this set if implementation strategies to promote sustainable practices and researchers are presented with enhanced opportunities on contributing to the body of knowledge systematically and effectively.*

***KEYWORDS:*** *Construction; Implementation Strategies; Procurement; SMEs; Sustainable.*

## 1. INTRODUCTION

Given that the construction sector is one of the leading growing industries (Oyegoke et al., 2024; Sarvari et al., 2021; Wedawatta et al., 2010), it significantly impacts sustainability outcomes. For instance, it is responsible for climate changes (Erasmus & Iyer-Raniga, 2022), approximately 38% of total of $CO_2$ emissions and around 35% of global energy consumption (UNEP, 2020). With highest accident rates, the construction sector is recognised among the most hazardous industries for workers in terms of health

[1] PhD Candidate, Department of Built Environment Engineering, Auckland University of Technology, New Zealand, abiramy.sivakumar@aut.ac.nz
[2] Senior Lecturer, Department of Built Environment Engineering, Auckland University of Technology, New Zealand, anne.staal@aut.ac.nz
[3] Lecturer, Department of Built Environment Engineering, Auckland University of Technology, New Zealand, imelda.piri@aut.ac.nz

and safety performance (Bernaciak et al., 2021; Xia et al., 2018). On the other hand, construction supports creation of infrastructure, and is a source of employment, that shapes social lifestyle of people (Xia et al., 2018). This indicates that construction sector significantly impacts three pillars of sustainable development: social, environmental and economic (Opoku et al., 2022) and thereby influencing on the achievement of UN-SDGs, particularly on SDG12. Construction is generally driven by projects that are primarily made up of procurement-related activities (Khouja et al., 2021). Hence, sustainability measures must be initiated through project procurement (Ershadi et al., 2021). Subsequently, the concept of 'Sustainable Procurement' (hereafter referred to as SP) in construction projects emerged and gained prominence among scholars seeking to advance sustainable development within construction (Erasmus & Iyer-Raniga, 2022).

Small and medium-sized enterprises (hereafter referred to as SMEs) play a critical role in executing construction procurement (Tezel et al., 2020), as they constitute around 90% of organisations globally (Adzivor et al., 2023). Particularly, SMEs' cumulative procurement decisions exert a significant influence on sustainability outcomes across construction supply chains (Nangpiire et al., 2024). Subsequently, improving SP practices among SMEs has the potential to generate system-wide sustainability benefits that extend beyond individual projects. Yet, in the absence of support mechanisms, SMEs frequently struggle to successfully implement sustainable procurement practices (Charkaoui, 2025). Unlike large organisations, SMEs typically operate with limited financial resources, reduced access to specialist expertise, and less formalised management systems (Michna et al., 2020). These constraints often restrict their capacity to absorb high initial investments (Scipioni & Niccolini, 2021) and interpret complex sustainability standards (Balasubramanian et al., 2020). Although SP has been widely examined within the construction sector, existing research predominantly focuses on large organisations (for example, (Erasmus & Iyer-Raniga, 2022; Ershadi et al., 2021; Ruparathna & Hewage, 2015)). Far less attention has been given to how construction SMEs can practically implement SP with limited guidance available. To address this gap, the present study seeks to answer the research question: "*What implementation strategies are critical in promoting SP within construction SMEs?"* This finding could help SMEs, policy makers, and researchers in the promotion of SP in the construction industry.

The subsequent sections of this paper are structured as follows: Section 2 explains the methodology, Section 3 reports the results, Section 4 outlines the discussion and finally Section 5 concludes the study with limitations, and suggestions for future research directions.

## 2. RESEARCH METHODOLOGY

This study examines research question that is not sufficiently explored in existing studies. Due to this lack of theoretical development in the domain, it requires in-depth investigation of literature through a rigorous, and evidence-based protocol (Briner & Denyer, 2012; Durach et al., 2017; Taherdoost, 2023). Subsequently, this study adopts the systematic literature review methodology based on Tranfield et al. (2003), and Durach et al. (2017). The review process entails three stages: (i) planning; (ii) screening and selection; and (iii) analysis and reporting.

In Stage 1, a preliminary search for the exploration of literature on the key concepts was performed to ensure that appropriate search string is developed that consists of all

possible keywords. This was performed since the construction of search strings critically affects the validity, reliability, and comprehensiveness of the extracted research papers (Yu et al., 2020). Afterward, the following keywords (Table 1) were generated and combined with 'AND' to develop the search string used in the literature search.

*Table 1: Keywords used in the literature search (Author's own work)*

| Concepts | Keywords | Search Through |
|---|---|---|
| Sustainable Procurement | sustainab* OR green OR environment* OR tbl OR "triple bottom line" OR "construction procure*" OR "project procure*" OR procur* | Title, abstract, keyword |
| Construction | construction OR "construction industry" OR building OR "built environment" | All fields |
| SMEs | sme* OR "small firm*" OR "small business*" OR "small enterprise*" OR "medium enterprise*" OR "small compan*" OR "medium business*" OR "medium compan*" OR "mid-sized compan*" | Title, abstract, keyword |

Stage 2 comprises of literature search and the selection of relevant papers for the study. Scopus database was used to explore potentially relevant articles due to its widespread repository known for multidisciplinary scientific writings in line with other scholars who used this as standalone academic database (Adekunle et al. (2022); Nagariya et al. (2021); Wang et al. (2020); and Yu et al. (2020)). Moreover, eligibility criteria were used to define inclusion and exclusion parameters as:

- publication stage - final publications.
- document types - peer-reviewed journal articles and conference papers.
- subject areas – 'Engineering, Business, Management and Accounting, Decision Science, Environmental Science, Energy, Earth and Planetary Sciences, and Materials Science'
- language - English.

Applying these criteria yielded 295 papers. An initial screening of titles, abstracts, and keywords reduced the number to 193 papers. A subsequent cross-checking process was conducted to obtain full texts, during which 6 papers were excluded due to unavailable full text access. Finally, a comprehensive full text assessment was undertaken, resulting in 38 papers being retained for detailed analysis. An additional 9 studies were identified through snowball citation sampling. Figure 1 summarises this research process.

During Stage 3, a descriptive analysis of the final set of 47 studies was conducted in Excel. Further, the selected papers were carefully scrutinised through inductive and deductive content analysis proposed by Xia et al (2018) to identify the most frequently researched 'Implementation Strategies' (hereafter referred to as ISs). Findings are reported in Section 3 to ensure the rigor and transparency of the review protocol.

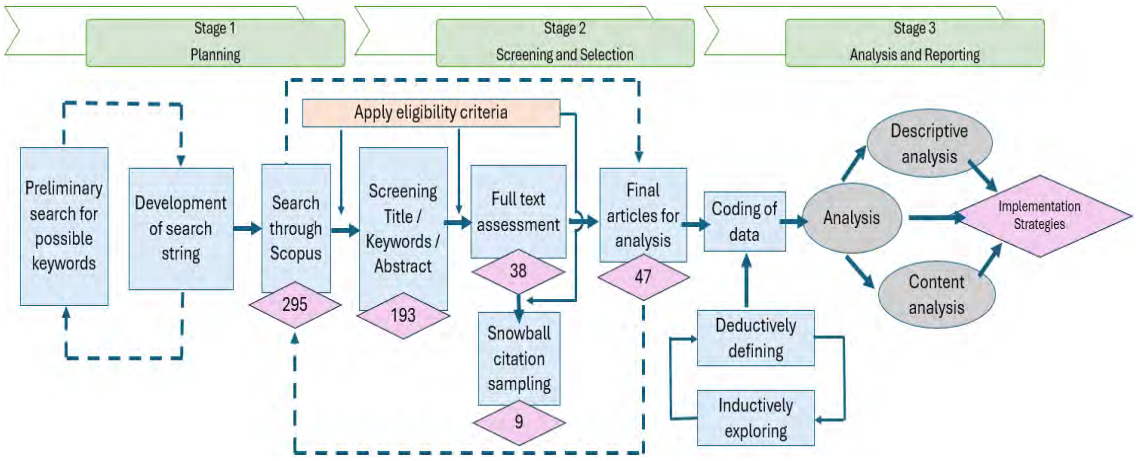



*Figure 1: Research process*

# 3. ANALYSIS AND RESULTS OF SYSTEMATIC REVIEW

## 3.1 PRESENTATION OF DESCRIPTIVE ANALYSIS

The descriptive analysis presented in this section offers insight into the characteristics of research contributions to the paradigm of SP of construction SMEs, specifically in relation to annual publication trends, publications by countries, and journal distribution.

### 3.1.1 Annual Publication Trends

Figure 2 illustrates a general upward trend in research activity after 2000, although certain years show an absence of publications on SP. The increase from an average of 1.12 papers per year (2000-2018) to 3.85 papers per year (2019-May, 2025) reflects the growing scholarly attention to SP, with the first notable spike occurring in 2019.This rise may be attributed to the renewed global emphasis on sustainable development in the aftermath of the COVID-19 pandemic and subsequent economic disruptions (Baral et al., 2023).

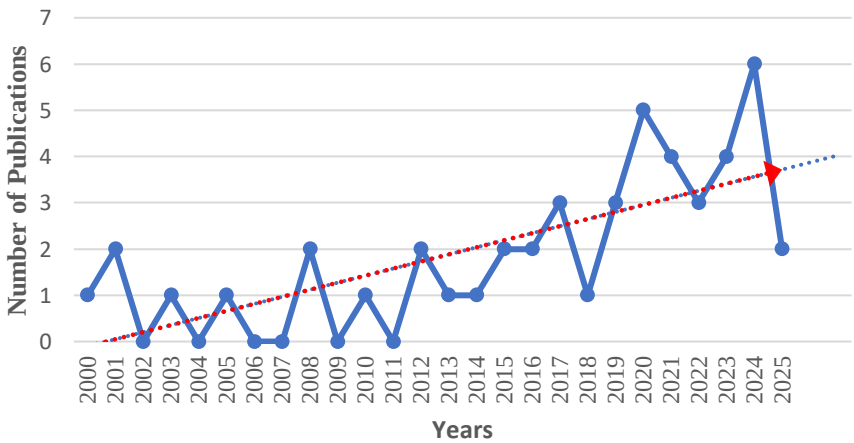



*Figure 2: Annual publication trends*

### 3.1.2 Publications by Countries

As illustrated in Figure 3, the United Kingdom emerges as the leading contributor to research on this domain. Other countries, including Indonesia, the United States, and Italy

have also made notable contributions. The category labelled 'International' refers to studies conducted across multiple countries, most commonly in the form of literature reviews.

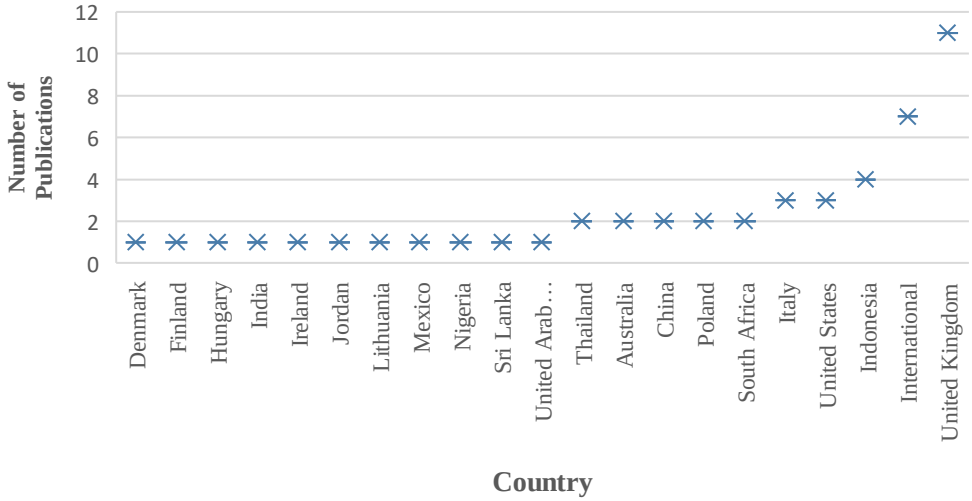



*Figure 3: Publication by countries*

### 3.1.3 Journal Distribution

The review indicates that research concerning SP in construction is dispersed across a wide range of academic journals (Table 2). Among these, *Sustainability (MDPI)* and *Construction Management and Economics* emerge as the most prominent sources of relevant publications. Notably, both journals are classified as Q1 in the Scimago Journal and Country Rank (SJR), reflecting strong scholarly interest and the growing academic significance of this research domain.

*Table 2: Distribution of publication outlets*

| Paper Outlets | Number of Publications |
|---|---|
| Sustainability | 5 |
| Construction Management and Economics | 3 |
| Association of Researchers in Construction Management, ARCOM | 2 |
| European Journal of Purchasing & Supply Management | 2 |
| Journal of Cleaner Production | 2 |
| IOP Conference Series: Earth and Environmental Science | 2 |
| Advances in Intelligent Systems and Computing | 2 |
| Automation in Construction | 2 |
| Buildings | 2 |
| Construction Innovation | 2 |
| Engineering, Construction and Architectural Management | 1 |
| Engineering Economics | 1 |
| Frontiers in Built Environment | 1 |
| Institution of Civil Engineers: Management, Procurement and Law | 1 |
| International Business Management | 1 |
| International Conference on System Sciences | 1 |

| Paper Outlets | Number of Publications |
|---|---|
| International Journal of Agile Systems and Management | 1 |
| International Journal of Building Pathology and Adaptation | 1 |
| International Journal of Life Cycle Assessment | 1 |
| International Journal of Manufacturing Technology and Management | 1 |
| International Journal of Project Management | 1 |
| International Structural Engineering and Construction | 1 |
| Journal of Civil Engineering and Management | 1 |
| Journal of Construction Engineering | 1 |
| Journal of Construction Engineering and Management | 1 |
| Journal of Financial Management of Property and Construction | 1 |
| Logforum | 1 |
| Management of Environmental Quality: An International Journal | 1 |
| Nanotechnology Perceptions | 1 |
| Resources | 1 |
| Sinergie | 1 |
| Structural Integrity and Life | 1 |
| World Construction Symposium | 1 |

## 3.2 PRESENTATION OF CONTENT ANALYSIS

The following sub-sections present the key findings from the content analysis conducted through coding, synthesis, and categorisation techniques as outlined by Seuring and Gold (2012). Initially, the codes were inductively explored from the selected literature based on the key themes of the pertinent research question. Subsequently, the papers were deductively re-examined enabling the systematic synthesis and categorisation of identified codes across studies (Xia et al., 2018).

### 3.2.1 Inductive Content Analysis

This part includes the identification of codes during the inducive content analysis on the implementation strategies (ISs) which promote SP. A total of 12 ISs emerged (Table 2) and were subsequently coded to enable further deductive analysis.

*Table 3: Implementation strategies for promoting SP*

| Codes | Implementation Strategies for Promoting SP |
|---|---|
| IS1 | Communication channels |
| IS2 | Stakeholder collaboration |
| IS3 | Effective information flow |
| IS4 | Top-management support |
| IS5 | Client accountability |
| IS6 | Role of government and industry body |
| IS7 | Project and site-specific measures |
| IS8 | Change management protocol |
| IS9 | Training to leverage skills and competencies |

| Codes | Implementation Strategies for Promoting SP |
|---|---|
| IS10 | Increase awareness and knowledge |
| IS11 | Use of power structure of project |
| IS12 | Integrating to existing business and systems |

### 3.2.2 Deductive Content Analysis

Further to the inductive analysis, the deductive content analysis of all the selected papers was carried out to re-examine the codes on ISs (Section 3.2.1). From Table 2, the descriptions of the potential ISs were extracted as additional attributes to these strategies. Figure 4 summarises the frequency distribution of the strategies using a radar image. The numerical values in the figure indicate the total frequency of citations corresponding to each implementation strategy across the reviewed studies.

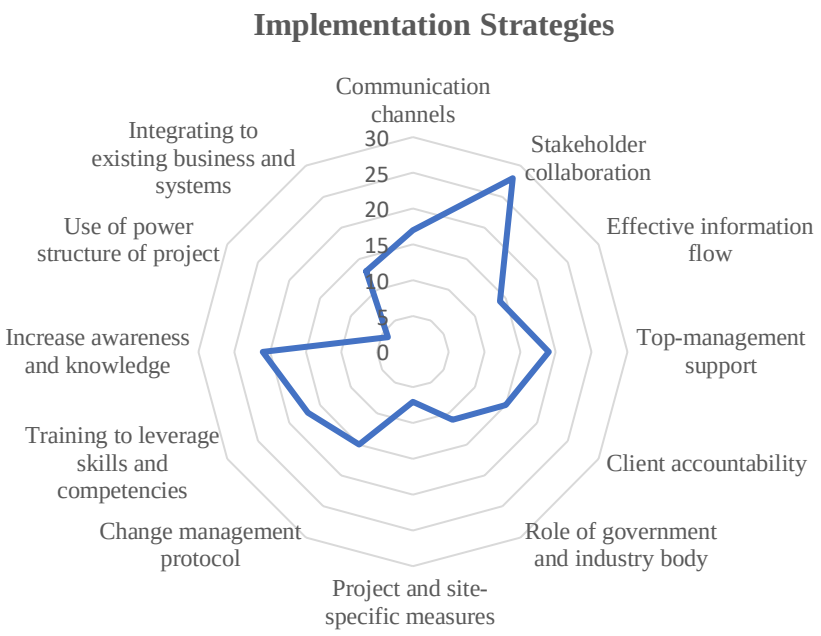



*Figure 4: Citation frequency distribution for ISs*

Focusing on the top strategies identified across studies based on occurrence, *stakeholder collaboration (IS2)* seemed the most popular strategy. Manu et al. (2015) stated the collaboration is more contractual due to greater emphasis on money. In contrast, Dey et al. (2008) and Taggart et al. (2014) identified it is based on personal trust rather than contract laws. Yet, mapping and prioritising the main business targets of partners towards the ecosystem help to achieve initial holistic collaboration (Han et al., 2017; Korpela et al., 2016), which is facilitated through open knowledge sharing (Cyfert et al., 2024). This helps SMEs to overcome the barriers of resource constrains and to improve agility (Han et al., 2017; Scipioni & Niccolini, 2021). In line with these scholars, the strategy to *increase awareness and knowledge (IS10)* appears as second highest that emphasises the need for conducting promotion campaigns on various aspects of sustainable development. For instance, Arvizu-Piña et al. (2017) and Garoghan et al. (2025) emphasised the importance of awareness campaigns focusing on waste management practices and the adoption of a life-cycle approach, whereas Alnhoud et al. (2021) highlighted the need to promote safety culture in procurement.

*Top-management support (IS4)* in embedding sustainability within procurement processes of SMEs is widely recognised as a critical strategy, given their central influence on organisational culture (Scipioni et al., 2021; Scipioni & Niccolini, 2021). Positive management can manifest through the provision of training and incentives for environmentally responsible initiatives (Qi et al., 2010), as well as safety tours and workforce engagement activities that reinforce sustainable and safe practices (Stiles et al., 2019). This can be further operationalised with the use of appropriate *communication channels (IS1)*, along with *training to leverage skills and competencies (IS9)*. Appropriate communication channels are essential to ensure that accurate and timely information is conveyed, thereby supporting informed decision-making within procurement processes (Ko et al., 2016; Lukson et al., 2024). In specific, communicating with local authorities, research institutions, and public organisations plays a crucial role in enabling sustainable procurement among SMEs (Salvador et al., 2023). In parallel, targeted training on SP approaches like safety management practices is especially important (Alnhoud et al., 2021). However, SMEs face notable challenges in this regard, for example, substantial financial costs associated with external training programmes (Briscoe et al., 2001). To mitigate these constraints, internal training for existing personnel is recommended (Scipioni & Niccolini, 2021).

The literature assigns considerable importance to *client accountability (IS5)* and *change-management protocols (IS8)* within SMEs. Clients influence several sustainability-oriented practices. For example, responsible material sourcing (Glass et al., 2012), the adoption of e-procurement systems (Vitkauskaite & Gatautis, 2008), and the procurement of green products and sustainable construction technologies (Scipioni & Niccolini, 2021). This indicates the involvement of client throughout the procurement life cycle. Transitioning SME culture from traditional routines to environmentally responsible practices represent another central strategy for supporting sustainable procurement (Gusmao Brissi & Debs, 2023; Lukson et al., 2024; Scipioni & Niccolini, 2021). Nonetheless, SMEs frequently exhibit resistance to organisational change, particularly when it disrupts established procedures or when return on investment is perceived as uncertain (Ashish Mankar et al., 2024; Taggart et al., 2014). To overcome this, *effective information flow (IS3)* strategy can be utilised. Yet, issues like data reliability, traceability, and completeness disincentives SMEs to share information truthfully, that in result negatively impact on procurement performance (Di Giuda et al., 2020). Addressing this issue, SMEs can think of *integrating to existing business and systems (IS12)* to ensure SMEs' commitment to sustainability (Balasubramanian et al., 2020). Relatedly, Robeiro and Love (2003) and Upstill-Goddard et al. (2012) also emphasises the need of more holistic approach that could be integrated into corporate decision making.

The *role of government and industry body (IS6)* strategy provides motivations for the uptake of SP, as fines and penalties for non-compliance led to a negative impact among contractors (Qi et al., 2010). Alternatively support mechanisms, such as incentives, tax discount, and preferential treatment to be deployed to increase the implementation of SP among construction SMEs (Glass et al., 2012; Balasubramanian et al., 2020). Distinctly government and regulatory bodies could set clear rules without frequent revisions (Ashish Mankar et al., 2024). Finally, *project- and site-specific measures (IS7)*, as well as the strategic *use of power structures of project (IS11)*, receive comparatively less attention in the literature than other implementation strategies. These measures are highly

context-dependent, i.e. varying significantly across projects and procurement arrangements. Thus, it is difficult to generalise them across studies (Taggart et al., 2014), resulting in limited scholarly focus relative to broader organisational or sector-wide strategies (Manu et al., 2015). Yet, implementing green is highly depending on power of different members in the project team (Glass et al., 2012). Stiles et al. (2019) further highlighted the divergent power relationship between main contractor and subcontractors that influence the reported levels of safety culture for the project. In addition, trust issue linked to payment practices of main contractor is observed due to the lower power position of subcontractor (Manu et al., 2015).

# 4. DISCUSSION

The best practices for SP in construction seem less developed (Wirahadikusumah et al., 2020). Specially, SMEs face several challenges implementing SP in construction (Ashish Mankar et al., 2024; Balasubramanian et al., 2020; Gusmao Brissi & Debs, 2023; Robeiro & Love, 2003; Scipioni et al., 2021). Nonetheless, the findings of Kelly et al. (2019) indicate that construction SMEs are generally receptive to a wide range of sustainable initiatives. This provides a strong motivation for the present study and a potential to explore implementation strategies. The reviewed articles most often emphasise stakeholder collaboration, increased awareness and knowledge, and top management support as implementation strategies. As the construction process involves many participants, intra and inter relationship and collaboration between members are basic requirement (Dey et al., 2008; Di Giuda et al., 2020). In contrast, project- and site-specific measures and the strategic use of project power structures received considerably less scholarly attention, indicating that these areas remain underexplored within the existing literature.

While this review findings are drawn from international contexts, the findings hold strong relevance for Sri Lanka, as SMEs constitute most construction firms and play a critical role in procurement (Lukson et al., 2024). Moreover, several policies emphasis on sustainable development, infrastructure revitalisation and reforms has created increasing pressure for SME contractors to demonstrate environmental and social responsibility (Ratnayake et al., 2025). In this context, the outcomes of this review provide a transferable and contextually relevant foundation of implementation strategies among construction SMEs in Sri Lanka.

Further, this study offers valuable recommendations to SMEs and policy makers in general. Firstly, the existing literature stressed high initial investment costs consistently emerge as the most frequently cited obstacle for SMEs (Ashish Mankar et al., 2024; Balasubramanian et al., 2020; Gusmao Brissi & Debs, 2023; Robeiro & Love, 2003; Scipioni et al., 2021). To overcome this, SMEs are encouraged to adopt incremental implementation approaches, seek government grants or green financing schemes, and leverage collaborative procurement models that allow cost and resource-sharing with partners. Secondly, SP requires expertise knowledge and technical infrastructure (Ashish Mankar et al., 2024; Scipioni et al., 2021). SMEs should therefore invest in internal capacity-building through targeted training and upskilling initiatives. Where external training costs are prohibitive, SMEs may prioritise low-cost internal training, peer-learning networks, or participation in industry-led workshops that provide accessible knowledge resources. Thirdly, SMEs need to put more effort into maintaining partnerships with industry associations, and technology providers to overcome resource

and development constraints (Cyfert et al., 2024). Despite these challenges, SMEs' ability to adopt radical changes support transition of business towards sustainability when proactive measures are taken (Scipioni & Niccolini, 2021). Industry bodies in construction can also use the proposed ISs to promote sustainable practices and researchers are presented with enhancing opportunities on contributing to the body of knowledge systematically and effectively.

## 5. CONCLUSIONS

This study conducted a systematic review of existing literature on SP in construction. A total of 12 ISs were retrieved for SP implementation in construction SMEs from literature. Moreover, this review enables the identification of several important gaps in the existing literature. First, it highlights that project- and site-specific measures, as well as the strategic use of project power structures, have received comparatively little attention as effective implementation strategies for sustainable procurement. Second, clients can encourage SMEs adopting these ISs through enforcement of mandatory sustainability clauses in tender submissions and engage SMEs from early stages. Together, these observations point to clear opportunities for future research to explore these underexamined areas and to advance both theoretical understanding and practical application. This study also has its limitations. It performed through a single database and included only peer-reviewed papers, excluding other valuable sources such as grey literature. Although Scopus is a widely recognised database that indexes high-quality publications, relying solely on this source may limit access to the full breadth of potentially relevant literature. Replicating this review using multiple databases and broader literature sources is therefore recommended. One key limitation is the absence of empirical evidence, like other literature reviews. Hence, it could be the starting point for future research to empirically validate the proposed implementation strategies.

## 6. REFERENCES

2020 Global Status Report for Buildings and Construction towards a Zero-emissions, efficient and Resilient Buildings and Construction sector. (2020). In *Global ABC*. Retrieved July 7, 2026, from https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf

Adekunle, S. A., Aigbavboa, C., Ejohwomu, O., Ikuabe, M., & Ogunbayo, B. (2022). A critical review of maturity model development in the digitisation era. *Buildings 12*(6). https://doi.org/10.3390/buildings12060858

Adzivor, E. K., Emuze, F., & Das, D. K. (2023). Indicators for safety culture in SME construction firms: a Delphi study in Ghana. *Journal of Financial Management of Property and Construction*, *28*(3), 293–316. https://doi.org/10.1108/JFMPC-04-2022-0020

Alnhoud, O. T., Shaqadan, A., & Alkasasbeh, R. (2021). Developing framework for safety analysis and risk assessment in construction site environment in Jordan. *Structural Integrity and Life*, *21*(2), 135–145. http://divk.inovacionicentar.rs/ivk/ivk21/135-IVK2-2021-OTA-AS-RA.pdf

Arvizu-Piña, V. A., & Cuchí Burgos, A. (2017). Promoting sustainability in Mexico's building sector via environmental product declarations. *International Journal of Life Cycle Assessment*, *22*(11), 1744–1759. https://doi.org/10.1007/s11367-017-1269-z

Ashish Mankar, V., Vichoray, C., & Shukla, H. (2024). Sustainable Supply Chain Management in SMEs: Analyzing Drivers and Barriers to Green Practices in Nagpur. *Nanotechnology Perceptions*, *20*(S7), 1133–1140. www.nano-ntp.com

Balasubramanian, S., Shukla, V., & Chanchaichujit, J. (2020). Firm size implications for environmental sustainability of supply chains: evidence from the UAE. *Management of Environmental Quality: An International Journal*, *31*(5), 1375–1406. https://doi.org/10.1108/MEQ-01-2020-0004

Baral, M. M., Singh, R. K., & Kazançoğlu, Y. (2023). Analysis of factors impacting survivability of sustainable supply chain during COVID-19 pandemic: an empirical study in the context of SMEs. *International Journal of Logistics Management*, *34*(4), 935–961. https://doi.org/10.1108/IJLM-04-2021-0198

Bernaciak, A., Halaburda, M., & Bernaciak, A. (2021). The construction industry as the subject of implementing corporate social responsibility (The case of Poland). *Sustainability (Switzerland)*, *13*(17). https://doi.org/10.3390/su13179728

Briner, R. B., & Denyer, D. (2012). Systematic review and evidence synthesis as a practice and scholarship tool. In *The Oxford Handbook of Evidence-Based Management* (pp. 112–129). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199763986.001.0001

Briscoe, G., Dainty, A. R. J., & Millett, S. (2001). Construction supply chain partnerships: skills, knowledge and attitudinal requirements. *European Journal of Purchasing & Supply Management*, *7*, 243–255. http://www.cf.ac.uk/masts/

Charkaoui, A. (2025). Developing a Sustainable Procurement Performance Index based on ISO 20400 Standard: A Structural Equation Modelling Approach. *Journal of Optimization and Supply Chain Management*, *2*(3), 198–214. https://doi.org/10.22034/ISS.2025.9021.1034

Cyfert, S., Szumowski, W., & Glabiszewski, W. (2024). Building SME performance through relationship quality. The role of supply chain flexibility. *Logforum*, *20*(1), 71–80. https://doi.org/10.17270/J.LOG.000946

Dey, P. K., Ho, W., Charoenngam, C., & Deewong, W. (2008). Relationship characteristics within the supply chain of small and medium-sized construction enterprises in Thailand. *Int. J. Manufacturing Technology and Management*, *15*(1), 102–118. https://doi.org/10.1504/IJMTM.2008.018242

Di Giuda, G. M., Giana, P. E., & Pattini, G. (2020). The shortening and the automation of payments: The potentiality of smart contract in the aeco sector. *Proceedings of International Structural Engineering and Construction*, *7*(2). https://doi.org/10.14455/ISEC.2020.7(2).CON-12

Durach, C. F., Kembro, J., & Wieland, A. (2017). A New Paradigm for Systematic Literature Reviews in Supply Chain Management. *Journal of Supply Chain Management*, *53*(4), 67–85. https://doi.org/10.1111/jscm.12145

Erasmus, P., & Iyer-Raniga, U. (2022). Sustainability in Construction Procurement. In W. Leal Filho, A.M. Azul, L Brandli, P. G. Özuyar, T. Wall (Ed.), *UN Sustainable Development Goals* (pp. 1–10). Responsible Consumption and Production. https://doi.org/10.1007/978-3-319-71062-4_105-1

Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. (2021). Barriers to achieving sustainable construction project procurement in the private sector. *Cleaner Engineering and Technology*, *3*. https://doi.org/10.1016/j.clet.2021.100125

Garoghan, S., Adewumi, A. S., Ofetotse, E. L., Onyango, V., & Dawodu, A. (2025). Enhancing sustainable waste management strategies for small and medium-sized enterprises: a focus on commercial refurbishment projects in the United Kingdom. *Frontiers in Built Environment*, *11*. https://doi.org/10.3389/fbuil.2025.1469398

Glass, J., Achour, N., Parry, T., & Nicholson, I. (2012). Engaging small firms in sustainable supply chains: responsible sourcing practices in the UK construction industry. *Int. J. Agile Systems and Management*, *5*(1), 29–58. http://www.responsible-sourcing.co.uk/

Gusmao Brissi, S., & Debs, L. (2023). Principles for adopting offsite construction in design and construction companies focused on multifamily projects in the USA. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-03-2022-0262

Han, Y., Skibniewski, M. J., & Wang, L. (2017). A market equilibrium supply chain model for supporting self-manufacturing or outsourcing decisions in prefabricated construction. *Sustainability (Switzerland)*, *9*(11). https://doi.org/10.3390/su9112069

Kelly, M., Burke, K., & Gottsche, J. (2019). Exploring material circularity opportunities for a construction-SME on small-scale projects in Ireland. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012066

Khouja, A., Lehoux, N., Cimon, Y., & Cloutier, C. (2021). Collaborative interorganizational relationships in a project-based industry. *Buildings*, *11*(11). https://doi.org/10.3390/buildings11110502

Ko, H. S., Azambuja, M., & Felix Lee, H. (2016). Cloud-based Materials Tracking System Prototype Integrated with Radio Frequency Identification Tagging Technology. *Automation in Construction*, *63*, 144–154. https://doi.org/10.1016/j.autcon.2015.12.011

Korpela, K., Mikkonen, K., Hallikas, J., & Pynnonen, M. (2016). Digital business ecosystem transformation - Towards cloud integration. *Proceedings of the Annual Hawaii International Conference on System Sciences*, *2016-March*, 3959–3968. https://doi.org/10.1109/HICSS.2016.491

Lukson, E. E., Ranadewa, K. A. T. O., Parameswaran, A., Wijerathna, M. R. D. P., & Kodituwakku, D. (2024). Integrated project delivery implementation among construction SMEs in Sri Lanka: barriers and strategies. *12th World Construction Symposium - 2024*, 619–633. https://doi.org/10.31705/WCS.2024.49

Manu, E., Ankrah, N., Chinyio, E., & Proverbs, D. (2015). Trust influencing factors in main contractor and subcontractor relationships during projects. *International Journal of Project Management*, *33*(7), 1495–1508. https://doi.org/10.1016/j.ijproman.2015.06.006

Michna, A., Kmieciak, R., & Czerwinska-Lubszczyk, A. (2020). Dimensions of intercompany cooperation in the construction industry and their relations to performance of SMEs. *Engineering Economics*, *31*(2), 221–232. https://doi.org/10.5755/j01.ee.31.2.21212

Nagariya, R., Kumar, D., & Kumar, I. (2021). Service supply chain: from bibliometric analysis to content analysis, current research trends and future research directions. *Benchmarking*, *28*(1), 333–369. https://doi.org/10.1108/BIJ-04-2020-0137

Nangpiire, C., Gyebi, F. O., & Nasse, T. (2024). Sustainable Procurement Practices and Organisational Performance of Small and Medium Enterprises in Ghana. *International Journal of Economics and Financial Issues*, *14*(1), 95–106. https://doi.org/10.32479/ijefi.15444

Opoku, A., Deng, J., Elmualim, A., Ekung, S., Hussein, A. A., & Buhashima Abdalla, S. (2022). Sustainable procurement in construction and the realisation of the sustainable development goal (SDG) 12. *Journal of Cleaner Production*, *376*. https://doi.org/10.1016/j.jclepro.2022.134294

Oyegoke, A. S., Fisher, B. W., Ajayi, S., Omotayo, T. S., & Ewuga, D. (2024). The disruptive factors and longevity effects of Covid-19 and Brexit on the SMEs construction supply chain in the UK. *Journal of Financial Management of Property and Construction*, *29*(1), 115–134. https://doi.org/10.1108/JFMPC-11-2022-0057

Qi, G. Y., Shen, L. Y., Zeng, S. X., & Jorge, O. J. (2010). The drivers for contractors' green innovation: An industry perspective. *Journal of Cleaner Production*, *18*(14), 1358–1365. https://doi.org/10.1016/j.jclepro.2010.04.017

Ratnayake, M. R. I. U. K., Wijerathna, M. R. D. P., Ranadewa, K. A. T. O., & Perera, B. A. K. S. (2025). A scoping review of construction SMEs: Global vs local. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 13th World Construction Symposium, 15-16 August 2025, Sri Lanka.* pp. 69-82. https://doi.org/10.31705/WCS.2025.6.

Robeiro, F. L., & Love, P. E. D. (2003). Value creation through an e-business strategy: implication for SMEs in construction. *Construction Innovation*, *3*, 3–14. https://doi.org/10.1191=1471417503ci043oa

Ruparathna, R., & Hewage, K. (2015). Sustainable procurement in the Canadian construction industry: Current practices, drivers and opportunities. *Journal of Cleaner Production*, *109*, 305–314. https://doi.org/10.1016/j.jclepro.2015.07.007

Salvador, R., Søberg, P. V., Jørgensen, M. S., Schmidt-Kallesøe, L. L., & Larsen, S. B. (2023). Explaining sustainability performance and maturity in SMEs – Learnings from a 100-participant sustainability innovation project. *Journal of Cleaner Production*, *419*. https://doi.org/10.1016/j.jclepro.2023.138248

Sarvari, H., Chan, D. W. M., Alaeos, A. K. F., Olawumi, T. O., & Abdalridah Aldaud, A. A. (2021). Critical success factors for managing construction small and medium-sized enterprises in developing countries of Middle East: Evidence from Iranian construction enterprises. *Journal of Building Engineering*, *43*. https://doi.org/10.1016/j.jobe.2021.103152

Scipioni, S., & Niccolini, F. (2021). How to close the loop? Organizational learning processes and contextual factors for small and medium enterprises' circular business models introduction. *Italian Journal of Management*, *39*(3), 141–162. https://doi.org/10.7433/s116.2021.08

Scipioni, S., Russ, M., & Niccolini, F. (2021). From barriers to enablers: The role of organizational learning in transitioning smes into the circular economy. *Sustainability (Switzerland)*, *13*(3), 1–32. https://doi.org/10.3390/su13031021

Seuring, S., & Gold, S. (2012). Conducting content-analysis based literature reviews in supply chain management. *Supply Chain Management*, *17*(5), 544–555. https://doi.org/10.1108/13598541211258609

Stiles, S., Ryan, B., & Golightly, D. (2019). Readiness to Change: Perceptions of Safety Culture up and down the Supply Chain. In S. Bagnara et al. (Ed.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)* (Vol. 819, pp. 213–223). Springer Verlag. https://doi.org/10.1007/978-3-319-96089-0_24

Taggart, M., Koskela, L. K., & Rooke, J. A. (2014). An improvement strategy for the defects and rework management process within an SME: An action research. In A. B. Raiden & E. Aboagye- Nimo (Eds.), *In: Proceedings of the 30th Annual ARCOM Conference.* (pp. 1059–1068). Association of Researchers in Construction Management. http://eprints.hud.ac.uk/id/eprint/26210/http://eprints.hud.ac.uk/

Taherdoost, H. (2023). Towards nuts and bolts of conducting literature review: A typology of literature review. *Electronics (Switzerland) 12*(4). https://doi.org/10.3390/electronics12040800

Tezel, A., Taggart, M., Koskela, L., Tzortzopoulos, P., Hanahoe, J., & Kelly, M. (2020). Lean construction and BIM in small and medium-sized enterprises (SMEs) in construction: A systematic literature review. *Canadian Journal of Civil Engineering*, *47*(2), 186–201. https://doi.org/10.1139/cjce-2018-0408

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review*. In *British Journal of Management* (Vol. 14).

Upstill-Goddard J, Glass J, Dainty A.R.J, & Nicholson, I. (2012). Integrating responsible sourcing in the construction supply chain. In S. D. Smith (Ed.), *Proceedings of 28th Annual ARCOM Conference* (pp. 1311–1319). Association of Researchers in Construction Management.

Vitkauskaite, E., & Gatautis, R. (2008). e-Procurement perspectives in construction sector SMEs. *Journal of Civil Engineering and Management*, *14*(4), 287–294. https://doi.org/10.3846/1392-3730.2008.14.28

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A systematic review of digital technology adoption in off-site construction: Current status and future direction towards industry 4.0. *Buildings*, *10*(11), 1–29. https://doi.org/10.3390/buildings10110204

Wedawatta, G., Ingirige, B., & Amaratunga, D. (2010). Building up resilienc e of construction sector SMEs and their supply chains to extreme weather events. In *International Journal of Strategic Property Management* 14(4), 362–375. https://doi.org/10.3846/ijspm.2010.27

Wirahadikusumah, R., Abduh, M., & Messah, Y. (2020). Framework for Sustainable Procurement - Identifying Elements for Construction Works. *Applied Mechanics and Materials*, *897*, 245–249. https://doi.org/10.4028/www.scientific.net/amm.897.245

Xia, B., Olanipekun, A., Chen, Q., Xie, L., & Liu, Y. (2018). Conceptualising the state of the art of corporate social responsibility (CSR) in the construction industry and its nexus to sustainable development. *Journal of Cleaner Production*, *195*, 340–353. https://doi.org/10.1016/j.jclepro.2018.05.157

Yu, A. T. W., Yevu, S. K., & Nani, G. (2020). Towards an integration framework for promoting electronic procurement and sustainable procurement in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *250*. https://doi.org/10.1016/j.jclepro.2019.119493

Bandara, W.M.P.M., Waidyasekara, K.G.A.S. and Ranasinghe, P.H.G.M.A., 2026. From waste to use: Plywood usage and wastage in slab and beam construction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 855-869. DOI: https://doi.org/10.31705/WCS.2026.63. Available from: https://ciobwcs.com/papers/

# FROM WASTE TO USE: PLYWOOD USAGE AND WASTAGE IN SLAB AND BEAM CONSTRUCTION

**W.M.P.M. Bandara[1], K.G.A.S. Waidyasekara[2] and P.H.G.M.A. Ranasinghe[3]**

## *ABSTRACT*

*Plywood formwork is widely used in reinforced concrete slabs and beams construction due to its flexibility, availability, and ability to produce smooth finishes. Nonetheless, a considerable amount of plywood is usually wasted on the construction sites due to inefficient operations such as cutting, recurring reuses, improper stripping, and improper handling. This results in increased material consumption, higher project costs, and greater construction waste, particularly in large-scale projects. Despite its widespread application, limited research has examined plywood usage and wastage in real construction settings, especially in developing countries such as Sri Lanka. This paper presents plywood usage practices and associated wastage in slab and beam formwork in projects undertaken by major contractors in Sri Lanka. A case study strategy was adopted, involving five case studies of large-scale construction projects. Data were collected through semi-structured interviews, site observations, and document reviews, and analysed using cross-case analysis. The results show that plywood is primarily used for slab soffits and beam sides formwork, with an average reuse life of three to five cycles, depending on material quality, level of supervision, and labour handling practices. Offcuts generated during the cutting processes were identified as the major source of plywood waste, while damaged sheets mainly occur during stripping and repeated use. The paper explains the improved supervision, the planning of cutting layout, and better material handling practices to enhance reuse cycles and minimise waste. These findings provide practical guidance for contractors and policymakers to improve resource efficiency and promote more sustainable construction practices in large-scale projects.*

***Keywords:*** *Construction Waste; Material Reuse; Plywood Formwork; Reuse Cycles Slab and Beam.*

## 1. INTRODUCTION

The construction industry is the largest user of natural resources and the most significant producer of construction and demolition (C&D) waste on the planet, and the wood-based formwork is often regarded as one of the most popular types of waste materials that are deposited on the construction site (Kurniawan et al., 2024; Victar & Waidyasekara, 2023). According to Tighnavard et al. (2024), temporary works, such as formwork, consume a

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, bandarawmpm.21@uom,lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ranasinghephgma.20@uom.lk

lot of wood and plywood and have limited reuse, with lower reuse cycles, which is resulting in monetary loss and environmental liability. Plywood concrete formwork also embodies significant embodied greenhouse gas emissions due to the energy-intensive manufacture and use of resin and coatings (Pronk et al., 2022).

In reinforced concrete construction, slab soffits and beam sides are commonly built using plywood since it has an effective strength-to-weight ratio, workability and smooth finishes, and is prevalent in formwork selections in many high-rise and large-scale construction (Rajeshkumar et al., 2021; Tighnavard et al., 2024). Nevertheless, site-level analyses and surveys indicate that timber and plywood formwork are typically reused only a few times, generally around 3 to 4 cycles, after which they are disposed of through burning or landfill and this suggests that a significant proportion of procured boards ultimately ends up as waste (Pronk et al., 2022; Victar & Waidyasekara, 2023).

The design-related and operational factors have a strong impact on the efficiency of plywood utilization (Ajayi & Oyedele, 2018). Moreover, research highlights that dimensional mismatches between structural layouts and standard material sizes are a key root cause of construction waste, and that designing to standard module sizes is one of the most effective strategies for "designing out" waste at source (Ajayi & Oyedele, 2018). On-site operational aspects, such as labour skills, supervision, and material handling practices, are repeatedly found to be driving forces behind the generation of construction waste (Salah et al., 2025).

Although construction waste management has attracted growing attention, most research examines construction waste at the aggregate level or focuses on permanent materials, with relatively few studies isolating temporary materials, such as plywood formwork, as a distinct waste stream (Albsoul et al., 2025). Broader studies on Sri Lankan C&D waste highlight numerous management issues across project life-cycle stages; however, they do not provide detailed evidence on plywood formwork use, reuse, and associated wastage in structural works (Victar & Waidyasekara, 2023). Moreover, the rapid growth of large-scale construction projects has intensified C&D waste generation in the country, while wood waste continues to be primarily managed through open dumping, landfilling, and incineration (Maduwage et al., 2025; Victar & Waidyasekara, 2023). In Sri Lanka, large-scale construction projects are defined based on Construction Industry Development Authority (CIDA) grading thresholds and public investment criteria. These typically include projects with a total estimated cost exceeding Rs. 250 million. Such projects align with contractor grades C1 to CS2, which can handle tenders ranging from Rs. 600 million to over Rs. 6,000 million (Construction Industry Development Authority, 2021; Ministry of Finance, 2025).

Although previous studies have discussed construction waste management, timber reuse, and CLT applications, limited research has specifically examined plywood formwork waste as a distinct waste stream within the Sri Lankan construction industry. Given the heavy reliance on plywood formwork in Sri Lankan concrete construction and the absence of systematic project-scale data on its utilisation and wastage, a clear research gap exists (Maduwage et al., 2025; Victar & Waidyasekara, 2023). Therefore, this study aims to investigate plywood usage practices and wastage patterns in slab and beam formwork within large-scale construction projects undertaken by major contractors in Sri Lanka using a cross-case study analysis, while contributing towards sustainable construction and circular economy practices.

## 2. LITERATURE REVIEW

Construction and demolition (C&D) waste is a major global waste stream that drives project cost overruns, excessive raw material consumption, environmental degradation, and public-health risks (Lee et al., 2024; Tafesse et al., 2022). Moreover, international reviews and scient metric analyses confirm that C&D waste has significant environmental impacts across the project life cycle and is now a central focus of sustainable construction policy and research (Chen et al., 2021; Islam et al., 2024). Furthermore, Mohammad (2025) stated that in developing countries, weak waste governance and limited monitoring further exacerbate these impacts at the project level.

In this broader context, formwork is a serious temporary system in reinforced concrete construction, which directly affects structural elements and considers a significant portion of the construction cost and consumption of materials (Devi & Yadav, 2023). According to Setiawan et al. (2025), conventional practice uses timber and plywood formwork to erect slabs and beams, which are assembled, stripped and moved around in the construction cycle. Moreover, case-based assessments indicate that variance between cost budget plans, unit rate analysis and actual purchases of timber and plywood tend to reflect excessive ordering, under-recorded reuse, and concealed wastage in column and beam formwork (Sidiq et al., 2025; Setiawan et al., 2025).

Plywood has been widely used as a sheathing material since it provides a good strength-to-weight ratio, handling, and concrete surface finish (Devi & Yadav, 2023). Nevertheless, the life cycle studies and the circular economy studies have shown that concrete formwork with plywood has significant embodied greenhouse gas emissions due to manufacturing energy and the consumption of resin, which implies that wastage increases the environmental and economic costs (Papamichael et al., 2023; Tighnavard et al., 2024). Additionally, comparative Life Cycle Assessment (LCA) of reusable formwork materials demonstrates that under high reuse cycles, plastic and steel formwork can be better than plywood in a combination of environmental and cost indicators, but findings are highly sensitive to the real reuse rates and wear-out behaviour at the site (Baskaran et al., 2025; Tighnavard et al., 2024).

At the technical level, experimental work on plywood for concrete formwork has examined how repeated use affects material properties and concrete surface quality (Aramaki et al., 2021; Papamichael et al., 2023). Aramaki et al. (2021) further stated that, with increasing reuse (up to about four cycles), bending strength and stiffness decline, while surface roughness rises, which in turn affects gloss, colour uniformity, and water absorption of the resulting concrete surface. According to Papamichael et al. (2023), softwood plywood is commonly used across foundations, walls, slabs, and columns, often without systematic optimisation of panel thickness, grade, or reuse planning for different elements. Furthermore, these patterns suggest that the inherent reuse potential of plywood is not fully realised, and that many panels are discarded earlier than technically necessary, becoming a notable component of structural wood waste (Aramaki et al., 2021; Setiawan et al., 2025).

Overall, literature indicates that although plywood formwork has a wide range of applications in the reinforcement of concrete constructions because of its convenient benefits, the reuse potential of this material is not always met in real-life situations (Devi & Yadav, 2023). Increased reuse cycles with inefficient practices in site management, handling, and storage are also associated with high material waste and environmental and

economic negative effects (Kothalawala et al., 2025). This shows that plywood formwork is still a significant waste of construction in large-scale projects, especially when there is no effective waste management and reuse policies need to be implemented.

## 3. RESEARCH METHODOLOGY

The case study strategy was selected as it allows an in-depth investigation of real construction practices within their practical project environments while enabling comparisons across multiple projects (Sanda et al., 2021). Five large-scale building construction projects (C1–C5) were purposively selected from ongoing building construction projects in Sri Lanka to represent different project types, including commercial, residential, and infrastructure-related developments. All of the selected building projects were contracted under the CIDA CS2 grading category. The projects were selected based on their high usage of plywood in slab and beam formwork operations, accessibility for data collection, and relevance to the research objectives. The selected projects were actively under construction during the data collection period, enabling the observation of real-time plywood usage, handling, reuse, and wastage practices across different construction environments. The selection of five case studies was considered adequate as repetitive patterns and consistent findings related to plywood usage and wastage practices were observed across the projects, indicating data saturation (Guest et al., 2006). The key characteristics of the selected case study projects are presented in Table 1.

*Table 1 : Summary of selected case study projects*

| Case Study | Project Duration | Project Cost (Mn) | Contract Type | Location | Type of project |
|---|---|---|---|---|---|
| C1 | 36 Months | 23000 | Measure and pay | Kandy, Sri Lanka | Building projects within the civil construction |
| C2 | 24 Months | 1700 | Measure and pay | Colombo 03, Sri Lanka | Commercial Building |
| C3 | 18 Months | 850 | Measure and pay | Colombo 06, Sri Lanka | Commercial Building |
| C4 | 24 Months | 13600 | Measure and pay | Colombo 08, Sri Lanka | Government Administrative Building |
| C5 | 36 Months | 1300 | Lump sum | Wadduwa, Sri Lanka | Apartment Building Project |

Data collection for the study was primarily carried out through semi-structured interviews with construction professionals and site personnel directly involved in formwork operations. In addition, site observations and document reviews were conducted to collect information related to plywood usage, handling practices, reuse methods, and wastage generation on construction sites. The interview participants included Project Managers (PM), Quantity Surveyors (QS), Site Engineers (EN), Technical Officers (TO), Quality Assurance personnel (QA), Operation Engineers (OE), and Formwork Carpenters or Gang Leaders (F). The interviewees were selected from each case study to capture both managerial-level and operational-level perspectives related to plywood usage practices

and associated wastage onsite. Moreover, QSs were included as participants because they are involved in material quantity assessment, wastage evaluation, cost monitoring, and verification of plywood usage related to formwork operations on construction sites. The interview guideline for the interviews are mainly focused on plywood usage practices, procurement methods, reuse cycles, treatment practices, wastage generation, storage conditions, disposal methods, and waste reduction strategies related to slab and beam formwork. The distribution of interview respondents across the five case studies is summarised in Table 2.

*Table 2: Distribution of interviewees across case study projects*

| Case Study Interviews | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| Project Manager (PM) | PM1-C1/ PM2-C1 | _ | _ | _ | _ |
| Quantity Surveyor (QS) | QS-C1 | QS-C2 | QS-C3 | QS-C4 | QS-C5 |
| Site Engineer (EN) | _ | EN-C2 | EN-C3 | EN1-C4/EN2-C4 | EN1-C5 / EN2-C5 |
| Technical Officer (TO) | _ | TO-C2 | _ | _ | _ |
| Quality Assurance (QA) | _ | _ | QA-C3 | _ | _ |
| Operation Engineer (OE) | _ | _ | _ | OE-C4 | _ |
| Formwork Carpenter / Gang Leader (F) | F1-C1/ F2-C1 | F1-C2 / F2-C2 | F1-C3 / F2-C3 | F1-C4 / F2-C4 | F1-C5 / F2-C5 |

The collected interview data were analysed using cross-case analysis, which allows comparison of plywood usage practices, operational challenges, and waste generation patterns across different construction projects. Through this comparative analysis, the study was able to identify recurring operational factors influencing plywood wastage in slab and beam formwork within large-scale construction projects in Sri Lanka.

# 4. DATA ANALYSIS AND FINDINGS

As per the main themes identified through the case study interviews, this section analyses the key practices and factors influencing plywood usage and associated wastage in slab and beam formwork, and challenges using cross-case comparison.

## 4.1 PLYWOOD USAGE PRACTICES

Across five case studies, plywood usage is also largely concentrated on slab and beam formwork, particularly for slab soffits and beam sides during structural works. PM1-C1 explained, *"Plywood is primarily used in structural formwork, with significant application in slab and beam construction."* Similarly, TO-C2 mentioned that plywood is used especially for basement slabs to transfer floors, including lift walls and lintels. In case 4, EN1-C4 and F1-C3 mentioned that plywood was also observed in secondary applications such as temporary site huts, retaining works, site protection elements, and temporary coverings. However, slab and beam formwork remained the primary source of plywood usage and wastage considered in these projects as per the interviewees.

*Figure 1 : Typical use of plywood in large-scale construction projects*

## 4.2 PROCUREMENT AND RECORDING PRACTICES

Across the five cases (C1–C5), plywood usage is recorded through store systems, material issue records, or procurement databases, while associated wastage is rarely measured separately. Moreover, the study revealed that wastage is typically managed through assumed percentages, reuse cycle estimates, or reconciliation methods. For instance, PM1-C1 stated *"we record the usage, but we don't record the wastage specifically because we already allow the wastage percentage, and it is time-consuming to calculate."* Similarly, QS-C2 explained *"we have records of the usage from stores, but wastage is not recorded because formwork is given to subcontractors."* In some cases, digital systems assist monitoring; QS-C1 mentioned *"wastage is calculated through the ERP system by deducting the issued material from the net quantity."* In Case 5, QS-C5 stated *"we use reconciliation for wastage calculations, but it is not 100% accurate because calculating wastage for formwork is not practical."* Technical respondents also highlighted the practical difficulty of measuring wastage directly, as EN1-C4 noted *"wastage is not measured separately because it is not practical to calculate physical wastage on site."* Overall, usage in large-scale projects is systematically tracked through procurement systems, while wastage is mainly managed through allowances and lifecycle considerations. In terms of procurement, projects often purchase large quantities (approximately 1000–2500 plywood boards) during the initial slab cycles, with further orders based on reuse cycles and site progress. Figure 2 shows how procurement and recording practices happen in the sites.

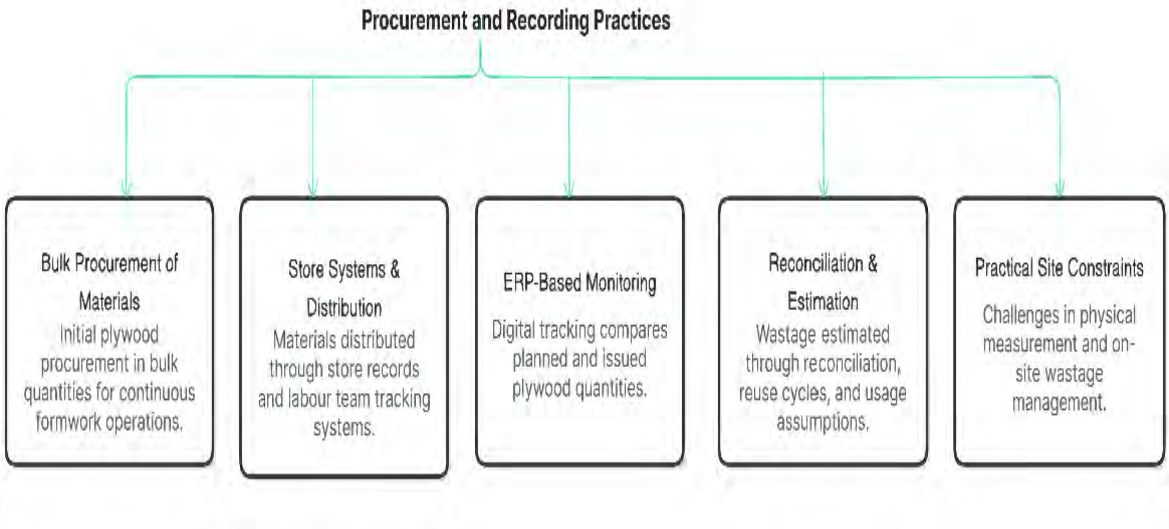



*Figure 2: Procurement and recording practices of plywood*

## 4.3 MATERIAL SPECIFICATION AND TECHNICAL SELECTION

Across the five case studies, plywood selection showed greater variation, although slab and beam formwork remained the primary application. Many respondents indicated the use of film-faced (coated) plywood because of its durability and better concrete finish. For instance, PM1-C1 mentioned, *"film-faced plywood is mainly used because it provides a good concrete finish and higher reuse cycles."* However, normal shuttering plywood was still used in some projects for cost reasons. EN-C2 emphasised, *"Sanstha shuttering boards are sometimes selected because they are more cost-effective even though coated boards perform better."* In case 4, Merbok film-faced plywood was used for its high reuse potential, although respondents noted that cut edges can be vulnerable to moisture. Generally, 15 mm-thickness boards and the standard size of 1220 × 2440 mm were commonly used. Overall, the findings indicate that material selection in large-scale projects balances durability, cost, and reuse potential, depending on project requirements and site conditions.

## 4.4 REUSE CYCLES AND LIFECYCLE PERFORMANCE

It is noted that plywood boards were generally reused around 3–5 cycles in all cases, although the reuse rate varied depending on material quality, supervision, and handling practices. Larger slab areas required approximately 800–1500 plywood sheets per slab cycle, reflecting the scale of structural works. New plywood boards were mainly used for the first slab, while later cycles involved a combination of new and reused boards. PM1-C1 stated *"plywood can normally be reused about five times, but it depends on supervision during handling and removal."* Another observation was reported in C4, where Merbok film-faced plywood allowed significantly higher reuse cycles. QS-C4 stated *"Merbok boards can be reused around 10–15 times, while normal plywood is usually reused only about 3–4 times."* Overall, plywood lifecycle performance in large-scale projects is influenced by board quality, supervision, and reuse strategies adopted during successive slab cycles.

## 4.5 TREATMENT PRACTICES AND THEIR EFFECTIVENESS

The study revealed that mould oil (form oil) was the primary treatment used for plywood formwork. The oil was generally applied after installing the formwork to prevent the boards from sticking to concrete during striping. For example, PM1-C1 explained *"mould oil is applied after placing the plywood formwork so that the boards do not stick to the concrete during removal."* Similarly, QS-C2 mentioned *"the oil helps increase reusability and reduce damage to the plywood when removing the slab formwork."* Some respondents also mentioned that the treatment reduces water absorption and improves board durability during repeated reuse cycles. In one case, EN-C5 stated *"burnt oil can sometimes be used instead of mould oil, but petrol-based oil is better while diesel-based oil is not recommended."* Overall, treatment practices in large-scale projects serve as a preventive strategy to improve stripping efficiency, protect plywood surfaces, and extend reuse cycles.

## 4.6 WASTE GENERATION PATTERNS

Across the five cases (C1–C5), based on respondents, plywood wastage percentage of 10–15% represents the estimated proportion of plywood material wasted in relation to the total plywood quantity procured and used for formwork operations on the construction

site which varied depending on slab geometry, reuse cycles, and labour handling practices. PM1-C1 explained *"for the initial slabs it is around ten to fifteen percent, but if the structure repeats, the wastage can reduce to around five to ten percent for subsequent slabs."* However, EN-C3 noted that wastage may increase after several reuse cycles as boards begin to deteriorate. Quantity Surveyors reported relatively lower wastage values based on reconciliation estimates. For instance, QS-C1 stated *"three to five percent for slabs and overall wastage is about ten percent,"* while QS-C3 indicated *"around five to ten percent."* Offcuts were consistently identified as the dominant type of plywood waste, mainly produced during cutting operations for slab edges and beam sides. Several respondents also reported damaged sheets after stripping or repeated reuse cycles, particularly when boards are reused multiple times. Overall, the findings suggest that cutting activities and repeated reuse cycles are the main contributors to plywood waste generation, with the most common waste type remaining. Figure 3 illustrates the summary of the waste generation patterns as discussed above.

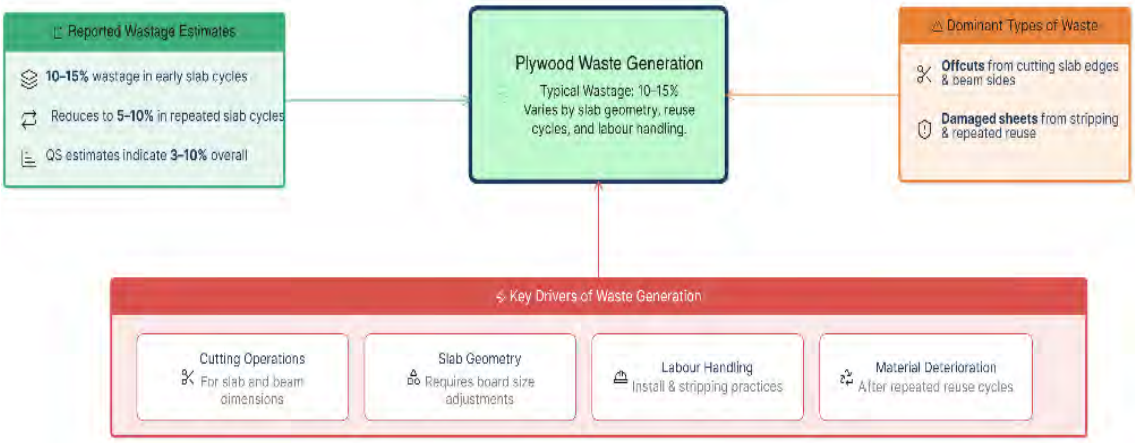



*Figure 3: Plywood waste generation and key drivers*

## 4.7 DAMAGE CLASSIFICATION AND REUSE STRATEGY

Across the five cases (C1–C5), plywood boards were also classified based on damage severity after stripping operations, generally under major and moderate damage categories. Major damage included cracking, sagging, severe layer peeling, delamination, and water-related deterioration, and such boards were usually disposed of. PM1-C1 highlighted *"major damages are like layers ripping off, cracks in the board, or sagging, and those boards are usually disposed."* In contrast, boards with minor damage, such as broken edges or surface wear were trimmed and reused for smaller elements, including beam sides, lintels, or temporary works. EN-C3 explained *"boards are assessed based on physical condition, and minor layer peeling is trimmed and reused for smaller works."* In most projects, reuse decisions were made through visual inspection by supervisors and labour teams, as highlighted by QS-C4, boards are inspected visually, and sheets with delamination or structural deformation are disposed while moderately damaged boards are trimmed and reused. Some respondents also noted material-specific behavior, where Merbok plywood can become brittle after several reuse cycles, increasing the likelihood of breakage. Overall, damage classification in large-scale projects relies mainly on visual inspection and practical reuse decisions, with an emphasis on maximizing material utilization before disposal. Figure 4 illustrates the common type of damaged plywood formwork on construction sites.

*Figure 4: Damaged and discarded plywood formwork after reuse cycles*

## 4.8 OPERATIONAL CAUSES AND TASKS OF WASTE

As discussed, plywood waste generation was also mainly influenced by slab geometry, labor handling practices, and operational formwork activities. Several respondents highlighted that dimensional mismatches between slab layouts and standard board sizes require frequent cutting, which produces offcuts. PM1-C1 stated *"the main cause is the changes of the design of the different slabs,"* similarly EN-C3 stated *"slab geometry and dimensional mismatch with standard board sizes require cutting adjustments."* Labour handling during stripping was also identified as a major cause of plywood damage. F1-C3 explained *"Sometimes labourers remove boards roughly with crowbars and damage the plywood."* Similarly, QS-C4 emphasized *"cutting plywood sheets to match slab and beam dimensions produces the highest amount of waste."* Overall, respondents agreed that cutting operations and formwork removal (de-shuttering) are the main tasks generating plywood waste, demonstrating that design requirements and human handling practices are key operational drivers of waste in large-scale projects. Figure 5 illustrates the key operational processes and site-level factors contributing to plywood waste generation, including cutting operations, handling practices, and de-shuttering activities.

*Figure 5: Operational causes of plywood waste generation in slab and beam formwork*

## 4.9 STORAGE AND SITE CONSTRAINTS

It is noted that plywood boards were also mainly stored using covered tarpaulin protection combined with more organized storage arrangements. PM1-C1 mentioned *"plywood is mainly covered with tarpaulin without touching the ground,"* while EN-C2 explained *"the boards are stored covered with tarpaulin."* In several projects, plywood was additionally stored in designated site stores or storage areas, providing better protection from weather conditions. QA-C3 highlighted "*plywood is stored both in the store and on site, covered with tarpaulin,"* while QS-C5 mentioned that boards are often kept inside

site stores. Overall, the findings show that although tarpaulin-covered storage remains the common practice, large-scale projects are more likely to use dedicated storage spaces, which helps protect material stock and maintain plywood reuse potential.

### 4.10 DISPOSAL PRACTICES AND END-OF-LIFE HANDLING

Across the five cases (C1–C5), plywood boards were mainly disposed of through dump yards once they reached the end of their usable life. Several respondents confirmed this approach. For instance, PM1-C1 noted that boards are *"dumped to dump yards,"* while QS-C2 also explained that damaged boards are *"disposed to dump yards."* Despite this, some reuse of smaller pieces still occurs before final disposal. F2-C1 stated that boards are *"disposed to dump yards but some cut parts are reused on the site,"* indicating that small pieces may be used for temporary works. Similarly, EN1-C5 mentioned that offcuts are sometimes reused for minor applications such as drainage or temporary formwork before disposal. Overall, the findings suggest that dumping remains the dominant disposal practice, although limited reuse of smaller pieces occurs before final disposal. Figure 6 demonstrates the common disposal practices in Sri Lankan construction industry.

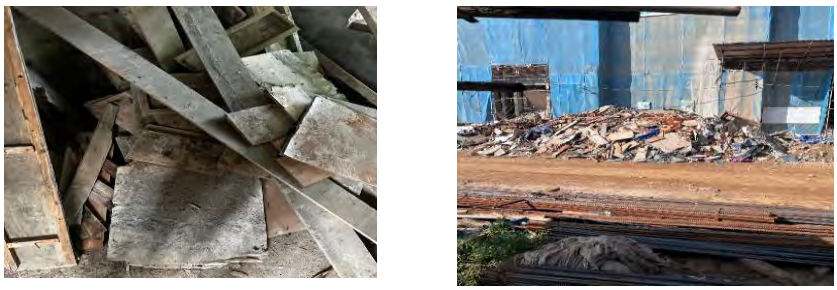


*Figure 6: Disposal practices of plywood formwork at the end-of-life in the construction site*

### 4.11 CHALLENGES IN MANAGING PLYWOOD WASTE

Across the five cases (C1–C5), it is revealed that plywood waste management challenges were mainly related to labour handling practices, time pressure, and supervision difficulties. Several respondents noted that labour behaviour during stripping operations significantly affects plywood damage. PM1-C1 stated *"labourers are likely to work with new plywood, and some labourers are careless about the materials."* Similarly, QS-C2 mentioned that labourers often focus on completing tasks rather than minimizing wastage. Time pressure during construction activities was also identified as a contributing factor. EN1-C4 explained *"when the schedule is tight, boards are sometimes cut quickly without checking properly, and workers remove plywood roughly using tools."* Design-related factors were also reported as a source of waste generation. QS-C3 emphasized, *"when slab geometry does not align with standard board dimensions, cutting adjustments create more offcuts."* Additionally, supervision and coordination challenges were observed, particularly when subcontractors manage formwork work. EN-C2 explained that controlling plywood wastage becomes difficult when subcontractors handle formwork operations. Finally, site constraints such as limited storage space and weather exposure were also identified as factors affecting reuse cycles.

### 4.12 PERCEPTION TOWARD WASTE REDUCTION IMPROVEMENT

Across the large-scale projects (C1–C5), most respondents agreed that better waste reduction practices are beneficial, particularly through improved supervision and labour

management. Several interviewees emphasized that supervision plays a critical role in controlling material handling and reuse. QS-C1 mentioned, *"even skilled labourers may not care about the materials without proper supervision."* Similarly, EN-C3 explained, *"monitoring labour is important because workers often prefer using new plywood rather than reusing existing boards."* Other respondents highlighted that improved supervision during stripping and handling operations could extend reuse cycles. F1-C2 stated *"if supervision is increased and workers are properly instructed, plywood can be reused more times."* However, some participants also emphasized the need to balance waste reduction with project productivity. QS-C3 indicated *"although improving supervision and planning can increase reuse cycles, excessive effort to reduce small offcuts may affect productivity."* Overall, the findings suggest that stronger supervision, better labour awareness, and improved coordination during cutting and removal activities are key strategies for reducing plywood waste in large-scale construction projects. Figure 7 illustrates the interaction between operational drivers, waste generation processes, and key strategies for reducing plywood waste in construction activities.

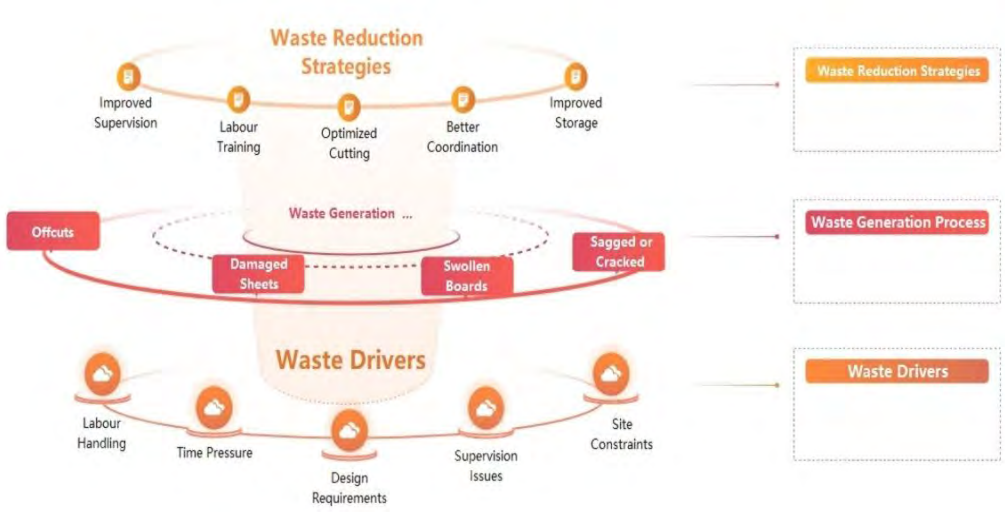



*Figure 7: Relationship between waste drivers and generation, and reduction strategies*

According to Bandara et al. (2025), adopting circular solutions, such as utilising plywood waste as value-added products, including its potential reprocessing into engineered panels offers significant opportunities to enhance resource efficiency in the construction sector. This indicates a strong potential for applying a waste-to-use approach to formwork materials in construction projects.

## 5. DISCUSSION

The findings of this study both align with and extend the existing literature related to plywood usage and wastage in reinforced concrete construction. Similar to the previous studies, all the five large-scale case studies confirmed that plywood is mainly used for the slab soffits and beam side formwork because of its workability, lightweight and smooth surface for concrete finishes (Rajeshkumar et al., 2021; Tighnavard et al., 2024). While the projects selected covered different building types (commercial, residential, institutional and infrastructure related), the pattern of usage of plywood was fairly similar for all cases. The cross-case consistency confirms that the two most common uses of plywood, slab and beam formwork, are still the most prevalent uses regardless of project,

while other uses such as temporary site huts, retaining works and site protection were less consistent and depended on project-specific requirements.

The study is also in line with previous studies which report that plywood generally has short re-use cycles before it is considered waste, because of material deterioration and repeated handling (Aramaki et al., 2021; Pronk et al., 2022; Victar & Waidyasekara, 2023) . The main reasons for using plywood boards in the five cases were, in most instances, delamination, moisture conditions, and damage during stripping operations, with boards typically reused 3-5 times. But there are some differences in the results from what is currently being published. The reuse cycles of coated Merbok film-faced plywood were found to be about 10-15 times (Case 4), which is much better than the typical 2-4 times reuse that is usually reported for plywood. In the same way, the previous studies focused on plywood waste in general, but in this study, offcuts created in the process of slab and beam cutting were identified as the most abundant type of waste in all the cases. The results further corroborate earlier studies that noted that dimensional mismatches, slab geometry, labour handling operations, and cutting operations were identified as significant operation factors that create waste in production (Ajayi & Oyedele, 2018; Salah et al., 2025).

The results of the waste recording and management practices findings support and challenge the previous studies. As found in previous studies, in the selected projects, the measurement of the actual wastage rate in plywood was not usually conducted, and wastage was predominantly managed by way of wastage allowances, wastage re-use assumptions, wastage reconciliation methods, and procurement estimates (Sidiq et al., 2025; Setiawan et al., 2025). This is in line with the observation that construction waste monitoring practices are weak in many developing countries (Mohammad, 2025). However, were some projects in this study that showcased more systematic procurement and tracking methods using ERP systems and store-based documentation, suggesting that there is a gradual improvement towards better material tracking systems in large-scale projects in Sri Lanka. However, due to practical considerations on site, labour constraints and time constraints, none of the projects undertook physical measurements of the waste generated from the plywood.

The study also makes several contributions to the existing body of knowledge in a practical and theoretical manner. From a practical perspective, the results indicate that redesigning the projects, organising the storage and supervision, raising labour awareness and careful planning of cutting can have a substantial impact on minimising plywood waste production and increasing the number of times it can be reused, depending on the type of project. Theoretically, this research makes a contribution by identifying plywood formwork as a separate waste stream of temporary construction material waste, rather than under the general categories of Sri Lankan C&D waste studies, which has been absent in some of the previous studies. The cross-case analysis further revealed that although the projects varied in terms of their characteristics and building functions, the patterns of wastage of plywood, operational causes, re-use practices and disposal methods were generally similar for the projects. This helps in establishing the reliability of the results and the potential of the observed problems of waste management in large scale construction projects in Sri Lanka. In addition, the study contributes to the existing literature by highlighting the potential for plywood waste to be diverted to more circular economy applications, such as value-added engineered wood products and systems based

on the CLT paradigm, which goes beyond the traditional concept of a linear waste management stream that focuses on disposal.

## 6. CONCLUSIONS AND WAY FORWARD

This paper examines the use of plywood and the associated wastage in slab and beam formwork in large-scale construction projects undertaken by major contractors in Sri Lanka. A cross-case study approach was adopted. The findings show that plywood is mainly used in slab soffits and beam sides. On average, plywood is reused 3-5 times, depending on material quality, level of supervision, and labour handling. The main types of waste identified are offcuts generated during cutting damaged boards during the stripping process. These are influenced by factors such as slab geometry, time pressure and inadequate supervision and handling practices. The overall wastage level is estimated to be approximately 10-15%. The study highlights the importance of improved supervision, proper cutting layouts, and better material handling practices to increase reuse cycles and reduce waste. Plywood waste was also identified as having potential value. The findings further demonstrate important practical implications for the Sri Lankan construction industry by highlighting opportunities to improve resource efficiency, minimise material wastage, and support circular economy practices through better plywood reuse and waste management strategies. As a next step, this ongoing research will investigate the feasibility of repurposing plywood waste into a sustainable partition wall system by adopting a cross-laminated timber (CLT)-inspired approach, offering a sustainable solution for partition wall applications in Sri Lanka.

## 7. REFERENCES

Ajayi, S. O., & Oyedele, L. O. (2018). Critical design factors for minimising waste in construction projects: A structural equation modelling approach. *Resources, Conservation and Recycling*, *137*, 302–313. https://doi.org/10.1016/j.resconrec.2018.06.005

Albsoul, H., Doan, D. T., Aigwi, I. E., & GhaffarianHoseini. A. (2025). A review of extant literature and recent trends in residential construction waste reduction. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *43*(3), 322–338. https://doi.org/10.1177/0734242X241241607

Aramaki, T., Nakata, Y., Otsuka, S., & Miyata, A. (2021). A study on quality changes accompanying the reuse of plywood for concrete formwork at construction sites. *AIJ Journal of Technology and Design*, *27*(65), 58–63. https://doi.org/10.3130/aijt.27.58

Balasbaneh, A. T., Sher, W., & Ibrahim, M.H.W. I. (2024). Life cycle assessment and economic analysis of Reusable formwork materials considering the circular economy. *Ain Shams Engineering Journal*, *15*(4), 102585. https://doi.org/10.1016/j.asej.2023.102585

Bandara, W. M. P. M., Waidyasekara, K. G. A. S., & Ranasinghe, P. H. G. M. A. (2025). From waste to worth: Feasibility of repurposing construction timber waste into CLT-inspired sustainable panels in developing countries. In *18th international research conference - FARU 2025* (pp. 598–577). Faculty of Architecture Research Unit, University of Moratuwa. https://doi.org/10.31705/FARU.2025.55

Baskaran, D., Chockkalingam, U., & Muthalvan, R.S. (2025). Assessment of sustainable hybrid formwork systems using life cycle assessment and the wear-out coefficient—A case study. *Buildings*, *15*(10), 1630. https://doi.org/10.3390/buildings15101630

Chen, K., Wang, J., Yu, B., Wu, H., & Zhang, J. (2021). Critical evaluation of construction and demolition waste and associated environmental impacts: A scientometric analysis. *Journal of Cleaner Production 287*, 125071. https://doi.org/10.1016/j.jclepro.2020.125071

Construction Industry Development Authority. (2021). *National Registration and Grading Scheme for Construction Contractors.* Construction Industry Development Authority, Ministry of Housing, Construction and Water Supply. https://www.cida.gov.lk/sea_con/pages_e.php?id=124

Devi, K., & Yadav, T. (2023). Cost comparison of different types of formworks. *Journal of Building Material Science*, *5*(1), 32–38. https://doi.org/10.30564/jbms.v5i1.5515

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? *Field Methods*, *18*(1), 59–82. https://doi.org/10.1177/1525822X05279903

Islam, N., Sandanayake, M., Muthukumaran, S., & Navaratna, D. (2024). Review on sustainable construction and demolition waste management—Challenges and research prospects. *Sustainability, 16(8), 3289*, https://doi.org/10.3390/su16083289

Kothalawala, N. T. B., Malkanthi, S. N., & Dharmaratne, P. D. (2025). Material wastage on cost overrun in construction projects: An impact study carried out in Sri Lanka. *Journal of Advances in Engineering and Technology*, *3*(2), 65–77. https://doi.org/10.54389/OUTQ9902

Kurniawan, H.A., Susilowati, F., & Jannah, R.M., (2024). Study on implementation of construction waste management in minimizing construction material. Jurnal PenSil, 13(1), 1–12. https://doi.org/10.21009/jpensil.v13i1.37863

Lee, S., Chang, H., & Lee, J. (2024). Construction and demolition waste management and its impacts on the environment and human health: Moving forward sustainability enhancement. *Sustainable Cities and Society*, *115*, 105855. https://doi.org/10.1016/j.scs.2024.105855

Maduwage, R. S., Ramachandra, T., Indikatiya, I. H. P. R., & Karunasinghe, N. S. (2025). Managing barriers affecting to implement sustainable construction wood waste management in Sri Lanka. In, *Proceedings of the international conference on facilities management futures 2025: Safety enabled and sustainable facilities* (pp. 212–220). Facilities Management Research Unit (FaMRU), University of Moratuwa. https://doi.org/10.31705/ICFMF2025.16

Ministry of Finance, Planning and Economic Development. (2025). *Major public investment projects*. Ministry of Finance, Planning and Economic Development. https://npd.treasury.gov.lk/files/2026-2028_english.pdf

Mohammad, A. H. (2025). Assessing the dual impact of construction waste on project inefficiencies and environmental sustainability in Iraq. *Journal of Sustainable Development*, *18*(5), 109. https://doi.org/10.5539/jsd.v18n5p109

Papamichael, I., Voukkali, I., Loizia, P., & Zorpas, A. A. (2023). Construction and demolition waste framework of circular economy: A mini review. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *41*(12), 1728–1740. https://doi.org/10.1177/0734242X231190804

Pronk, A., Brancart, S., & Sanders, F. (2022). Reusing timber formwork in building construction: Testing, redesign, and socio-economic reflection. *Urban Planning*, *7*(2), 81–96. https://doi.org/10.17645/up.v7i2.5117

Rajeshkumar, V., Anandaraj, S., Kavinkumar, V., & Elango, K. S. (2021). Analysis of factors influencing formwork material selection in construction buildings. *Materials Today: Proceedings*, *37*, 880–885. https://doi.org/10.1016/j.matpr.2020.06.044

Salah, M., Elbeltagi, E., Almoshaogeh, M., Alharbi, F., & Elnabwy, M. T. (2025). Identifying root causes and sustainable solutions for reducing construction waste using social network analysis. *Sustainability*, *17*(17), 7638. https://doi.org/10.3390/su17177638

Sanda, Y. N., Anigbogu, N. A., Izam, Y. D., & Nuhu, L. Y. (2021). Designing case study research in construction management. *Journal of Surveying, Construction & Property*, *12*(1), 27–35. https://doi.org/10.22452/jscp.vol12no1.3

Setiawan, A., Handayani, E., Dony, W., & Dwiretnani, A. (2025). Evaluation of the use of wooden formwork materials in the public service mall construction project in Mauro Jambi Regency. *Jurnal Talenta Sipil*, *8*(2), 875. https://doi.org/10.33087/talentasipil.v8i2.939

Sidiq, R.J., Micheal, L., Raflyanto, P., & Tota, P.K. (2025). Waste material in construction projects: Analyzing cost, schedule, and environmental impacts. Journal of Applied Engineering Science, 23(2), 303–313. https://doi.org/10.5937/jaes0-55779

Tafesse, S., Girma, Y. E., & Dessalegn, E. (2022). Analysis of the socio-economic and environmental impacts of construction waste and management practices. *Heliyon*, *8*(3), e09169. https://doi.org/10.1016/j.heliyon.2022.e09169

Victar, H. C., & Waidyasekara, K. G. A. S. (2023). Construction and demolition waste management issues in building project life cycle stages: A case of Sri Lanka. In Y.G. Sandanayake, K.G.A.S. Waidyasekara,

T. Ramachandra & K.A.T.O. Ranadewa (Eds). *Proceedings of the 11th World Construction Symposium* (pp. 392–406). Ceylon Institute of Builders, Sri Lanka. https://doi.org/10.31705/WCS.2023.33

Arthigan, K. and Eranga, B.A.I., 2026. From waste to worth: Digitalizing secondary materials market in construction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 870-883. DOI: https://doi.org/10.31705/WCS.2026.64. Available from: https://ciobwcs.com/papers/

# FROM WASTE TO WORTH: DIGITALIZING SECONDARY MATERIALS MARKET IN CONSTRUCTION

**K. Arthigan[1] and B.A.I. Eranga[2]**

## *ABSTRACT*

*The construction industry remains one of the largest consumers of raw materials globally, contributing approximately 39% of energy-related carbon dioxide emissions and generating substantial volumes of construction and demolition waste (CDW). Despite growing recognition of circular economy (CE) principles as a pathway toward sustainable construction, the secondary construction material market continues to operate informally, with no structured discovery, valuation, or trust mechanism in place. This research addresses the critical gap of underdeveloped digital infrastructure for secondary material procurement in the Sri Lankan construction sector. The study pursues three objectives: (1) to review the current technological landscape and assess the potential of digital technologies to support CE practices; (2) to identify key limitations and barriers affecting material circularity in construction; and (3) to investigate challenges in integrating primary and secondary material markets within construction procurement systems. Adopting a narrative literature review complemented by a questionnaire survey administered to thirty-one construction industry professionals, the study systematically identifies barriers to secondary material reuse. The findings confirm the total absence of a formalised secondary material market in Sri Lanka, with procurement occurring exclusively through informal networks. Three structural failures are identified: no price determination mechanism, no quality assurance or certification pathway, and no organised discovery infrastructure. These findings collectively demonstrate the urgent need for a dedicated digital platform to bridge the information and trust gap between suppliers and buyers of secondary construction materials, thereby facilitating CE implementation in the construction industry.*

***Keywords:*** *Circular Economy; Construction and Demolition Waste; Digital Platform; Secondary Material Market; Sustainable Construction.*

## 1. INTRODUCTION

Construction industry is vital in addressing global environmental concerns, as it is one of the largest consumers of raw materials and generators of waste (Pomponi & Moncaster, 2017). Further, the construction sector is responsible for over 36% of global final energy use and nearly 39% of energy-related carbon dioxide emissions, while also consuming about 50% of global raw materials and generating a large proportion of solid waste (Jin et al., 2024). This unsustainable trajectory has largely been driven by the traditional linear economy model, which involves extracting raw materials, transforming them into products, and discarding them after use. This model results in massive resource depletion,

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk

increased waste, and elevated carbon emissions, particularly in material-intensive sectors such as construction (Afteni et al., 2022).

The circular economy (CE) concept promotes a regenerative model where resource inputs, waste, emissions, and energy leakage are minimised through long-term product use, reuse, remanufacturing, and recycling. Unlike the linear "take-make-dispose" model, the CE model facilitates continual material loops and has been increasingly recognised as essential for decarbonising material-intensive sectors such as construction (De Wolf et al., 2024). Studies have suggested that up to £130 million in gains could be made by reducing UK construction waste by only 5% (Oyedele et al., 2014).

The secondary market in the construction industry refers to the exchange and reuse of recovered or reprocessed materials from demolition waste, including bricks, metals, timber, fixtures, and other salvageable components (Tennakoon et al., 2022). This market plays a vital role in enabling CE practices, as it provides a mechanism for reintegrating materials from end-of-life buildings back into new construction projects, thereby minimising landfill use and preserving virgin resources. However, limited information on product quality, quantity, and availability hinders efficient market transactions (Rose & Stegemann, 2018). Furthermore, the absence of digital platforms impairs effective material matching and impedes transaction flows (Tennakoon et al., 2021).

Despite growing interest in CE, the construction industry continues to struggle with practical implementation due to limited awareness, multiple stakeholders with limited coordination, and a lack of standard practices that reduce the adoption of circular principles (Munaro & Tavares, 2023). A key technological knowledge gap is identified: the underdevelopment of digital platforms that can bridge the value chain and enable real-time coordination among stakeholders for material reuse, tracking, and redistribution (Byers et al., 2024). This creates a clear research problem: the absence of a dedicated, digitally enabled CE platform that facilitates transparent and efficient interaction among suppliers, buyers, and regulators in the secondary materials market within the construction sector (Pittri et al., 2025). The research problem therefore lies in the lack of a centralised, digitally enabled CE platform tailored for the construction industry, one that can close the gap between theory and practice by supporting reverse logistics, stakeholder engagement, and real-time secondary market operations.

In response, digital technologies and online marketplaces are increasingly viewed as transformative tools for enabling CE in construction. Digital platforms can bridge the information and trust gap between material suppliers, such as demolition firms, and buyers, such as contractors or architects, by providing searchable inventories, product certification details, geolocation features, and logistics integration (De Wolf et al., 2024). This study addresses the urgent need for sustainable practices in the construction sector by proposing a digitally enabled solution that enhances transparency, stakeholder collaboration, and decision-making efficiency. The aim of this research is to examine the barriers to secondary construction material procurement in the Sri Lankan construction sector and to identify the digital platform requirements necessary to facilitate a formalised, digitally enabled secondary materials market that supports CE implementation. The objectives of this study are to:

1. Review the current technological landscape in the construction industry and assess the potential of digital technologies to support CE practices.

2. Identify key limitations and barriers affecting the implementation of material circularity within the CE in construction; and
3. Investigate challenges in integrating primary and secondary material markets within construction procurement systems.

# 2. LITERATURE REVIEW

## 2.1 CONCEPTUAL FOUNDATIONS OF THE CIRCULAR ECONOMY IN CONSTRUCTION

The construction sector is among the most resource-intensive and environmentally impactful industries, contributing nearly 40% of global energy use and more than one-third of greenhouse gas emissions (Cervantes et al., 2025). Traditionally, the industry has operated under a linear model of "take, make, use, and dispose", which has led to significant resource depletion and environmental degradation (Ghisellini et al., 2016). In contrast, the CE offers an alternative paradigm that seeks to decouple economic growth from resource consumption by maintaining materials and components at their highest utility and value for as long as possible (Kirchherr et al., 2023).

The evolution of the CE concept can be traced through the progressive development of the "R" frameworks that define strategies for sustainable resource use. The earliest framework, based on the 3Rs-reduce, reuse, and recycle, originated in waste management discourses in the late twentieth century (Adams et al., 2017). Over time, this model expanded into more comprehensive versions including the 6Rs or more, encompassing refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover (Dsilva et al., 2023). In the context of construction, these principles encourage a shift from waste-oriented management to resource-oriented regeneration, where buildings are viewed as material banks capable of supplying reusable components for future projects (Reike et al., 2018).

## 2.2 CIRCULAR ECONOMY AND RESOURCE EFFICIENCY IN CONSTRUCTION

The construction industry plays a vital role in driving economic growth; however, it also contributes significantly to environmental deterioration due to its excessive consumption of resources and the vast amounts of waste it generates (Rose & Stegemann, 2018). The sector's conventional adherence to a linear economic paradigm of "take, make, dispose" has exacerbated environmental challenges, resulting in high carbon emissions and mounting waste generation (Bui et al., 2022). CDW includes materials such as concrete, timber, bricks, steel, glass, metals, plasterboard, and plastics, many of which still possess high residual value but are underutilised due to fragmented recovery systems and weak market mechanisms (Joseph et al., 2023; Shooshtarian et al., 2022).

CE principles greatly cut operating costs, boost energy efficiency, and minimise carbon footprints. Using recycled resources can significantly cut material procurement costs and lower the environmental impact of extraction and processing. CE techniques also cut waste disposal costs and boost operating efficiency; for example, modular building and prefabrication optimise resource consumption by eliminating offcuts and construction waste, leading to budgetary savings (Finamore & Oltean-Dumbrava, 2024). CE can potentially cut primary material usage by 32% by 2030 and 53% by 2050.

## 2.3 CIRCULAR SUPPLY CHAINS: FORWARD AND REVERSE LOGISTICS

Circular Business Models (CBMs) serve as the organisational rationale and mechanism for how firms create, deliver, and capture value within a circular system, primarily by slowing, closing, or narrowing resource loops (Bestul & Gruis, 2024). Effective circularity begins at the earliest stages of the product lifecycle, necessitating a fundamental change in the design process. This forward integration relies heavily on Design for Disassembly (DfD), modularity, and digital tools like Material Passports and Building Information Modelling (BIM) (Chen et al., 2024). BIM, defined as the use of a shared digital representation of an asset throughout its lifecycle, acts as a foundational data supplier and contains static data essential for planning and construction documentation (Askar et al., 2024).

The reverse logistics aspect of CBMs focuses on managing materials once products reach their end-of-life, encompassing collection, processing, and reintroduction to the supply chain (Chen et al., 2024). Material recovery typically focuses on CDW streams, and key processes include acquisition of used products, disassembly, cleaning, rework, and assembly. However, managing this flow presents complex challenges, notably the variability of product quality and volume upon return. Despite clear environmental and potential economic benefits, several pervasive barriers spanning organisational, economic, regulatory, and technological domains hinder the seamless alignment of forward and reverse construction supply chains.

## 2.4 DIGITAL PLATFORMS FOR SECONDARY MATERIAL MARKETS

The need for web-based or IT-enabled platforms to facilitate demand–supply coordination, product listings, traceability, and online procurement is identified as a key enabler for improving the secondary market's performance (Shooshtarian et al., 2022). Key barriers in the secondary material market include low visibility of available materials, lack of quality certification mechanisms, inconsistent supply chains, and negative perceptions regarding reused materials (Idir et al., 2025). Moreover, many stakeholders, including demolition contractors, builders, and project managers, often lack the necessary information or incentives to engage in such exchanges (Tennakoon et al., 2023).

Digital platforms can bridge the information and trust gap between material suppliers and buyers by providing searchable inventories, product certification details, geolocation features, and logistics integration (De Wolf et al., 2024). For example, Loopfront, a platform launched in Norway, facilitates reuse by offering real-time listings of surplus building materials along with $CO_2$ savings data, thereby improving transparency and sustainability accounting. Empirical research identifies six distinct circular business model types focused on component reuse: up-cyclers, component-specific suppliers, material resellers, reuse platforms, reuse consulting offices, and deconstruction companies (Bestul & Gruis, 2024). These highlight the separation of functions across specialised actors rather than centralisation in a single organisation.

## 2.5 POLICY AND REGULATORY FRAMEWORKS

The transition toward material circularity in the construction sector is significantly influenced by policy and regulatory frameworks. The main barrier to the development of CE in the construction industry, especially in developing countries, is that there are

insufficiently strong and focused policies related to circularity in material usage and waste management (Weerakoon et al., 2023). In Sri Lanka specifically, the absence of coherent policies on waste management is compounded by governance issues, creating systemic weaknesses that limit the capacity of governments to design and enforce effective CE policies (Dewagoda et al., 2022).

In contrast, the EU's Circular Economy Action Plan establishes a global benchmark, yet implementation remains challenged by technical and standardisation concerns. The lack of harmonised end-of-waste criteria, chemical safety regulatory burdens, and limited standardised design values within structural codes collectively constrain the integration of recycled materials into mainstream construction projects. Globally, CE initiatives such as public procurement policies in Denmark, BIM-driven Digital Twin frameworks in North America, and mandatory waste segregation in Malaysia demonstrate that both policy-driven and industrial approaches are indispensable for driving CE adoption at scale.

*Table 1: Thematic key areas*

| ***1: Awareness & Understanding of CE and Secondary Materials*** | ***2: Current Practices & Challenges in Secondary Material Sourcing*** |
|---|---|
| Familiarity with CE principles (reduce, reuse, recycle, recover) (1), (2), (3)<br>Understanding of CDW as a recoverable resource (4), (5)<br>Knowledge of secondary material types (bricks, timber, metals, concrete) (6), (7)<br>Awareness of environmental & carbon implications of linear model (8), (9)<br>Familiarity with global CE examples (Loopfront, EU CEAP, Malaysia) (10), (11), (12) | Current secondary material sourcing methods (formal vs. informal networks) (6), (13)<br>Extent of CDW segregation at demolition sites (5), (4)<br>Reverse logistics management (collection, disassembly, reintroduction) (14), (15)<br>Use of digital tools (BIM, Material Passports) in procurement (16), (17)<br>Inclusion of secondary materials in Bills of Quantities / project budgets (18), (19) |
| ***3: Barriers to Secondary Material Adoption*** | ***4: Interest in & Requirements for a Digital Platform Solution*** |
| Absence of price discovery / depreciation framework for secondary materials (20), (6)<br>Lack of quality assurance and certification protocols (e.g., SLS equivalents) (21), (22), (11)<br>No organised material discovery or matchmaking infrastructure (13), (10)<br>Institutional inertia and resistance to circular procurement norms (23), (1)<br>Regulatory gaps and absence of enforceable CE policies in Sri Lanka (12), (19)<br>Negative stakeholder perceptions and liability concerns over secondary materials (11), (24) | Centralised searchable marketplace / material discovery interface (10), (25)<br>Price transparency module with cost benchmarking and comparison tools (5), (26)<br>Condition grading, certification and quality assurance system (13), (11)<br>Geolocation and logistics integration for material tracking (10), (27)<br>Sustainability impact quantification ($CO_2$ savings, waste diversion metrics) (25), (28)<br>Administrative governance and authoritative oversight layer (25), (12) |

[1] (Ghisellini et al., 2016), [2] (Kirchherr et al., 2023), [3] (Adams et al., 2017), [4] (Joseph et al., 2023), [5] (Shooshtarian et al., 2022), [6] (Tennakoon et al., 2022), [7] (Rose & Stegemann, 2018), [8] (Jin et al., 2024), [9] (Cervantes et al., 2025), [10] (De Wolf et al., 2024), [11] (Idir et al., 2025), [12] (Weerakoon et al., 2023), [13] (Byers et al., 2024), [14] (Chen et al., 2024), [15] (Chen et al., 2024), [16] (Askar et al., 2024), [17] (Honic et al., 2019), [18] (Pittri et al., 2025), [19] (Dewagoda et al., 2022), [20] (Hopkinson et al., 2018), [21] (Adams et al., 2017), [22] (Tingley et al., 2017), [23] (Munaro & Tavares, 2023), [24] (Pomponi & Moncaster, 2017), [25] (Bestul & Gruis, 2024), [26] (Tennakoon et al., 2023), [27] (Sivers et al., 2022), [28] (Finamore & Oltean-Dumbrava, 2024)

# 3. METHODOLOGY

This study adopted a two-phase methodology comprising a narrative literature review followed by a questionnaire survey. The literature review was conducted to establish the theoretical foundations of CE principles, secondary material markets, and digital procurement platforms in the construction sector. A systematic search of peer-reviewed literature was undertaken using the databases Scopus, Web of Science, and Google Scholar. The search combined keywords including "circular economy", "secondary materials", "construction and demolition waste", "digital platform", "material marketplace", "sustainable procurement", and "reverse logistics", applied individually and in combination using Boolean operators (AND, OR). The search was limited to peer-reviewed journal articles, conference papers, and institutional reports published between 2015 and 2025, supplemented by foundational earlier works where necessary. Articles were screened for relevance based on title and abstract, with full-text analysis applied to those addressing the study's core themes.

Following the literature review, primary data were collected through a questionnaire survey administered electronically to thirty-one construction industry professionals actively involved in the Sri Lankan construction sector. The questionnaire comprised a combination of closed-ended Likert-scale items (five-point scale), multiple-choice questions, and open-ended items, enabling both quantitative trend analysis and qualitative insight capture. The survey was piloted with three academic experts prior to full distribution to validate clarity and content relevance, and revisions were made accordingly.

Respondents were selected using purposive sampling, targeting professionals with direct involvement in construction procurement, project management, quantity surveying, sustainability consulting, and regulatory roles. Purposive sampling is particularly appropriate for exploratory industry studies where subject-matter expertise is the primary selection criterion (Tongco, 2007). This approach is well-established in construction management research, where the depth and relevance of respondent expertise are prioritised over large probabilistic samples (Naoum, 2012). The sample of thirty-one professionals represents a purposefully constituted expert group drawn from the principal stakeholder categories involved in secondary material procurement in Sri Lanka: contractors (32%), quantity surveyors (23%), academic and research professionals (16%), government and regulatory officers (16%), and environmental and sustainability consultants (13%). The adequacy of this sample size is justified on three grounds. First, given the exploratory and qualitative focus of this study, expert-based purposive samples of twenty to thirty-five participants are widely considered sufficient for achieving thematic saturation in construction management research (Naoum, 2012; Tongco, 2007).

Second, all five principal stakeholder categories involved in secondary material procurement are represented, ensuring that findings reflect the full spectrum of relevant professional perspectives rather than a single-sector viewpoint. Third, the study's primary contribution is the identification and contextualisation of structural market failures rather than the generation of generalisable statistical distributions, a goal for which depth of expertise is more analytically appropriate than sample size. Acknowledging this limitation, future research employing larger probabilistic samples would be valuable for validating and extending the descriptive findings reported here. Survey responses were analysed using descriptive statistics and frequency distributions, with open-ended responses subjected to content analysis to identify recurring themes. Figure 1 illustrates the overall methodological design adopted in this study.

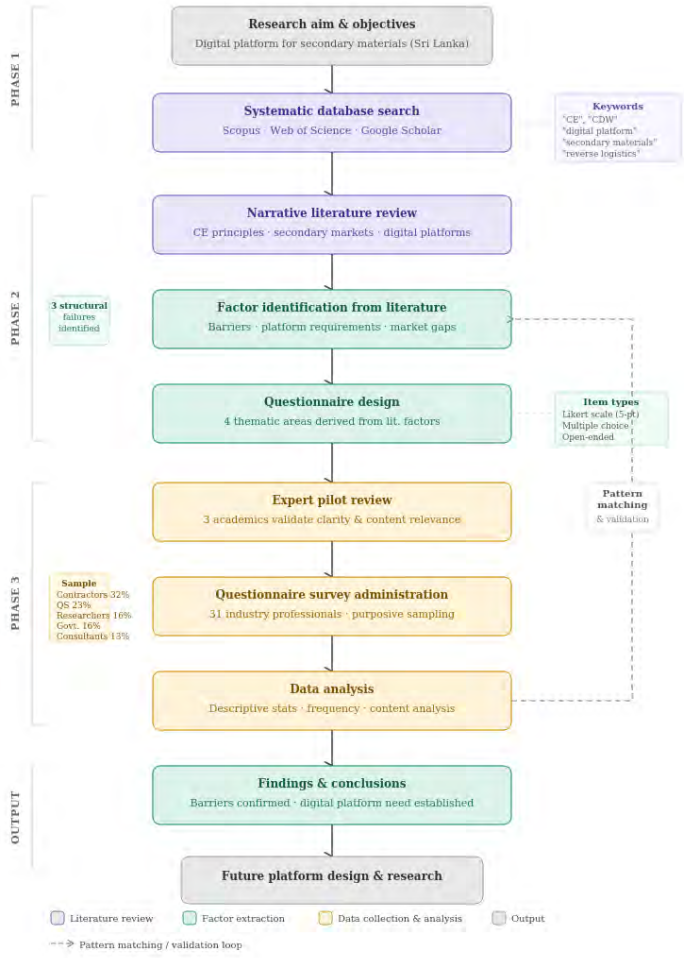



*Figure 1: Methodology flow design*

# 4. RESEARCH FINDINGS AND ANALYSIS

## 4.1 LITERATURE REVIEW FINDINGS

The literature review identified three overarching themes that collectively define the state of knowledge on secondary material markets and digital CE enablers in construction.

First, the review confirmed that CE adoption in construction globally remains largely theoretical, with implementation constrained by deeply embedded linear economy practices, institutional inertia, and weak regulatory enforcement. While European contexts have progressed further through policy mandates and digital innovation, developing economies including Sri Lanka exhibit pronounced gaps in both policy frameworks and market infrastructure for secondary materials (Weerakoon et al., 2023; Ghisellini et al., 2016).

Second, the literature consistently identifies three structural barriers to secondary material market functioning: the absence of price discovery mechanisms that appropriately discount secondary materials relative to new equivalents; the lack of standardised quality assurance and certification pathways; and the absence of organised discovery infrastructure enabling buyers to locate and evaluate available materials (Tennakoon et al., 2022; Byers et al., 2024; Idir et al., 2025). These barriers are mutually reinforcing: without price transparency, quality certification, or searchable supply, formal procurement channels cannot develop, and secondary material exchange remains confined to informal personal networks.

Third, the literature identifies digital platforms as the most viable mechanism for simultaneously addressing all three structural barriers. Evidence from operational platforms in Norway (Loopfront), the Netherlands, and the United Kingdom demonstrates that web-based material marketplaces incorporating condition grading, geolocation, pricing benchmarks, and administrative governance can catalyse secondary material market activity in contexts where informal exchange previously dominated (De Wolf et al., 2024; Sivers et al., 2022). The literature further identifies six functional requirements for effective secondary material platforms: centralised discovery, communication infrastructure, price transparency, quality certification, impact quantification, and authoritative governance (Bestul & Gruis, 2024). These literature-derived requirements provided the conceptual framework for the questionnaire instrument used in primary data collection.

## 4.2 QUESTIONNAIRE SURVEY FINDINGS

The questionnaire survey, administered to thirty-one construction industry professionals spanning contractors (32%), quantity surveyors (23%), academic and research professionals (16%), government and regulatory officers (16%), and environmental and sustainability consultants (13%), generated four critical research insights directly aligned with the study's objectives. The disciplines of the respondents are illustrated in Figure 2.

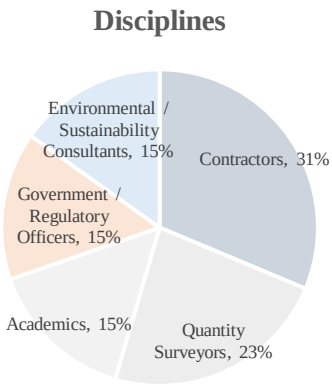


*Figure 2: Disciplines of the respondents*

First, all thirty-one respondents demonstrated awareness of CE principles, predominantly associating CE with waste reduction, reuse, and material loop closure. However, this awareness did not translate into practice, signalling structural rather than attitudinal barriers as the primary constraint on CE adoption. This finding is consistent with the literature's identification of implementation barriers as being systemic rather than individual. Notably, the gap between awareness and practice was most pronounced among contractors (32% of respondents), who, despite familiarity with CE terminology, reported that informal procurement norms, lack of standardised pricing, and client resistance rendered secondary material adoption practically untenable in commercial project environments. Quantity surveyors similarly reported that the absence of recognised rate schedules precluded formal inclusion of secondary materials in bills of quantities. In contrast, academic and sustainability professionals expressed stronger conceptual alignment with CE adoption, suggesting that the awareness-practice divide is not uniform across stakeholder groups but is shaped by professional role, procurement responsibility, and exposure to market-level risk. This distinction implies that digital platform interventions should primarily address the operational constraints of procurement-facing professionals particularly contractors and quantity surveyors rather than focusing solely on awareness-raising, which is already adequate across the sector (Pittri et al., 2025).

Second, all thirty-one respondents confirmed the total absence of any formalised secondary material marketplace in Sri Lanka. No respondent identified a formalised procurement channel; all described ad hoc and informal sourcing through personal networks and project-based contacts. This empirical confirmation of market absence validates the central research problem identified through the literature review: the gap is not one of awareness, but of infrastructure.

Third, the pricing challenge emerged as a critical structural barrier. The absence of any depreciation or price discovery framework for secondary construction materials means that such materials are frequently priced at or near the cost of new equivalents, eliminating the financial incentive for buyers to choose secondary options. Twenty-seven of thirty-one respondents (87%) identified the absence of a standardised pricing mechanism as a significant barrier. From a quantity surveying perspective, the absence of standard rates for secondary material valuation prevents these options from being included in bills of quantities on a comparable basis with new materials, effectively excluding them from formal project budgeting. This barrier has specific contextual roots in Sri Lanka: the construction industry's heavy reliance on informal, trust-based trading networks means that secondary material transactions are negotiated bilaterally without reference to any benchmarked rate, creating wide price variability that deters formal buyers. Additionally, the economic volatility experienced in Sri Lanka between 2021 and 2023 intensified material cost pressures, yet the secondary market failed to expand, suggesting that price instability alone does not drive adoption in the absence of institutional infrastructure. Government and regulatory respondents noted that no legislative basis exists for mandating or incentivising depreciation-based pricing of recovered materials, which distinguishes Sri Lanka from jurisdictions such as the Netherlands and the United Kingdom where fiscal instruments support secondary material market formation (Sivers et al., 2022). This contextual analysis reveals that the pricing barrier in Sri Lanka is not merely technical but is structurally embedded in the

intersection of informality, weak policy, and institutional inertia factors that a digital platform alone cannot resolve without accompanying policy reform.

Fourth, quality and liability concerns represented the most consistently cited demand-side barrier. Twenty-nine of thirty-one respondents (94%) identified the absence of any quality assurance or certification protocol as a critical gap. The lack of any equivalent to Sri Lanka Standards (SLS) certification for secondary materials was noted as making it professionally risky for contractors, architects, and quantity surveyors to specify such materials in formal project documentation. The nature of this concern, however, varied meaningfully across stakeholder groups. Contractors and quantity surveyors framed the barrier primarily in terms of legal liability: specifying materials without certification exposes them to professional and contractual risk if structural or performance failures arise. Government and regulatory respondents acknowledged that no formal certification framework for secondary construction materials exists within current regulatory structures, nor is one under active development. Environmental and sustainability consultants, in contrast, expressed greater willingness to accept condition-graded secondary materials if supported by documented quality assessments, indicating that risk tolerance is partially determined by the nature of professional responsibility rather than by scepticism about material quality per se. This divergence highlights a key tension within the secondary market: the actors most willing to engage with secondary materials (sustainability-oriented professionals) are rarely the decision-makers in procurement, while those who control procurement (contractors, quantity surveyors) face the highest institutional barriers to adoption. Addressing this structural mismatch requires not only quality certification mechanisms within a digital platform but also changes to procurement documentation norms and professional indemnity frameworks — areas where policy intervention is indispensable (Idir et al., 2025).

All thirty-one respondents expressed strong interest in a dedicated digital platform as the preferred solution to address these structural failures. The demand for platform features aligned closely with the six functional requirements identified in the literature: a centralised searchable marketplace, a seller dashboard for material listing, a buyer dashboard for discovery and tracking, a pricing transparency module with cost comparison, a condition grading and certification system, and an administrative governance layer. This convergence between literature-derived requirements and practitioner demand confirms that a digital platform represents both a theoretically sound and practically supported response to the identified market failures. Stakeholder group preferences for specific platform features, however, revealed instructive differences. Contractors prioritised real-time material availability and logistics integration, reflecting their operational need to manage procurement timelines. Quantity surveyors emphasised the pricing transparency module and its compatibility with standard bill of quantities formats. Government and regulatory respondents identified the administrative governance layer including oversight of material listings and dispute resolution mechanisms as the most critical component for ensuring the platform's credibility and regulatory acceptability. Environmental and sustainability consultants prioritised sustainability impact quantification (such as, $CO_2$ savings and waste diversion metrics), consistent with their professional focus on environmental performance reporting. These differentiated preferences indicate that a one-size-fits-all platform design would be insufficient; effective implementation requires stakeholder-responsive interface design that foregrounds role-relevant features for each user category. The research contributions

of this study are therefore twofold: (1) it provides the first empirically grounded mapping of secondary material market failures in the Sri Lankan construction sector, disaggregated by stakeholder perspective; and (2) it establishes a theoretically and practically validated functional requirement set for a dedicated digital CE platform tailored to developing economy conditions, where institutional infrastructure, regulatory capacity, and market formality cannot be assumed.

### 4.3 SYNTHESIS AND PATTERN MATCHING

A pattern matching exercise confirmed the theoretical validity of the primary findings. The total absence of a formalised secondary material market in Sri Lanka, confirmed by all thirty-one survey respondents, is consistent with literature on developing economies where informal networks dominate material reuse and CE infrastructure remains nascent (Ghisellini et al., 2016). The pricing challenge specifically the absence of depreciation in secondary material pricing is consistent with theoretical arguments that price discovery mechanisms are essential conditions for secondary material markets to function (Hopkinson et al., 2018), while also representing a novel contribution regarding how cultural and institutional factors shape the price-finding problem in ways not fully captured by existing European literature. The quality assurance barrier replicates the pattern consistently identified in international literature (Adams et al., 2017; Tingley et al., 2017), while the universal stakeholder demand for a digital platform aligns with emerging evidence that web-based marketplaces are the most effective mechanism for operationalising secondary material exchange in both developed and developing construction markets (De Wolf et al., 2024; Sivers et al., 2022).

The findings collectively point to a clear conclusion supported directly by the empirical data: CE awareness exists among Sri Lankan construction professionals, but the absence of price discovery, quality assurance, and organised discovery infrastructure renders secondary material procurement practically impossible through formal channels. These three structural failures are directly evidenced by respondent data, specifically the 100% confirmation of marketplace absence, the 87% identification of pricing as a significant barrier, and the 94% identification of quality assurance as a critical gap. The proposition that a dedicated digital platform is both necessary and sufficient to address these failures, however, requires qualification: the data supports platform necessity and stakeholder demand, but the conditions under which a platform would function effectively including complementary policy reform, third-party certification authority establishment, and professional indemnity framework revision are proposed as prerequisites informed by the findings, not directly evidenced by them. Future research should focus on validating these platform design requirements through prototype development and testing, and on assessing the policy and institutional interventions required to create the enabling conditions for platform adoption at scale.

## 5. CONCLUSIONS

This study examined the current state of secondary material procurement in Sri Lanka and the barriers to CE implementation in the construction industry, through a two-phase methodology comprising a narrative literature review and a questionnaire survey of thirty-one construction industry professionals. The following conclusions are drawn directly from the empirical data. The secondary material procurement landscape in Sri Lanka is entirely informal, reliant on personal networks, and characterised by three

fundamental structural failures confirmed by all thirty-one respondents: no price determination mechanism, no quality assurance or certification pathway, and no organised discovery or matching infrastructure. The awareness-practice gap is not uniform across stakeholder groups; procurement-facing professionals (contractors and quantity surveyors) face the highest institutional barriers to adoption, while sustainability-oriented professionals demonstrate greater willingness to engage with secondary materials a tension that digital platform design must address through role-responsive interface architecture. The pricing barrier is structurally embedded in the intersection of informality, economic volatility, and absent policy frameworks specific to the Sri Lankan context, distinguishing it from pricing challenges documented in European literature. Quality assurance concerns are driven primarily by professional liability risk rather than general scepticism about material quality, indicating that certification infrastructure and procurement documentation reform are necessary complements to any digital platform intervention.

The research contributions of this study are twofold. For industry, the findings provide the first stakeholder-disaggregated mapping of secondary material market failures in Sri Lanka, directly informing the design priorities for a national digital CE platform and highlighting the policy and certification prerequisites without which such a platform cannot succeed. For research, the study establishes an empirically validated functional requirement set for digital secondary material platforms in developing economy contexts, extending the existing literature beyond its predominantly European focus and demonstrating that informality, institutional absence, and liability-driven procurement norms require distinct design responses not captured by existing platform models. The following conclusions are proposed as directions informed by the evidence but requiring further validation: that a dedicated digital platform, designed around the six functional requirements identified through literature-survey convergence, represents the most viable mechanism for simultaneously addressing price discovery, quality certification, and material discovery failures; and that government-mandated minimum reuse requirements for public sector projects, the establishment of a recognised third-party certification authority for secondary materials, and the development of a national depreciation framework for used construction materials are essential complementary policy measures. Future research should focus on the design and development of a functional digital platform prototype, followed by longitudinal evaluation of adoption patterns, quantitative assessment of CE impact metrics, and investigation of integration pathways with national green building certification frameworks such as GreenSL. Expanded survey research with probabilistic sampling would additionally strengthen the generalisability of the descriptive findings reported here.

## 6. REFERENCES

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Afteni, C., Păunoiu, V., & Afteni, M. (2022). Study on the transition from the linear economy to the circular economy. *Annals of Dunarea de Jos University of Galati, Fascicle V, Technologies in Machine Building,* 39(1), 49–55. https://doi.org/10.35219/tmb.2021.1.08

Askar, R., Karaca, F., Bragança, L., & Gervásio, H. (2024). The role of BIM in Supporting Circularity: A conceptual framework for developing BIM-Based circularity assessment models in buildings. In *Lecture notes in civil engineering* (pp. 649–658). https://doi.org/10.1007/978-3-031-57800-7_60

Bestul, B., & Gruis, V. (2024). Six business model types for circular building component reuse actors. *Sustainability*, 16(13), 5425. https://doi.org/10.3390/su16135425

Bui, T., Tseng, J., Tseng, M., Wu, K., & Lim, M. K. (2022). Municipal solid waste management technological barriers: A hierarchical structure approach in Taiwan. *Resources Conservation and Recycling*, 190, 106842. https://doi.org/10.1016/j.resconrec.2022.106842

Byers, B. S., Raghu, D., Olumo, A., De Wolf, C., & Haas, C. (2024). From research to practice: A review on technologies for addressing the information gap for building material reuse in circular construction. *Sustainable Production and Consumption*, 45, 177–191. https://doi.org/10.1016/j.spc.2023.12.017

Cervantes P., G. C., Salles, A., Turk, J., et al. (2025). Circular economy best practices in the built environment. In L. Bragança et al. (Eds.), *Circular Economy Design and Management in the Built Environment*. Springer. https://doi.org/10.1007/978-3-031-73490-8_1

Chen, X., Qiu, D., & Chen, Y. (2024). Reverse logistics in the construction industry: status quo, challenges and opportunities. *Buildings*, *14*(6), 1850. https://doi.org/10.3390/buildings14061850

Chen, Q., Feng, H., & Garcia De Soto, B. (2024). Revamping construction supply chain processes with circular economy strategies. *Journal of Cleaner Production*, 335, 130240. https://doi.org/10.1016/j.jclepro.2021.130240

De Wolf, C., Byers, B. S., Raghu, D., Gordon, M., Schwarzkopf, V., & Triantafyllidis, E. (2024). D5 digital circular workflow: Five digital steps towards matchmaking for material reuse in construction. *npj Materials Sustainability*, 2(1), 36. https://doi.org/10.1038/s44296-024-00034-8

Dewagoda, K. G., Ng, S. T., & Chen, J. (2022). Driving systematic circular economy implementation in the construction industry: A construction value chain perspective. *Journal of Cleaner Production*, 381, 135197. https://doi.org/10.1016/j.jclepro.2022.135197

Dsilva, J., Zarmukhambetova, S., & Locke, J. (2023). Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. *Heliyon*, 9(10), e20404. https://doi.3org/10.1016/j.heliyon.2023.e20404

Finamore, M., & Oltean-Dumbrava, C. (2024). Circular economy in construction - findings from a literature review. Heliyon, 10(15), e34647. https://doi.org/10.1016/j.heliyon.2024.e34647

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Honic, M., Kovacic, I., Rechberger, H., & Doiber, U. (2019). BIM-based material passport for buildings: A proof-of-concept study. *IOP Conference Series: Earth and Environmental Science*, 225, 012073. https://doi.org/10.1088/1755-1315/225/1/012073

Hopkinson, P., Zils, M., Hawkins, P., & Roper, S. (2018). Managing a complex global Circular Economy Business Model: Opportunities and challenges. *California Management Review*, *60*(3), 71–94. https://doi.org/10.1177/0008125618764692

Idir, R., Djerbi, A., & Tazi, N. (2025). Optimising the circular economy for construction and demolition waste management in Europe: Best practices, innovations and regulatory avenues. *Sustainability*, 17(8), 3586. https://doi.org/10.3390/su17083586

Jin, Y., Sharifi, A., Li, Z., Chen, S., Zeng, S., & Zhao, S. (2024). Carbon emission prediction models: A review. *Science of The Total Environment*, 927, 172319. https://doi.org/10.1016/j.scitotenv.2024.172319

Joseph, H. S., Pachiappan, T., Avudaiappan, S., Maureira-Carsalade, N., Roco-Videla, Á., Guindos, P., & Parra, P. F. (2023). A comprehensive review on recycling of construction demolition waste in concrete. *Sustainability*, 15(6), 4932. https://doi.org/10.3390/su15064932

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualising the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Cleaner and Responsible Consumption*, 8, 100107. https://doi.org/10.1016/j.clrc.2023.100107

Naoum, S. G. (2012). *Dissertation research and writing for construction students* (2nd ed.). Butterworth-Heinemann. https://doi.org/10.4324/9780203720561.

Oyedele, L. O., Ajayi, S. O., & Kadiri, K. O. (2014). Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resources, Conservation and Recycling,* 93, 23–31. https://doi.org/10.1016/j.resconrec.2014.09.011

Pittri, H., Godawatte, G. A. G. R., Esangbedo, O. P., Antwi-Afari, P., & Bao, Z. (2025). Exploring barriers to the adoption of digital technologies for circular economy practices in the construction industry in developing countries: A case of Ghana. *Buildings,* 15(7), 1090. https://doi.org/10.3390/buildings15071090

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production,* 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or refurbished as CE 3.0? Exploring controversies in the conceptualisation of the circular economy. *Resources, Conservation and Recycling,* 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Rose, C., & Stegemann, J. (2018). From waste management to component management in the construction industry. *Sustainability,* 10(1), 229. https://doi.org/10.3390/su10010229

Shooshtarian, S., Caldera, S., Maqsood, T., Ryley, T., Wong, P. S. P., & Zaman, A. (2022). Analysis of factors influencing the creation and stimulation of the Australian market for recycled construction and demolition waste products. *Sustainable Production and Consumption,* 34, 163–176. https://doi.org/10.1016/j.spc.2022.09.005

Sivers, M., Fröhlich, M., & Fivet, C. (2022). Circular economy digital market solutions for reuse in the European construction sector. *IOP Conference Series: Earth and Environmental Science,* 1078(1), 012121. https://doi.org/10.1088/1755-1315/1078/1/012121

Tennakoon, G. A., Rameezdeen, R., & Chileshe, N. (2023). Identifying factors affecting the low uptake of reprocessed construction materials: A systematic literature review. *Waste Management & Research,* 41(4), 781–800. https://doi.org/10.1177/0734242x221135244

Tennakoon, G., Rameezdeen, R., & Chileshe, N. (2022). Diverting demolition waste toward secondary markets through integrated reverse logistics supply chains: A systematic literature review. *Waste Management & Research,* 40(3), 274–293. https://doi.org/10.1177/0734242X211021478

Tingley, D. D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production, 148,* 642–652. https://doi.org/10.1016/j.jclepro.2017.02.006

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications,* 5, 147–158. https://doi.org/10.17348/era.5.0.147-158

Weerakoon, T. G., Wimalasena, S., & Zvirgzdins, J. (2023). Assessment of implementation of circular economy framework in the Sri Lankan construction sector. *Baltic Journal of Real Estate Economics and Construction Management,* 11(1), 133–152. https://doi.org/10.2478/bjreecm-2023-0009

Wu, H., Weng, X., Li, Y., Liu, S., Ma, J., Chen, R., Yu, B., & Bao, Z. (2025). Critical construction waste minimisation strategies for a circular economy in developing countries: A contractor's perspective in China. *International Journal of Environmental Science and Technology,* 22. https://doi.org/10.1007/s13762-024-06150-1

Herath. H.M.O.V., Wijesinghe W.M.M. and Senarathne, R.T., 2026. Harnessing socio-cultural practices of shanty dwellers for inclusive urban development in Sri Lanka: Evidence from Wattala. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 884-896. DOI: https://doi.org/10.31705/WCS.2026.65. Available from: https://ciobwcs.com/papers/

# HARNESSING SOCIO-CULTURAL PRACTICES OF SHANTY DWELLERS FOR INCLUSIVE URBAN DEVELOPMENT IN SRI LANKA: EVIDENCE FROM WATTALA

**Oshadhi Herath[1], Moksha Wijesinghe[2] and Rusin Thathsara[3]**

## *ABSTRACT*

*The fast urbanization in Sri Lanka has aggravated social-spatial disparities, and especially among the shanty population, who continue to be disadvantaged in the formal urban planning process despite their socio-cultural input to the urban life. The paper explores how the socio-cultural life of shanty residents in Wattala can be utilized to harness inclusivity in urbanization and help in achieving sustainable development goal 11 (SDG 11): Sustainable Cities and Communities. A mixed research design was chosen, involving quantitative survey data from 150 respondents and qualitative data to be collected through focus groups and interviews with key informants, policy makers, urban planners, and community representatives. Participation and exclusion patterns, as well as community resilience, were analysed using descriptive statistical analysis and thematic interpretation. The results show that social cohesiveness is high in informal settlements, with 69 percent of the residents ready to engage in community-based sustainability projects. The paper also singles out fundamental infrastructural issues, such as a lack of clean water, sanitation, and electricity, that are closely linked to informational and institutional obstacles. Informal settlements have high levels of mutual support, adaptive coping, and collective agency despite these limitations, which can be utilized in participatory urban governance. The paper proposes that, to attain inclusive urban sustainability, infrastructural investment alone is insufficient; there should also be awareness-raising, educational empowerment, and behaviour change among policymakers and communities.*

***Keywords:*** *Behavioural Change; Inclusive Urban Development; Informal Settlements; Socio-Cultural Practices; Sustainable Development Goals.*

## 1. INTRODUCTION

The urban structure of Sri Lanka is characterized by rapid development, but socio-economic disparities persist in the spatial structure. The inclusion of Shanty dwellers, who are usually sidelined in planning initiatives, helps cities become socio-culturally rich. Their informal settlements are, however, often seen as a barrier to modernization instead of communities with adaptive knowledge and resilience (Urban Development Authority, 2010). Thus, this study fits within the context of awareness, education, and behaviour

[1] Senior Lecturer, Department of Philosophy, University of Kelaniya, Sri Lanka, oshadhi@kln.ac.lk
[2] Charted Civil Engineer, Advanced Steel Structure (Pvt) Ltd, Sri Lanka, mokshaw@gmail.com
[3] Undergraduate, Department of Building Economics, University or Moratuwa, Sri Lanka, rusinthathsaraofficial@gmail.com

change, as it endeavours to determine how the socio-cultural practices of shanty dwellers can be leveraged to create a sustainable built environment. The study aims to pursue Sustainable Development Goal (SDG) 11, "Make cities and human settlements inclusive, safe, resilient, and sustainable", and to achieve inclusive urban development in Sri Lanka through the incorporation of disadvantaged communities into participatory planning (Department of Census and Statistics, 2023).

The current issue of urban inequality in Sri Lanka can be greatly associated with the historical marginalization of informal settlements. The residents of Colombo live in shanties, slums or in the poor housing schemes and occupy almost nine percent of the total land area of the city (Urban Development Authority, 2010). These communities are not part of formal governance systems, even though they contribute greatly to urban economies by providing informal labour and enhancing cultural diversity. The lack of cohesive urban structures and evidence-based policy models that limit the attainment of Sustainable Development Goal 11 is noted in the State of Sri Lankan Cities Report (2018) (UN-Habitat, 2018). The local literature has mostly focused on housing shortages, the lack of infrastructure, and service provision, while overlooking the socio-cultural aspects of resilience and adaptation. It was a theoretical gap in the urban studies of Sri Lanka because informal settlements are hardly considered as part of the sustainable urban futures. Most studies have focused empirically on underserved settlements in Colombo, but peripheral urban areas, including Wattala, have been understudied (Perera, 2016).

The Wattala area has been considered in this study because it can be framed by its unique socio-spatial and cultural significance within Sri Lanka's urban landscape. Wattala, located adjacent to Colombo, represents one of the most densely populated clusters of underserved settlements, where informal housing patterns intersect with rapid urban expansion. Scholars such as D'Cruz et al. (2009) emphasize that peri-urban shanty communities often develop strong social networks and collective practices that act as informal governance systems, enabling resilience despite exclusion from formal planning. Similarly, Korala (2017) highlights how identity formation among Colombo's shanty dwellers is deeply tied to cultural practices, which makes Wattala an ideal site to examine how socio-cultural behaviors can be harnessed for inclusive development. Moreover, the Urban Development Authority (2010) and SEVANATHA Urban Resource Centre & Colombo Urban Lab (2023) note that relocation and regeneration programs disproportionately affect Wattala's communities, disrupting kinship ties and economic survival strategies. This aligns with Braun and Clarke's (2006) argument that thematic analysis of lived experiences is crucial to uncovering hidden forms of resilience. Wattala thus provides a microcosm of the paradox facing Sri Lanka's urbanization: while aiming for modernization, policies risk deepening inequality unless socio-cultural practices of marginalized groups are integrated into planning. By situating the research in Wattala, the study contributes to the growing body of literature on inclusive urban planning and SDG 11, offering evidence that community-based practices such as savings groups, informal leadership, and cultural rituals can serve as entry points for sustainable urban governance. This makes Wattala not only a representative case but also a critical site for theorizing how socio-cultural capital can bridge the divide between disadvantaged communities and formal planning processes.

Further, Wattala, situated on the periphery of Colombo's metropolitan region, exemplifies the reproduction of urban exclusion beyond the capital's core. Despite its proximity to the city, shanty dwellers in Wattala remain marginalized within the

mainstream planning system, where their socio-cultural contributions to the urban environment are overlooked. The persistence of stigmatization, coupled with inadequate educational opportunities and entrenched behavioural prejudices, sustains cycles of vulnerability and displacement. These communities are systematically neglected in regeneration programmes, reinforcing their precarious status as "outsiders" in the urban fabric. Such exclusion underscores the paradox of Sri Lanka's urban transition: while national policy aspires to modernize and align with SDG 11, peripheral areas like Wattala reveal how socio-spatial divides are deepened when marginalized groups are denied recognition as legitimate urban actors. Addressing Wattala's exclusion thus becomes critical for theorizing inclusive urban development that integrates socio-cultural resilience into sustainable planning.

Also, studies in the world recognizes the relevance of participatory planning in solving the inequalities in the urban world. Participatory methods emphasize the agency of the marginalized communities, which makes them co-producers of knowledge and creators of the city futures (Charmes & Keil, 2015; Mitlin, 2008). South Asia informal settlements are being comprehended as not just places of deprivation but innovative places, resilience places, and adaptive places (Roy, 2005). Yet theoretical gaps remain. Most world urban theories largely continue to define informality as an issue to be addressed and not as a store of adaptive knowledge. Participatory planning models tend to focus on institutional design without much theorization of lived cultures of marginalized people. On the same note, sustainability discourses are more likely to give prominence to infrastructure and governance but pay minimal attention to behavioural change rooted in socio-cultural practices (Satterthwaite, 2009).

Global studies also reveal gaps in empirical research. Most research works base their models on macro-level variables such as housing quality and access to services and fail to focus on micro-level ethnographic data on resilience and cultural adaptation (Patel et al., 2012). In comparison, urban studies are disproportionately represented in African and Latin American settings at the expense of South Asia, which is underrepresented in the discourse on informal settlements. Where empirically tested models of participation have been implemented, as in the case of favela upgrading programs in Brazil, there is limited evidence on how these lessons can be applied in other socio-political environments. Taken together, these gaps point to the importance of a study that would bridge global and local perspectives. Theoretical literature relating SDG 11 to shanty-dwelling culture is limited in Sri Lanka, and few empirical studies examine the agency of shanty dwellers or analyse behavioural transformation. The theory of participatory planning has under-theorized cultural practices in the world, and evidence is not evenly distributed or even geographically balanced. This paper fills these gaps by situating the shanty residents of Wattala within the world discourses on informality, resilience, and participatory town planning. It adds empirical richness through digital ethnography and mixed methods, producing micro-level evidence not captured by macro-level policy discourse. In addition, it realizes SDG 11 by placing a context on the sustainability goals in the local socio-cultural practices and provides action plans on inclusive urban governance in Sri Lanka.

To be more precise, the main aim of the current research is to explore how the socio-cultural behavior of shanty inhabitants in Wattala can be leveraged to stimulate the inclusive urbanization and help achieve Sri Lanka's Sustainable Development Goal 11. To accomplish this goal, the study has three objectives. To start with, it aims to investigate

the perceptions of dwellers in shanties among policymakers, planners, and the general population at large, and to determine how awareness can reshape the attitudes of institutions and society towards underprivileged communities. Second, it will identify knowledge gaps and suggest educational interventions to enable shanty dwellers to actively engage in urban decision-making and planning processes. Third, the paper examines behavioural change methods at the policy and community levels, and ways in which changes in institutional operations and societal beliefs may promote inclusivity and reduce socio-spatial disparities. When combined, these goals offer a holistic approach to awareness, education, and behaviour change in promoting sustainable and equitable urban government. Further, this study intends to begin by fostering dialogue between shanty dwellers and policymakers to reshape perceptions. It will then design education programs to close knowledge gaps and empower active participation in urban planning. At the same time, behavioural change will be promoted through inclusive policy reforms and community initiatives. These combined strategies enhance awareness, build capacity, and transform institutional and societal attitudes. Ultimately, this holistic approach reduces socio-spatial disparities while advancing Sri Lanka's SDG 11 on sustainable cities and communities.

## 2. RESEARCH PROBLEM

More than half of the population of Colombo, Sri Lanka's largest metropolitan area, live in shanties and slums, covering just 9% of the urban land area. Surveys show more than 68,000 families living in unsustainable pockets who have no access to clean water, sanitation, electricity or safe homes, with many having been forcibly displaced under the Urban Regeneration Programme, breaking community bonds and further limiting their economic opportunities. In addition to the facts that utilities costs are rising and that household taxes are also increasing, national data reveals that slum housing is not evenly distributed among the districts. This paradox itself highlights the systematic eviction of low-income residents from Colombo in the name of its bid to make it a "world city", thus perpetrating poverty and inequality. To overcome socio spatial divides and sustainable development, inclusive urban planning is crucial and needs to be aligned to SDG 11. This is not only a problem in Colombo, but the peripheral urban areas also such as Wattala have a similar problem as the marginalized groups continue to be marginalised in the mainstream planning system. Despite the socio-cultural contribution of the shanty dwellers to the urban context, they are still stigmatized and neglected in Wattala. The communities mentioned remain vulnerable to displacement and marginalization because of ignorance on the part of policymakers, lack of education by the people and systematic behavioural stigmas.

Figure 1 provides a statistical summary of the under-served settlements in Colombo, Sri Lanka, to show the extent and concentration of urban inequality. It shows that half of the population in Colombo resides in shanties, slums or run down housing schemes that occupy 9 per cent of the total land area of Colombo. In such settlements, 68,812 families are sharing 1,499 community clusters with most of them having no access to primary services like clean water, sanitation, electricity, and safe housing conditions. All these characters point to the fact that there is a vicious circle between colonisation and poverty, a vicious urban paradox, in this one city on the road to becoming a world-class city, the poor and the shanty residents are increasingly being stigmatised.

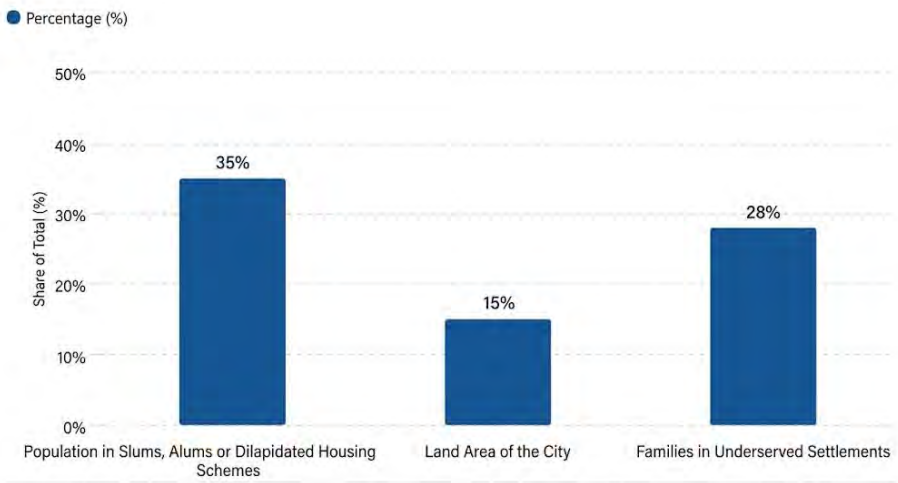



*Figure 1: Survey of underserved settlements in Colombo municipal council area. Colombo: Urban Development Authority of Sri Lanka.*

*Source: Urban Development Authority (2010)*

However, whilst the number of surveys indicating Wattala does not indicate a high percentage, it mirrors most of the issues in Colombo. The enclosure of shanty dwellers from formal planning processes is also felt in Wattala where there is a similar lack of service delivery and housing security. The visualization reinforces the power of inclusive city planning and emphasises the socio-spatial inequities that threaten the sustainability and equity for the urban future of Sri Lanka. Otherwise, Colombo, Wattala and like cities would continue to be the world of poverty, of failing to deliver on promises in SDG 11: Sustainable Cities and Communities without the need to bring in the socio-cultural contribution of these communities.

This background is the context within which the current study explores the role played by socio-cultural activities of the slum dwellers in the sustainability of the urban areas and how socio-cultural activities awareness, education and behaviour change can play a role in bridging the gap between the slum dwellers and the formal planning processes. A socio-cultural impact to the urban environment by the shanty dwellers on Sri Lanka will be answered on the basis of this, the study will take four important questions. How do we change the perception of people and institutions on disadvantaged communities via awareness-raising? Which educational systems will help the inhabitants of slums to join sustainable urban development? And lastly, what needs to change in the behaviour of policymakers and communities to attain inclusive urban governance?

## 3. RESEARCH METHODOLOGY

This study used mixed method research design which investigates the socio-cultural practices of the shanty dwellers in Wattala and how these practices can contribute in inclusive urban development in Sri Lanka. The study was ontological, based on a constructivist perspective that sees the construction of social reality as shaped by lived experiences and community practices (Creswell & Plano Clark, 2018). Epistemologically, an interpretivist perspective was used which focused on the need to grasp the process of meaning making and the agency of marginalised groups in the field of urban sustainability (Schwandt, 1994). This methodological approach brings both qualitative and quantitative approaches together to capture depth of community narratives

and the breadth of socio-economic circumstances (Tashakkori & Teddlie, 2010). Primary data has been gathered using structured surveys with the shanty dwellers, focus group discussions with community members and key informant interviews with key persons in the field of community, urban planning and policy. These approaches offer a glimpse into perceptions of exclusion, community resilience, and informal governance systems (D'Cruz et al., 2009). Secondary data has been gathered from policy documents, urban planning reports, census data, and previous investigations done on underserved settlements in Colombo and other districts which provide a comparative context (Urban Development Authority, 2010). The total population of the interest is about 2500 families in the informal settlements of Wattala and from which a purposive sample of 150 families has been selected based on gender, age, tenure and leadership (Korala, 2017).

The purposive sampling of 150 respondents for the survey was well-distributed across the economically active population (25-45) and youth (18-24) and older adults (46+). Gender-wise, the distribution was nearly even, and ethnic-wise, it was mainly Sinhala, Tamil and Muslim households, as expected in Wattala which is a multi-ethnic place. The majority of the respondents were involved in informal work or small-scale businesses or in daily wage employment, and the tenure of housing had been variable from both long-term residents and recent migrants. Focus group discussions (FGDs) were held with the same respondents as the survey, and they addressed the context, which is the three groups of respondents, namely: the community leaders, the university educators and the cultural practitioners (some of the artists). Key informant interviews (KIIs) were held with religious leaders and Grama Niladhari (GN) officials. To this end three focus group discussions (FGDs) were held, each with a membership of 8 – 12 participants, and split into three categories of community leaders, university educators and cultural practitioners. Four key informant interviews (KIIs) were conducted with the three Grama Niladhari officials and religious leaders, to gain institutional and cultural insights into issues of exclusion. Qualitative input data analysis are accompanied by thematic coding and quantitative input analysis based on descriptive statistics from survey results. The qualitative stories have been analysed thematically in order to identify any common patterns of exclusion and resilience (Braun & Clarke, 2006) and the quantitative data as part of survey has been analysed using SPSS software to generate descriptive statistics. This mixed method approach allows the study to investigate how awareness, education and behavioural change can help narrow the gap between the disadvantaged and formal planning processes and contribute to Sri Lanka's pledge towards SDG 11 on sustainable cities and communities (SEVANATHA Urban Resource Centre & Colombo Urban Lab, 2023).

The methodology adopted is justified because it brings depth and breadth in the analysis of socio-cultural practices of shanty dwellers in the study area of Wattala, as it incorporates both qualitative information about their lived experiences and quantitative information about their socio-economic situation (Creswell & Plano Clark, 2018; Schwandt, 1994). Structured surveys, focus group discussions, and key informant interviews provide triangulation of perspectives, reflecting community voices and institutional perspectives, and secondary sources provide a broader context for findings in terms of the urban development trends. (D'Cruz et al., 2009; Urban Development Authority, 2010) Qualitative narratives are analysed theatrically to identify patterns of exclusion and resilience (Braun & Clarke, 2006) and survey data are analysed descriptively to provide measurable evidence of disparities and participation. This holistic

approach is especially applicable to the integration of SDG 11, which works to promote inclusive and sustainable urban governance, and connects to the disadvantaged communities and the formal planning processes (SEVANATHA Urban Resource Centre & Colombo Urban Lab, 2023).

## 4. FINDINGS AND DISCUSSION

The results of the study shed light on the experiences of Wattala's shanties and their socio-cultural practices in the backdrop of inclusive urban development. The analysis is triangulated based on the survey data, focus group discussions, and key informant interviews to gain a more complete picture of the structural aspect of exclusion and the everyday strategies of resilience. The section starts by summarizing the themes that were identified from the data and how community voice and institutional voice are encountered. The themes are then discussed in the context of current scholarship and policy work, and connections are made between experiences of marginalisation at the local level and Sri Lanka's national SDG 11. The study highlights the need to acknowledge socio cultural agency as a basis for the sustainable and equitable city administration.

**Theme I - Socio-Cultural Practices and Community Resilience.**

Even though infrastructure was lacking, the results of the questionnaire indicated that 69% of the population was prepared for community-based programming. Respondents also reported on mutual aid and cooperation, including water sharing and helping with house building that reflect high levels of community cohesion. These quantifiable findings highlight the importance of informal networks as a functional asset with a direct connection to SDG 11 on sustainable cities and communities.

These survey findings were reinforced by the stories heard during the focus group discussions, which highlighted solidarity-based adaptive practices. Participants shared what they do to support each other, such as sharing water when needed, lending each other tools to repair houses, etc., and described with words like we share water when we need, we assist each other to repair houses. In these narratives, resilience was seen as more than just a material fact; they were also social and social networks were seen as the core of what was needed to survive in the face of hardship. The discussions also reflected the need for empowerment, indicating the potential for extending the empowerment activities at the community level to increase resilience and promote inclusive development.

These findings were corroborated by inputs from an outside group through interviews. The informal network can fill the gap where formal support systems are absent and has the history of helping communities bargain with formal systems, as noted by key informants, such as local leaders and representatives from NGOs. Such is the case of D’Cruz et al. (2009) who recorded slum dwellers' federations in Moratuwa successfully claiming rights to housing through collective action. Interviews thus highlighted the role of agency in the community in driving sustainability and the need for institutional recognition of such practices for inclusive governance.

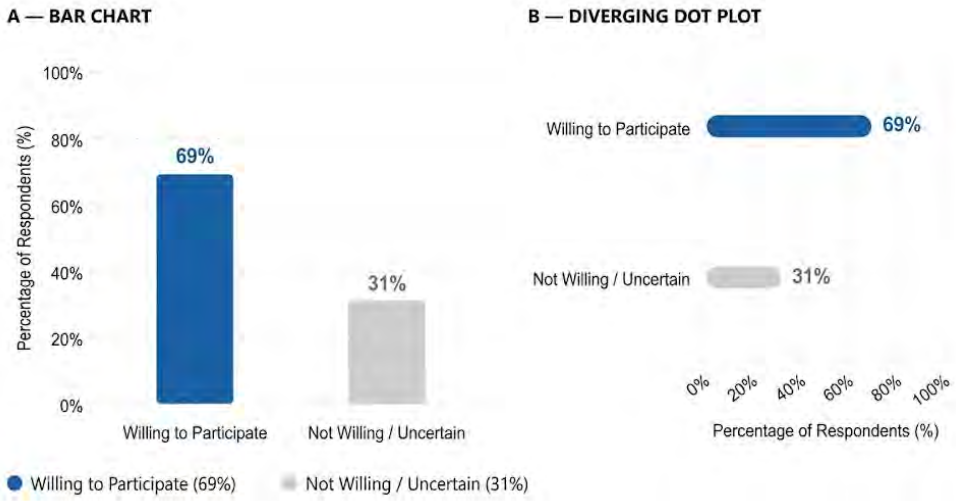



*Figure 2: Survey results in the access, perceptions and aspirations of the shanty dwellers in Wattala,2026*

**Theme II- Institutional Perceptions and Planning Exclusion.**

Results of the questionnaire showed that the perception of "exclusion from the planning processes" was widespread among the shanty dwellers, with 81% saying that they felt excluded from urban planning and 76% saying that policymakers perceived them as hindering modernization. These quantitative findings emphasize the concept of systemic marginalisation, in which communities are excluded from the legitimacy to define the city. This exclusion highlights the critical need for institutional changes that recognize and respect the rights of informal settlers as citizens, not as obstacles to development.

The focus group narratives gave further expression to these perceptions, and a number of the participants felt frustrated that they were stigmatised and turned down in planning discourses. A planner's statement that "There is somehow a stigma associated with shanty dwellers. They are perceived as occupants, rather than as citizens who have rights" gives a good example of how deep-seated these stereotypes are. In addition to infrastructural neglect, these conversations showed that there was symbolical marginalisation as well: the community was socially constructed as a community without merit. In this sense, Korala (2017) noted that slum dwellers in Colombo were being presented as "undeserved," which further stunted their stigmatisation and exclusion.

The findings were reinforced by the insights gained from the interviews: institutionalized values and attitudes that conflict with inclusive governance persist. Local leaders and urban planners recognized that attitudes often view the occupants of the shanties as illegitimate, inauthentic, and not entitled to a voice in decision making. These views underline the importance of awareness campaigns and institutional changes in the process of rebranding the attitude of marginalized communities. These interviews highlighted the need to include the voices of the disadvantaged in planning, as called for by SEVANATHA Urban Resource Centre and Colombo Urban Lab (2023) to remove stigma and progress inclusive urban development.

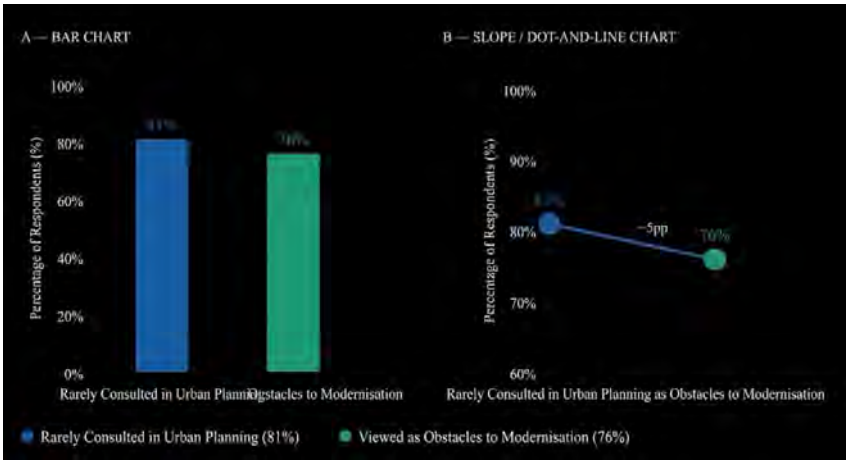



*Figure 3: Survey data results on planning exclusion and perceptions of institutions ( Note: Each point represents the proportion of survey respondents agreeing with the respective governance perception statement. The slope illustrates the 5-percentage-point differential between the two perception dimensions. Values rounded to the nearest whole percentage.)*

**Theme III - Knowledge Gaps and Educational Empowerment.**

The results of the questionnaire showed that in Wattala, the shanty dwellers were facing serious infrastructural problems as 72 % of them had no access to clean water, 68 % had no sanitation facilities, 64 % had no stable electricity supply and so on. The quantitative findings illustrate, and are representative of, the material shortages that persist and continue to affect the daily lives of these disadvantaged communities, and therefore the continued influence of basic service deprivation on the daily lives of these communities.

But these statistics were complemented by stories that came from the focus groups which highlighted the desire of the community for empowerment in the context of such marginalisation. They complained that they were not given an opportunity to learn and participate and one added “If we know how to approach officials, we will be able to speak to them about our problems, we want to learn.” These stories show how informational barriers to participation are interwoven with infrastructural barriers to participation—when individuals do not have civic education and advocacy skills, they are unable to meaningfully engage their concerns.

These perspectives were further supported by insights gained from interviews, which emphasized the need for education-based interventions that foster negotiation strategies, advocacy and participatory engagement. Key informants emphasized that addressing the gaps in urban governance infrastructure and information is crucial for enabling the poor and vulnerable to assert their rights and engage in meaningful governance. This is in line with Mataraarachchi (2024), who has suggested the need to incorporate social aspects into urban sustainability, and Creswell and Plano Clark's (2018) claim that mixed methods can have a positive effect on disadvantaged communities, as they provide narratives that are deep and statistical that are broad.

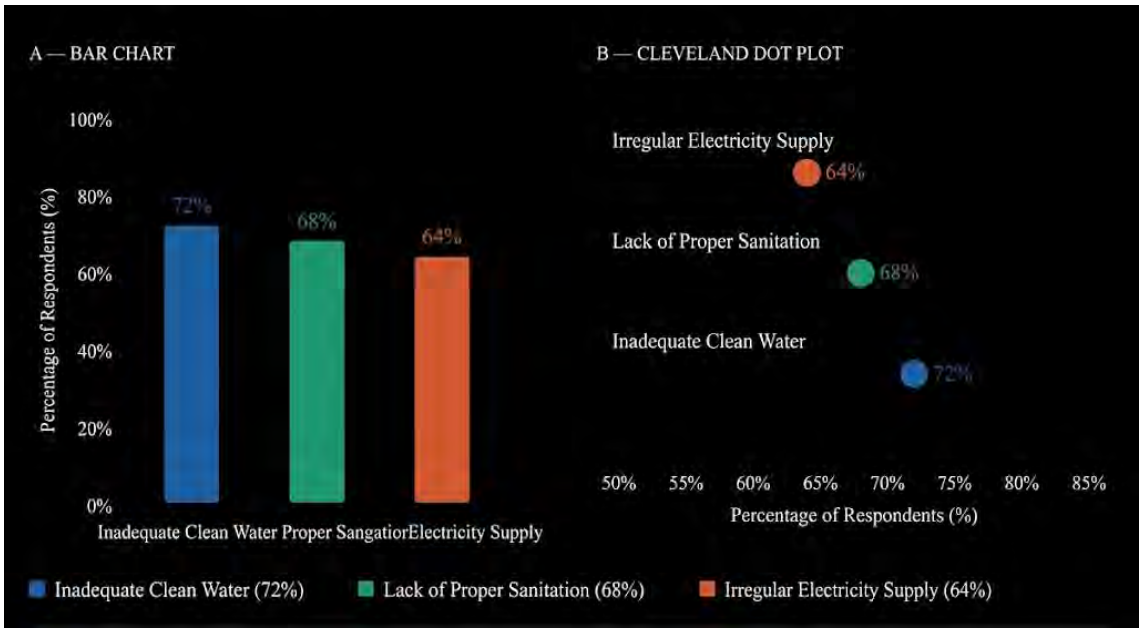



*Figure 4: Survey results on perceived infrastructural shortages among the respondents*

**Theme IV- Behavioural Change and Inclusive Urban Governance.**

The questionnaire findings revealed that while policymakers often stigmatize shanty A substantial portion of the population in the dwellers (69%) showed their willingness to participate in sustainable programs. This quantitative evidence demonstrates the community's willingness to participate in urban development projects in a positive manner despite being excluded by systems. These findings suggest that community action to further inclusive governance may be possible through participatory techniques.

These findings were extended by adding a depth perspective in the narratives produced by focus groups, which expressed residents' frustration with displacement policies. Concerns expressed included that “relocation breaks our lives” and “We are told to move all the time; nobody asks how we live here.” These comments highlight how relocation can affect social relationships and impact resilience. Important themes discussed in these accounts include the need to achieve behavioural change, not just within the community, but in institutional practice, and why trust and cooperation cannot be built in a setting where displacement is repeated and unconsult.

These views were supported by insights from the interviews, which highlighted the need for institutional change to reduce stigma and for community work to increase trust. Key informants emphasized the need for behavioral change approaches to take place at both the institutional and the community level, with shanty dwellers being perceived as legitimate citizens by the institutions and communities being supported to cooperate in sustainable programmes. This two-pronged approach helps to distil recurring stories and follows the thematic analysis framework outlined by Braun and Clarke (2006) and the call to participatory governance as a route to inclusivity by SEVANATHA Urban Resource Centre and Colombo Urban Lab (2023). The findings of both studies show that behavioural change strategies play a crucial role in diminishing the socio-spatial disparities and promote sustainable urban governance.

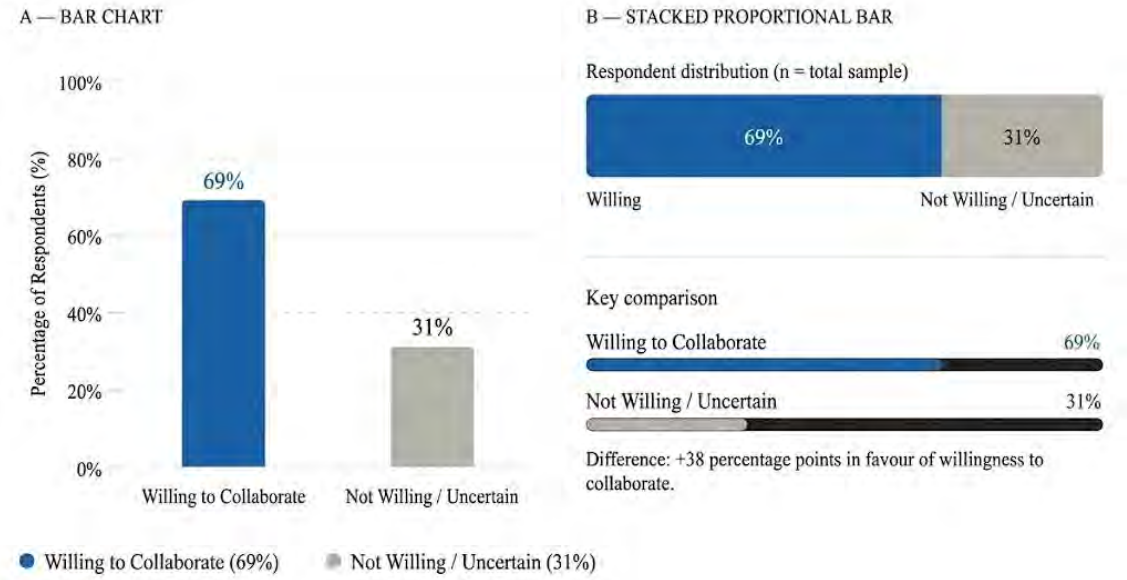



*Figure 5: Survey- based results of the readiness of the residents to cooperate in sustainable projects.*

The study shows that socio cultural practices of the shanty dwellers in Wattala are not only survival mechanisms, but it is also a practical resource to promote inclusive urban development process. Informal networks, mutual supports and adaptive strategies demonstrate resilience, which, if systematically incorporated, could enhance participatory governance. But entrenched institutional exclusion and stigmatisation persist in blocking this potential, highlighting the need for changes which acknowledge and give legitimacy to community agency. The evidence also indicates that there is a link between infrastructural deprivation and knowledge gaps and civic empowerment, and hence, there is a need for pragmatic educational interventions on negotiation and advocacy skills. Meanwhile, residents expressed readiness to join sustainability programs underlines the need to employ behavioural change strategies that reach to policymakers and support the removal of stigmas and participatory approaches and communities that build trust and collaboration. Finally, the results show that the transition to SDG 11 in Sri Lanka calls for a two-part approach, both infrastructural investments and institutional change and empowerment of voices of the marginalised for equitable and sustainable urban future.

## 5. CONCLUSIONS

The study shows that, even though the infrastructure lacks in the shanty slums and the institutions are marginalized, the people of the slums have strong socio-cultural capital, which can be used as the basis for inclusive urban development. Findings indicate that there is a high level of community receptivity to collective activities (69%), but that actors are still facing many structural barriers, such as involving only selected communities in the consultation process (81%) and negative perceptions of institutions (76%). These findings show an obvious lack of coherence between local resilience and government processes. It also highlights that infrastructural gaps (e.g. clean water, sanitation, electricity) do not only stem from technical issues but are linked to knowledge gaps and lack of access to participatory mechanisms. Qualitative evidence reinforces that within communities' adaptive practices, mutual support systems and collective agency exist. Yet these practices are not institutionalized, limiting their ability to be translated into formal

urban policy frameworks. Importantly, the study points to a need to target institutional stigmas for policymakers and to build mutual trust and collaboration among communities, as part of the behavioural change strategies. Policymakers need to shift from stigmatizing narratives to more participatory approaches acknowledging informal settlements as critical contributors to the urban socio-economic fabric. At the same time, capacity-building interventions to improve community negotiation, advocacy, and engagement capacities is critical to fill governance gaps. Overall, the findings support the global debate on Sustainable Development Goal 11, which calls for inclusive urban urban development, not only through investments in infrastructure but also through the need for institutional change and strengthening of marginalised groups. Going forward, there is a need to explore more in-depth how policy mechanisms can incorporate informal socio-cultural systems into formal planning processes to promote sustainable and equitable city transformation.

## 6. ACKNOWLEDGMENTS

The authors acknowledge and recognize the valuable contributions of previous authors whose work has laid the foundation for this study and provided essential insights that guided the research.

## 7. REFERENCES

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

SEVANATHA Urban Resource Centre, & Colombo Urban Lab. (2023). *Colombo Settlements Survey 2023*. Colombo Municipal Council. https://www.csf-asia.org/wp-content/uploads/2024/03/CSS-Survey-2023-report_Final.pdf

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). Sage.

D'Cruz, C., McGranahan, G., & Sumithre, U. (2009). The efforts of a federation of slum and shanty dwellers to secure land and improve housing in Moratuwa: from savings groups to citywide strategies. *Environment and Urbanization*, *21*(2), 367–388. https://doi.org/10.1177/0956247809342360

Department of Census and Statistics. (2023). *Sri Lanka sustainable development indicators report*. Government of Sri Lanka. https://www.statistics.gov.lk

Charmes, E., & Keil, R. (2015). The politics of post-suburban densification in Canada and France. *International Journal of Urban and Regional Research*, *39*(3), 581–602. https://doi.org/10.1111/1468-2427.12194

Korala, A. (2017). *"Underserved" or "undeserved"? A study on the identity formation of the "slum" and "shanty" dwellers in Colombo* [Conference presentation]. ICONArts 2017, Faculty of Arts, University of Colombo, Sri Lanka.

Mataraarachchi, S. (2024, August 21). Designing Our Future: The power of strategic approaches in town planning. *Ceylon Today*. https://ceylontoday.lk/2024/08/21/designing-our-future-the-power-of-strategic-approaches-in-town-planning/

Mitlin, D. (2008). With and beyond the state — Co-production as a route to political influence, power and transformation for grassroots organizations. *Environment and Urbanization*, *20*(2), 339–360. https://doi.org/10.1177/0956247808096117

Patel, S., Baptist, C., & D'Cruz, C. (2012). Knowledge is power – Informal communities assert their right to the city through SDI and community-led enumerations. *Environment and Urbanization*, *24*(1), 13–26. https://doi.org/10.1177/0956247812438366

Perera, N. (2009). People's spaces: Familiarization, subject formation and emergent spaces in Colombo. *Planning Theory*, *8*(1), 51–75. https://doi.org/10.1177/1473095208099298

Roy, A. (2005). Urban informality: Toward an epistemology of planning. *Journal of the American Planning Association, 71*(2), 147–158. https://doi.org/10.1080/01944360508976689

Satterthwaite, D. (2009). The implications of population growth and urbanization for climate change. *Environment and Urbanization, 26*(1), 3–11. https://doi.org/10.1177/0956247809344361

Schwandt, T. A. (1994). Constructivist, interpretivist approaches to human inquiry. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 118–137). Sage.

Tashakkori, A., & Teddlie, C. (Eds.). (2010). *SAGE handbook of mixed methods in social & behavioral research (2nd ed.).* SAGE Publications. https://doi.org/10.4135/9781506335193

Urban Development Authority. (2010). *Colombo urban development plan and undeserved settlements report*. Government of Sri Lanka.

UN-Habitat. (2018). *The state of Sri Lankan cities 2018 report*. United Nations Human Settlements Programme. https://unhabitat.org/the-state-of-sri-lankan-cities-2018-report.

Hemantha, H.H.A.P., Waidyasekara, K.G.A.S. and Uduwage, D.N.L.S., 2026. Identifying factors influencing construction material procurement performance through Latent Dirichlet Allocation analysis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 897-910. DOI: https://doi.org/10.31705/WCS.2026.66. Available from: https://ciobwcs.com/papers/

# IDENTIFYING FACTORS INFLUENCING CONSTRUCTION MATERIAL PROCUREMENT PERFORMANCE THROUGH LATENT DIRICHLET ALLOCATION ANALYSIS

**H.H.A.P Hemantha[1], K.G.A.S. Waidyasekara[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Construction material procurement plays a critical role in determining cost efficiency, schedule performance, and overall project success in construction. Although numerous studies have examined procurement practices and supply chain management, the factors influencing procurement performance remain fragmented across the literature. This fragmentation limits a comprehensive understanding of procurement performance and its key dimensions. To address this issue, this study conducts a Latent Dirichlet Allocation (LDA) based literature review to identify major themes and derive procurement performance factors. A dataset of 983 peer-reviewed journal articles was analysed to explore thematic patterns in construction material procurement research. The analysis identified four dominant domains: procurement risk and cost performance, environmental impact of construction materials, supply chain and logistics, and sustainable procurement and circular economy. Based on these themes, procurement-related factors were derived and organised to provide a structured understanding of procurement performance. The findings highlight the multidimensional nature of procurement systems and emphasise the importance of integrating cost management, logistics coordination, supplier performance, and sustainability considerations to improve construction project outcomes.*

***Keywords:*** *Construction Material Procurement; Construction Supply Chain; Latent Dirichlet Allocation; Procurement Performance; Topic Modelling.*

## 1. INTRODUCTION

The construction industry is a major contributor to economic development, supporting infrastructure growth and employment generation across both developed and developing economies (Momani et al., 2016). Within this sector, construction materials represent one of the most significant cost components, typically accounting for a substantial proportion of total project expenditure (Yunna & Ping, 2012). The availability, quality, and timely delivery of materials are therefore critical factors influencing project cost efficiency,

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, hemanthaprasad590@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

schedule adherence, and overall project success (Wawak et al., 2020). Despite their importance, construction projects frequently experience problems related to material procurement. Issues such as delayed deliveries, price fluctuations, poor coordination, and inaccurate quantity planning often lead to cost overruns, schedule delays, and productivity losses (Ajayi & Oyedele, 2018; Opoku et al., 2022). These challenges are further intensified by the fragmented nature of construction supply chains and the involvement of multiple stakeholders, including contractors, suppliers, and logistics providers (Hussain et al., 2023). As a result, material procurement has become a critical function that directly influences project performance and organisational competitiveness (Jusoh & Kasim, 2017).

Construction material procurement performance refers to the ability of an organisation to acquire required materials in the right quantity, quality, cost, and time while ensuring effective coordination across the supply chain (Alsamarraie & Ghazali, 2022). Traditionally, procurement performance has been evaluated based on key dimensions such as cost, time, and quality. However, recent studies highlight that procurement performance extends beyond these basic measures and includes additional dimensions such as supplier performance and process efficiency (Ibrahim et al., 2024). These dimensions collectively reflect the effectiveness of procurement systems in supporting project delivery and achieving desired outcomes. Given the high proportion of material-related costs and the direct impact of procurement activities on project outcomes, improving construction material procurement performance is essential. Effective procurement contributes to cost control, timely project completion, improved quality, and enhanced coordination among stakeholders. Conversely, poor procurement practices can disrupt project execution and reduce overall efficiency. Therefore, understanding and improving procurement performance is critical for achieving successful construction project outcomes.

Previous studies have examined various aspects of construction material procurement, including supplier selection, procurement planning, logistics coordination, and supply chain integration (Kamil & Mulyono, 2025; Parisi & Donyavi, 2025; Sivasubramaniam et al., 2024). These studies have identified several factors influencing procurement performance, such as supplier reliability, cost management practices, logistics efficiency, and information sharing. However, these factors are often studied separately across different research areas, resulting in a fragmented understanding of procurement performance (Zhao et al., 2022). In addition, the growing volume of research in this field makes it increasingly difficult to obtain a comprehensive and integrated view of the factors influencing construction material procurement performance. This lack of integration limits the ability of researchers and practitioners to fully understand how different factors interact and influence procurement outcomes. Addressing this issue is important for developing a more structured and holistic understanding of procurement performance, which can support better decision-making and improved project outcomes.

Therefore, this study conducts a LDA based review of construction material procurement literature using a structured search protocol. By analysing a large corpus of academic publications, the study aims to identify the key factors influencing construction material procurement performance. To achieve this aim, the following objectives are addressed:

1. To identify major themes related to construction material procurement performance.

2. To examine how these themes have developed over time.
3. To derive construction material procurement performance factors from the identified themes.

## 2. METHODOLOGY

This study is designed as a literature-based investigation to identify and organise factors influencing construction material procurement performance. The research focuses on systematically analysing existing academic publications to develop a comprehensive understanding of procurement-related factors within the construction domain. To achieve this, the study adopts a topic modelling approach using LDA to analyse the collected literature. The use of LDA allows the study to extract hidden structures within the literature that may not be readily observable through conventional analysis.

Figure 1 illustrates the overall workflow pipeline followed in this study, including literature retrieval, screening, and the subsequent analysis of the literature corpus using the LDA-based approach.

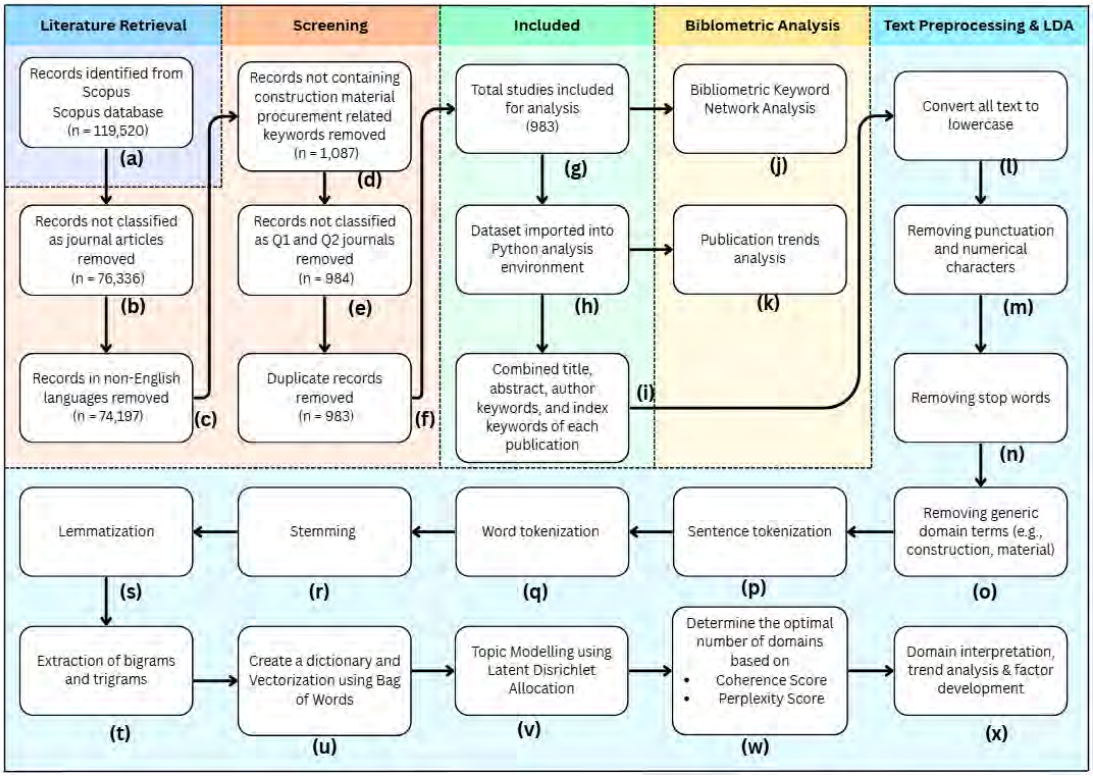



*Figure 1: Detailed workflow of the LDA-based literature review, illustrating the sequential stages of literature retrieval and screening (a–f), dataset preparation (g–i), bibliometric analysis (j–k), text preprocessing and normalization (l–t), corpus representation and topic modelling (u–v), model evaluation (w), and factor derivation and interpretation (x).*

The workflow is divided into a series of labelled stages (a–x), where each label represents a specific process within the research framework and is referenced throughout the methodology to describe the corresponding analytical procedures.

## 2.1 MATERIALS AND METHODS

The first stage of the research involved retrieving and screening relevant literature related to construction material procurement. The literature retrieval process began with the identification of publications indexed in the Scopus database as illustrated in Figure 1(a). Although both Scopus and Dimensions databases were initially explored, a comparison of search results indicated that nearly all relevant publications retrieved from Dimensions were already indexed in Scopus. Therefore, Scopus was selected as the primary data source due to its comprehensive coverage and structured bibliographic metadata suitable for bibliometric and LDA based analysis. A structured search query was then developed to retrieve publications related to construction materials, procurement processes, and performance-related factors. The search query combined three groups of keywords representing the research context, procurement domain, and performance attributes. Boolean operators were used to combine these keyword groups to ensure comprehensive retrieval of relevant studies. The search query used for retrieving the literature dataset is illustrated in Figure 2. The application of this query to the Scopus database resulted in 119,520 initial records, as shown in Figure 1(a).

```
TITLE-ABS-KEY (("construction" OR "building")
                AND material*
AND ("procurement" OR "sourcing" OR "supply chain" OR
                "logistics")
AND ("factor*" OR "driver*" OR "attribute*" OR "indicator*")
          AND ("performance" OR "success"))
           AND (LIMIT-TO (DOCTYPE, "ar"))
         AND (LIMIT-TO (LANGUAGE, "English"))
```

*Figure 2: Search query used for literature retrieval*

The retrieved records were subsequently filtered to ensure the relevance and quality of the dataset. In the first filtering stage, records that were not classified as journal articles were removed from the dataset as shown in Figure 1(b). This filtering step reduced the dataset to 76,336 records. In the next stage, publications written in languages other than English were excluded to ensure consistency in textual analysis. After removing non-English publications, 74,197 records remained for further screening as illustrated in Figure 1(c). The screening process then focused on identifying studies related specifically to construction material procurement. Records that did not contain construction material procurement related keywords were excluded from the dataset as shown in Figure 1(d). This filtering stage reduced the dataset to 1,087 potentially relevant articles. In the next step, the quality of the journals in which these articles were published was evaluated. Articles published in journals that were not classified as Q1 or Q2 according to the SCImago Journal Ranking were removed from the dataset as illustrated in Figure 1(e). This stage resulted in 984 articles being retained for further analysis.

Finally, duplicate publications were identified using Digital Object Identifier (DOI) cross-referencing and removed from the dataset. This process ensured that each publication was represented only once in the literature corpus. After removing duplicate records, the final dataset consisted of 983 journal articles, as shown in Figure 1(f). These articles formed the literature corpus used for the subsequent analytical procedures.

## 2.2 MATERIAL ANALYSIS

### 2.2.1 Bibliometric and Descriptive Analysis

An initial bibliometric analysis was conducted to obtain an overview of the research landscape. Keyword co-occurrence analysis was performed using extracted author and index keywords to identify relationships among frequently occurring concepts and to reveal dominant thematic clusters within construction material procurement research. In addition, a publication trend analysis was carried out to examine the temporal evolution of research activity within the dataset, as illustrated in Figure 1(j)–(k).

### 2.2.2 Text Preprocessing

Following bibliometric analysis, the textual dataset was prepared for topic modelling through a series of preprocessing steps. All textual data were first converted to lowercase to ensure consistency in word representation. Subsequently, punctuation marks and numerical characters were removed to eliminate non-informative elements from the corpus. Common stop words were then removed to reduce noise and improve the quality of the textual data. In addition, domain-specific generic terms such as “construction” and “material” were excluded, as these frequently occurring words do not contribute to meaningful topic differentiation. These preprocessing steps are illustrated in Figure 1(l)–(o).

### 2.2.3 Text Normalisation and Tokenization

After preprocessing, sentence segmentation was applied to structure the text into manageable units. The text was then tokenised into individual word tokens, forming the basis for further analysis. Subsequently, stemming and lemmatisation were applied to standardise word forms and reduce them to their base representations, ensuring consistency across the corpus. This tokenisation and normalisation process is presented in Figure 1(p)–(s).

### 2.2.4 Feature Extraction

To capture meaningful contextual information within the corpus, bigram and trigram extraction techniques were applied. These methods identify frequently co-occurring word combinations such as “supply chain”, “risk management”, and “waste management”, which represent important domain-specific concepts. This step enhances the semantic representation of the dataset by incorporating multi-word expressions, as shown in Figure 1(t).

### 2.2.5 Corpus Representation and Vectorization

A dictionary representing the vocabulary of the corpus was constructed based on the processed tokens. Subsequently, the textual data were transformed into a numerical representation using a bag-of-words approach. Each document was converted into a sparse document-term matrix, where the frequency of each term within a document is recorded. This vectorised representation serves as the input for the topic modelling process, as illustrated in Figure 1(u).

### 2.2.6 Topic Modelling Using LDA

Topic modelling was performed using LDA, a probabilistic method that identifies latent thematic structures by analysing word co-occurrence patterns across documents. The model assumes that each document is composed of a mixture of topics, while each topic

is represented by a distribution of words. The LDA model was implemented in Python using Gensim, NLTK, and pyLDAvis libraries, as illustrated in Figure 1(v).

### 2.2.7 Model Evaluation and Topic Interpretation

To determine the optimal number of topics, multiple LDA models were trained with different topic configurations. Model performance was evaluated using coherence and perplexity metrics. The coherence score assesses the semantic consistency of keywords within each topic, while perplexity measures the model's predictive performance. The optimal topic structure was selected based on a balance between interpretability and statistical reliability, as shown in Figure 1(w).

### 2.2.8 Factor Derivation and Integration

Once the optimal topic model was identified, the resulting topics were interpreted by analysing the most representative keywords associated with each topic as per Figure 1(x). These keywords were used to identify meaningful thematic domains within the literature. The factor derivation process consisted of three stages. First, the highest-weighted keywords associated with each topic were extracted from the LDA output and examined within their thematic context. Second, semantically related keywords were grouped based on conceptual similarity and their relevance to construction material procurement. Third, the preliminary factors were refined by eliminating overlapping concepts, improving terminology consistency, and converting keyword clusters into clearly defined procurement performance factors. The resulting factors were reviewed against the construction procurement literature to ensure conceptual relevance and practical applicability. Finally, the results were synthesised into a structured representation of procurement performance dimensions.

## 3. RESULTS AND DISCUSSION

### 3.1 BIBLIOMETRIC KEYWORD NETWORK ANALYSIS

Bibliometric keyword network analysis was conducted to identify relationships among frequently occurring keywords and reveal dominant thematic clusters within the literature. This step provides an overview of the intellectual structure of construction material procurement research and supports the analysis of the research landscape. The analysis was performed using VOSviewer based on three keyword datasets extracted from Scopus records: author keywords, index keywords, and the combined keyword set.

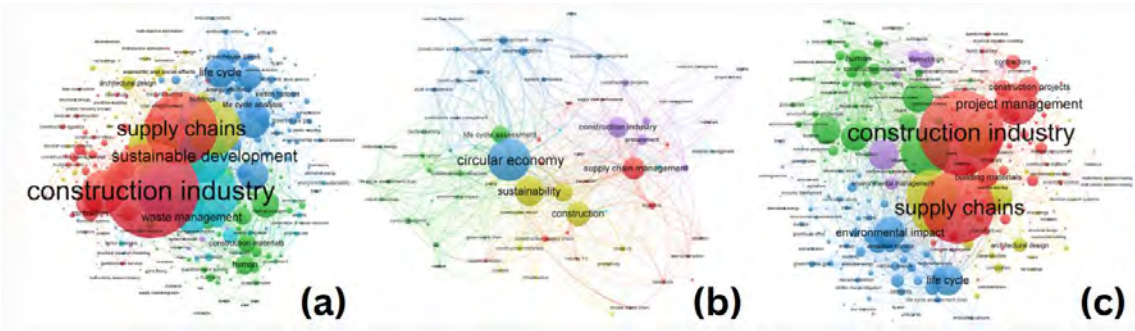



*Figure 3: Keyword co-occurrence networks generated from (a) author keywords, (b) index keywords, and (c) combined keywords.*

Figure 3 presents the keyword co-occurrence networks generated from these datasets, where Figure 4(a) corresponds to author keywords, Figure 3(b) to index keywords, and Figure 4(c) to the combined network. Each dataset offers a distinct perspective, enabling a more comprehensive understanding of thematic relationships within the literature.

The author keyword network as per Figure 3(a) highlights themes emphasized by researchers, with prominent nodes such as construction industry, supply chains, sustainable development, and waste management forming dense clusters. These clusters indicate strong research focus on procurement logistics, supply chain coordination, and sustainability in construction projects.

The index keyword network as per Figure 3(b) provides a broader conceptual representation, capturing themes such as circular economy, life cycle analysis, sustainability, and construction management. These patterns reflect the increasing importance of environmental performance, lifecycle assessment, and resource efficiency in construction material research.

The combined keyword network as per Figure 3(c) integrates both keyword sources to provide a comprehensive representation of the domain. Central nodes such as construction industry, supply chains, and project management highlight key research areas, while interconnected clusters reflect themes related to procurement practices, logistics management, and environmental sustainability.

Overall, the keyword network analysis reveals that construction material procurement research is strongly connected with supply chain management, sustainability, environmental impact assessment, and project management. These insights establish a foundation for the subsequent LDA-based analysis, which focuses on identifying latent thematic structures within the literature.

## 3.2 PUBLICATION TREND ANALYSIS

Following bibliometric keyword network analysis, publication trend analysis was conducted to examine the temporal evolution of research activity related to construction material procurement. Understanding publication trends provides insights into how research attention toward procurement performance has developed over time and helps contextualise the subsequent thematic analyses.

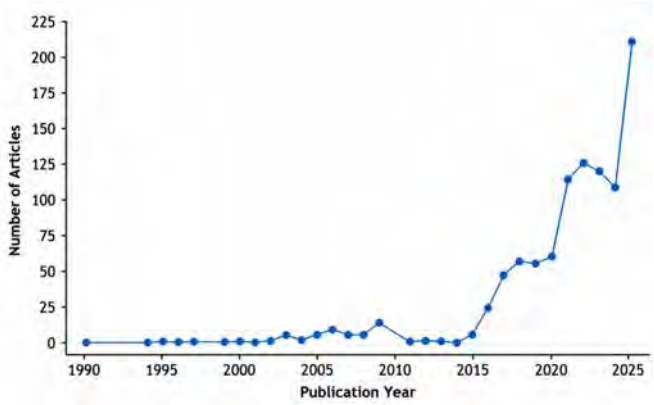



*Figure 4: Annual publication trend*

Figure 4 illustrates the annual publication trend of the articles included in the dataset. The earliest publications related to construction material procurement appear in the early 1990s, although research activity remained relatively limited during the following two decades. Between 1990 and 2014, the number of studies published each year remained relatively low, indicating that procurement performance had not yet emerged as a central research theme within construction management research. A noticeable increase in research activity can be observed after 2015. The number of studies rose steadily from fewer than ten publications per year before 2015 to more than one hundred publications annually after 2021. The peak in 2025 indicates that research on construction material procurement continues to expand rapidly. This growth reflects increasing attention to supply chain management, procurement performance, and sustainability within the construction industry. The increasing complexity of global supply chains, fluctuations in material prices, and growing environmental concerns have likely contributed to the rising research interest in procurement performance.

## 3.3 TOPIC MODEL SELECTION AND VALIDATION

Following the Bibliometric analysis, LDA was performed to identify latent thematic patterns within the literature corpus. Before interpreting the resulting topics, it is necessary to determine the optimal number of topics for the LDA model. This step corresponds to the model selection stage illustrated in Figure 1(u). This analysis is to ensure that the topic model produces themes that are both statistically reliable and semantically interpretable. To determine the optimal topic configuration, multiple LDA models were trained with different numbers of topics and evaluated using coherence and perplexity metrics. The coherence score measures the semantic consistency among the keywords within each topic, while the perplexity score evaluates the statistical performance of the model in predicting unseen data.

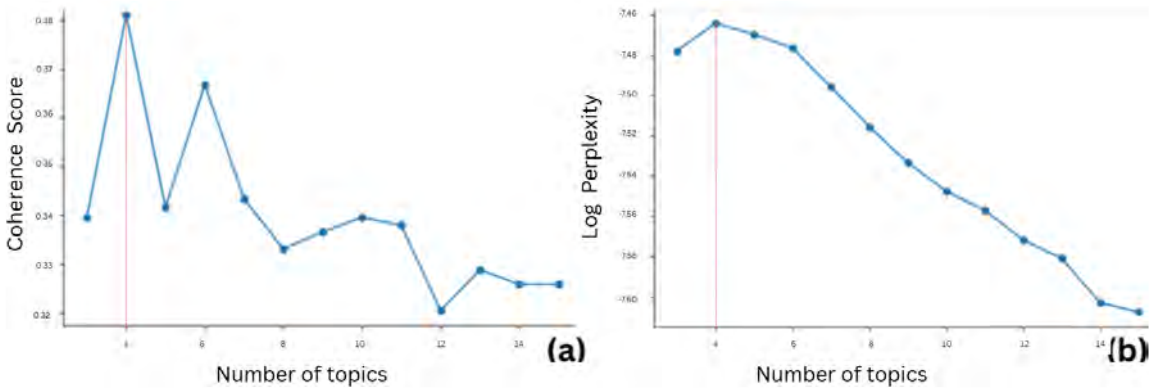



*Figure 5: Top coherence, perplexity vs number of topics*

As illustrated in Figure 5(a) and Figure 5(b), both the coherence score and perplexity values indicate that the optimal number of topics is 4. The coherence score reaches its maximum value at four topics, indicating strong semantic consistency among the keywords within each topic. Similarly, the perplexity analysis shows improved model performance at the four-topic configuration. Based on these results, the 4 topic model was selected as the optimal configuration because it provides the best balance between statistical reliability and semantic interpretability of the extracted topics.

## 3.4 LDA RESULTS

Once the optimal topic configuration was identified, the LDA model was applied to extract the dominant thematic domains within the literature corpus. Figure 8 illustrates the most representative keywords associated with each topic identified by the LDA model.

Figures 6(a)–6(d) show the highest weighted keywords for Topics 1–4 respectively.

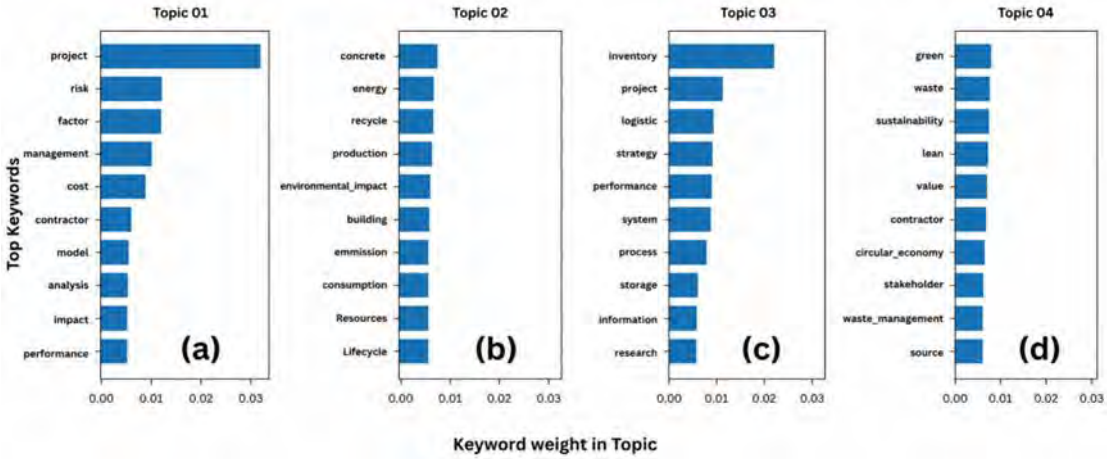



*Figure 6: Top keywords associated with each LDA topic. Figures (a)–(d) illustrate the most representative keywords and their corresponding weights for Topics 1–4 identified through the topic LDA analysis.*

Since LDA generates probabilistic distributions of words rather than explicit labels, the interpretation and naming of topics were performed by examining the semantic relationships among the highest probability keywords and their contextual relevance within procurement research. Identified four dominant thematic domains were named based on the keywords behaviour.

Topic 1 – Procurement Risk and Cost Performance

As illustrated in Figure 6(a), Topic 1 is characterised by high-weight keywords such as project, risk, factor, management, cost, and contractor. The clustering of these terms indicates that a significant body of the analysed literature is dedicated to identifying and mitigating procurement-related risks while maintaining cost efficiency.

Topic 2 – Environmental Impact of Construction Materials

The keyword distribution for Topic 2, shown in Figure 6(b), prominently features concrete, energy, production, environmental impact, and emission. This suggests a research concentration on the ecological footprint of the construction sector, specifically regarding material manufacturing and usage. This theme reflects a critical shift toward assessing carbon emissions and energy intensity through a lifecycle lens.

Topic 3 – Supply Chain and Logistics

As depicted in Figure 6(c), Topic 3 encompasses keywords such as inventory, project, logistic, strategy, performance, and system. These terms highlight the operational core of construction procurement, focusing on the seamless movement of resources. The research emphasizes the necessity of integrated logistics management and sophisticated information systems to coordinate complex supply chain networks.

Topic 4 – Sustainable Procurement and Circular Economy

Topic 4, illustrated in Figure 6(d), is defined by keywords including Green, waste, sustainability, circular economy, and stakeholder. This theme represents the modern evolution of procurement from a purely transactional function to a value-driven strategic pillar. Overall, these themes provide a structured foundation for linking LDA derived insights with procurement performance factors identified in the literature.

Collectively, the four topics demonstrate that construction material procurement performance is a multidimensional concept that extends beyond traditional cost and schedule considerations. Topic 1 highlights the continued importance of risk management and cost control in ensuring procurement effectiveness. Topic 2 reflects the growing emphasis on environmental performance and lifecycle impacts, indicating that procurement decisions are increasingly influenced by sustainability objectives. Topic 3 emphasises the critical role of logistics coordination, inventory management, and information integration in supporting uninterrupted material flows. Topic 4 demonstrates the increasing adoption of sustainable procurement principles, including circular economy practices and stakeholder-driven value creation. Together, these findings suggest that contemporary procurement performance requires a balanced consideration of economic, operational, environmental, and strategic dimensions.

## 3.5 TOPIC TREND ANALYSIS

After identifying the dominant thematic domains, a topic trend analysis was conducted as illustrated in Figure 7 to examine how these themes have evolved over time.

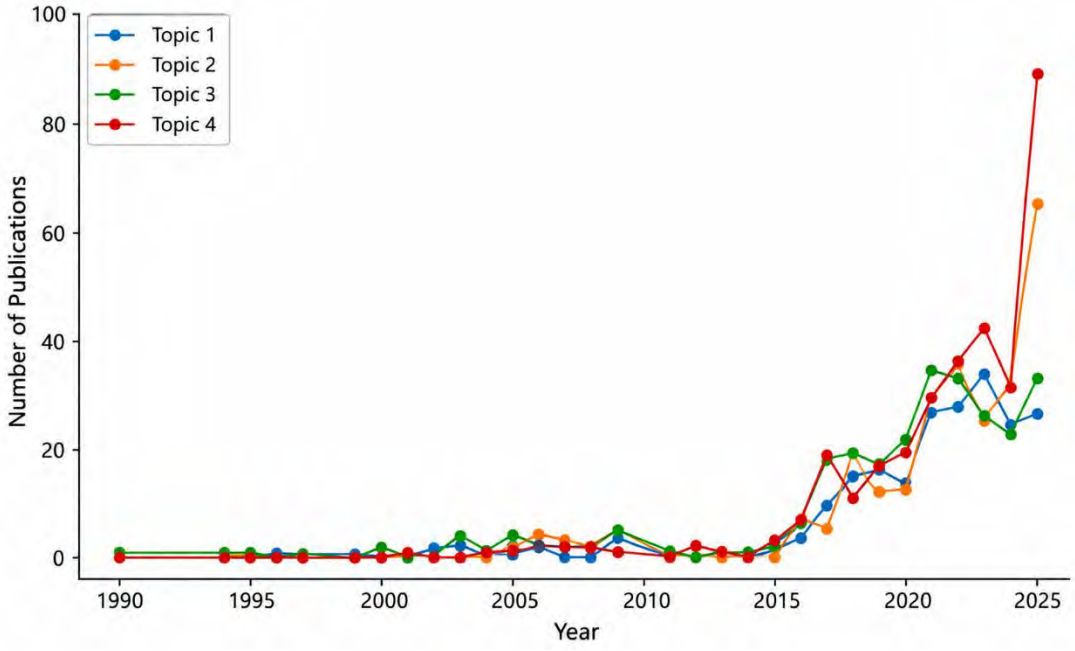



*Figure 7: Topic trends in construction material procurement research*

This analysis contributes to Objective 3, which aims to interpret the identified themes in relation to the development of procurement performance research. The results indicate that earlier studies primarily focused on procurement management and project-related issues. However, more recent publications demonstrate increasing attention toward sustainability, logistics management, and procurement performance evaluation. In

particular, the growth of Topic 4 in recent years highlights the rising importance of sustainable procurement practices and circular economy principles within the construction sector. This trend reflects the increasing emphasis on environmental responsibility and supply chain resilience in construction projects.

### 3.6 FACTOR DERIVATION FROM LDA TOPICS

Following the identification of dominant thematic domains through LDA, the extracted keywords were processed to derive procurement-related factors. Since the LDA model generates clusters of co-occurring terms rather than directly measurable constructs, an interpretation step was required to translate these keyword groups into meaningful factors within the context of construction material procurement. The derivation process involved analysing semantic relationships among high-weight keywords within each topic and grouping related terms to define distinct procurement performance factors. These factors were refined to ensure clarity, consistency, and applicability. An impact level was assigned to each factor based on keyword prominence and contextual relevance within the topic. Through this process, a total of thirty-five factors were derived and organised under four thematic domains: Procurement Risk and Cost Performance, Environmental Impact and Lifecycle, Supply Chain Operations and Logistics, and Sustainable Procurement and Circular Economy. These factors represent a data-driven interpretation of latent thematic structures identified from the literature corpus.

Compared with traditional literature reviews, the LDA-based approach adopted in this study enables the analysis of a substantially larger body of literature while reducing dependence on manual thematic classification. Rather than relying solely on researcher judgement, the identified themes emerged from statistically derived patterns of word co-occurrence across the literature corpus. This approach enhances transparency and provides a data-driven basis for identifying procurement performance factors. The findings therefore complement existing review studies by offering a systematic and reproducible framework for exploring construction material procurement research.

The complete set of derived factors, including associated topics, keywords, refined descriptions, and impact levels, is presented in Table 1.

## 4. CONCLUSIONS

This study identified the factors influencing construction material procurement performance through a structured review of existing literature. A dataset of 983 journal articles was analysed to identify dominant thematic patterns in construction material procurement research. The analysis revealed four key domains: procurement risk and cost performance, environmental impact of construction materials, supply chain and logistics management, and sustainable procurement practices. These domains highlight the multidimensional nature of procurement performance in construction projects. The findings further indicate emerging areas such as lifecycle environmental assessment, digital integration in supply chains, and circular procurement practices. Based on these insights, procurement-related factors were derived and organised to provide a structured understanding of procurement performance. From a practical perspective, the results emphasise the importance of managing cost, supplier relationships, logistics, and sustainability in an integrated manner to improve procurement performance. Future research can extend this work by validating the identified factors through empirical studies and expanding the analysis using additional data sources.

*Table 1: LDA-derived construction materials procurement performance factors*

| Factor No | Topic Name | Keywords | Factor from LDA | Refined Factor Name |
|---|---|---|---|---|
| F1 | Procurement Risk and Cost Performance | project, risk, factor, management, cost, contractor, model, analysis, impact, performance | Contractor Risk Management Effectiveness | Effectiveness of Contractor Risk Management |
| F2 | | | Project Cost Variance Analysis | Accuracy of Procurement Cost Estimation |
| F3 | | | Risk Factor Impact Assessment | Impact of External Risk Factors on Procurement |
| F4 | | | Contractor Cost Performance Index | Contractor Cost Efficiency in Material Procurement |
| F5 | | | Procurement Management Risk Model | Effectiveness of Procurement Risk Forecasting |
| F6 | | | Project Management Cost Factor | Procurement Management Cost Efficiency |
| F7 | | | Contractor Analysis Performance | Effectiveness of Contractor Evaluation Process |
| F8 | | | Risk-Adjusted Cost Performance | Cost Performance under Risk Conditions |
| F9 | | | Project Performance Impact Factor | Impact of Procurement Delays on Project Performance |
| F10 | | | Management Analysis Effectiveness | Effectiveness of Data-Driven Procurement Decisions |
| F11 | Environmental Impact and Lifecycle | concrete, energy, recycle, production, environmental_impact, building, emissions, consumption, Resources, Lifecycle | Lifecycle Environmental Impact Score | Overall Environmental Impact of Materials |
| F12 | | | Energy Consumption Efficiency | Energy Efficiency in Material Production |
| F13 | | | Recycled Resource Utilization Rate | Use of Recycled Materials in Procurement |
| F14 | | | Resource Consumption Impact | Resource Consumption in Material Sourcing |
| F15 | | | Concrete Lifecycle Sustainability | Sustainability of Concrete over Lifecycle |
| F16 | | | Production Resource Efficiency | Efficiency of Resource Use in Material Production |
| F17 | Supply Chain Operations and Logistics | inventory, project, logistic, strategy, performance, system, | Inventory Storage Efficiency | Efficiency of Material Storage Systems |
| F18 | | | Logistic System Performance | Performance of Material Logistics Systems |
| F19 | | | Information Process Integration | Integration of Procurement Information Systems |
| F20 | | | Strategic Logistic Performance | Effectiveness of Logistics Planning Strategy |

| Factor No | Topic Name | Keywords | Factor from LDA | Refined Factor Name |
|---|---|---|---|---|
| F21 | Sustainable Procurement and Circular Economy | process, storage, information, research | Inventory Management Strategy | Effectiveness of Inventory Management Practices |
| F22 | | | Supply Chain Research Application | Application of Supply Chain Innovations |
| F23 | | | Project Logistic System Reliability | Reliability of Material Delivery Systems |
| F24 | | | Process Performance Speed | Speed of Procurement Processes |
| F25 | | | Logistic Information Accuracy | Accuracy of Logistics and Inventory Data |
| F26 | | green, waste, sustainability, lean, value, contractor, circular_economy, stakeholder, waste_management, source | Green Sourcing Effectiveness | Effectiveness of Green Material Sourcing |
| F27 | | | Stakeholder Sustainability Alignment | Alignment of Stakeholders on Sustainability Goals |
| F28 | | | Waste Management Performance | Effectiveness of Material Waste Management |
| F29 | | | Lean Procurement Value | Implementation of Lean Procurement Practices |
| F30 | | | Contractor Sustainability Compliance | Contractor Compliance with Sustainability Standards |
| F31 | | | Circular Economy Waste Reduction | Waste Reduction through Circular Practices |
| F32 | | | Circular Economy Integration Value | Value Creation through Circular Procurement |
| F33 | | | Stakeholder Value Creation | Value Delivered to Stakeholders through Procurement |
| F34 | | | Green Waste Management Strategy | Implementation of Sustainable Waste Strategies |
| F35 | | | Sustainable Source Selection | Effectiveness of Sustainable Supplier Selection |

## 5. ACKNOWLEDGEMENT

This research was supported by the Senate Research Committee, University of Moratuwa under Grant No. SRC/LT/2025/23. The authors gratefully acknowledge this financial support.

## 6. REFERENCES

Momani, A. M., Al-Hawari, T. H., & Mousa, R. W. (2016). Using expanded real options analysis to evaluate capacity expansion decisions under uncertainty in the construction material industry. *South African Journal of Industrial Engineering*, 27(2), 1-14. https://doi.org/10.7166/27-2-1381

Alsamarraie, M. M., & Ghazali, F. (2022). Evaluation of organizational procurement performance for public construction projects: Systematic review. *International Journal of Construction Management*, 23(14), 2499–2508. https://doi.org/10.1080/15623599.2022.2070447

Yunna, W., & Ping, L. (2012). Centralized procurement of construction enterprises based on SCMS. In J. Luo (Ed.), *Affective Computing and Intelligent Interaction* (Vol. 137, pp. 515–520). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-27866-2_63

Kamil, M. I., & Mulyono, N. B. (2025). Developing construction project material procurement strategy using integrated FMEA-DEA approach in Kraljic's portfolio matrix. *European Journal of Business and Management Research*, *10*(1), 127–136. https://doi.org/10.24018/ejbmr.2025.10.1.2425

Wawak, S., Ljevo, Ž., & Vukomanović, M. (2020). Understanding the key quality factors in construction projects — A systematic literature review. *Sustainability*, 12(24), 10376. https://doi.org/10.3390/su122410376

Ajayi, S. O., & Oyedele, L. O. (2018). Waste-efficient materials procurement for construction projects: A structural equation modelling of critical success factors. *Waste Management*, 75, 60–69. https://doi.org/10.1016/j.wasman.2018.01.025

Opoku, A., Deng, J., Elmualim, A., Ekung, S., Hussien, A. A., & Buhashima Abdalla, S. (2022). Sustainable procurement in construction and the realisation of the Sustainable Development Goal (SDG) 12. *Journal of Cleaner Production*, 376, 134294. https://doi.org/10.1016/j.jclepro.2022.134294

Jusoh, Z. M., & Kasim, N. (2017). A review on implication of material management to project performance. In A. Hasan, A.A. Khan, Md. A. Mannan, C.N. Hipolito, N. M. Sutan, Al-K. Hj. Othman, M.R. Kabit & N. A, Wahab (Eds.), *The 9th International Unimas Stem Engineering Conference (ENCON 2016) "Innovative Solutions for Engineering and Technology Challenges"* (Vol. 87, pp. 01012). MATEC Web of Conferences. https://doi.org/10.1051/matecconf/20178701012

Parisi, L., & Donyavi, S. (2025). Advancing materials procurement processes in construction: A framework for optimising technology integration in SMEs' construction supply chains. *International Journal of Construction Management*, *26*(7), 1–25. https://doi.org/10.1080/15623599.2025.2553610

Hussain, G., Nazir, M. S., Rashid, M. A., & Sattar, M. A. (2023). From supply chain resilience to supply chain disruption orientation: The moderating role of supply chain complexity. *Journal of Enterprise Information Management*, 36(1), 70–90. https://doi.org/10.1108/JEIM-12-2020-0558

Ibrahim, A., Zayed, T., & Lafhaj, Z. (2024). Enhancing construction performance: A critical review of performance measurement practices at the project level. *Buildings*, *14*(7), 1988. https://doi.org/10.3390/buildings14071988

Sivasubramaniam, N., Abeynayake, D. N., Shanika, V. G., & Lingasabesan, V. (2024). Insights into centralized procurement for construction material supply chain: A study in Sri Lanka. *FARU Journal*, *11*(1), 47–56. https://doi.org/10.4038/faruj.v11i1.313

Zhao, N., Ying, F. J., & Tookey, J. (2022). Construction procurement selection criteria: A review and research agenda. *Sustainability*, *14*(22), 15242. https://doi.org/10.3390/su142215242

Senarathna, M.S.M. and Hettiarachchi, A.A., 2026. Incremental retrofitting and material - space adaptation in plantation line housing: Evidence from a wet-zone settlement in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 911-923. DOI: https://doi.org/10.31705/WCS.2026.67. Available from: https://ciobwcs.com/papers/

# INCREMENTAL RETROFITTING AND MATERIAL - SPACE ADAPTATION IN PLANTATION LINE HOUSING: EVIDENCE FROM A WET-ZONE SETTLEMENT IN SRI LANKA

**M.S.M. Senarathna[1] and A.A. Hettiarachchi[2]**

## *ABSTRACT*

*Plantation line housing represents a distinctive residential typology developed during the colonial plantation economy in Sri Lanka. These dwellings were originally constructed using simple material systems granite foundations, brick masonry walls, and clay tile roofing and designed to accommodate small worker households with limited spatial flexibility. However, contemporary plantation communities experience changing household structures, environmental pressures, and socio-economic transitions that require these rigid housing units to adapt over time. This study investigates material–space adaptation and incremental retrofitting in plantation line housing through a case study of a wet-zone settlement in the Kegalle District, Sri Lanka. It aims to examine how residents modify spatial arrangements and construction materials in response to environmental and spatial constraints, addressing the questions of how these adaptations occur and how they contribute to spatial resilience. Field observations, measured drawings, and resident narratives were used to document transformations in construction materials, interior partitions, and spatial organization. The findings reveal recurring spatial adaptation patterns, including rear-oriented extensions for cooking, vertical storage practices, and the use of lightweight partitions to reorganize interior space. Environmental pressures, particularly heavy rainfall and clay roof tiles damage caused by monkeys have also encouraged the replacement of traditional roofing with metal and asbestos sheets, producing hybrid material systems. The study demonstrates how resident-driven modifications enable plantation housing to remain functional despite spatial and environmental constraints. These insights highlight the importance of incremental and flexible retrofit strategies for improving low-income housing in resource-constrained contexts.*

***Keywords:*** *Incremental housing; Low-income housing; Material adaptation; Plantation housing; Spatial resilience*

## 1. INTRODUCTION

Housing plays a fundamental role in shaping social wellbeing, spatial functionality, and everyday living practices within the built environment. In many developing countries,

[1] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, sachini.senarathna20@gmail.com
[2] Senior Professor, Department of Architecture, University of Moratuwa, Sri Lanka, anishkah@uom.lk

however, large segments of the population continue to occupy housing environments originally designed for different socio-economic conditions and household structures. As household sizes increase and domestic practices evolve, such housing environments often become spatially constrained, requiring residents to adapt and reorganize their living spaces (Tipple, 2000; UN-Habitat, 2011).

Plantation line housing in Sri Lanka represents a historically significant housing typology developed during the colonial plantation economy to accommodate plantation workers in compact and standardized residential units. These dwellings, commonly known as line houses, typically consist of narrow rectangular units arranged in linear rows with minimal internal spaces and limited spatial flexibility (Peebles, 2001). While this configuration initially served the functional needs of plantation communities, contemporary household structures and living practices have significantly changed.

Increasing family sizes and evolving domestic activities have placed considerable pressure on these spatially constrained housing units, leading residents to modify and reorganize their interior spaces to accommodate changing needs (Perera, 2016; Tipple & Speak, 2009). Within housing studies, such transformations are commonly explained through the concept of incremental housing, which emphasizes how residents gradually adapt and extend their dwellings over time in response to spatial limitations (Turner, 1976; Hamdi, 2004).

More recently, the concept of spatial resilience has been used to describe the capacity of spatial systems to adapt and reorganize in response to social and environmental pressures while maintaining functional living conditions (Holling, 1973; Meerow et al., 2016). In the context of low-income housing, spatial resilience often emerges through resident-driven spatial adaptations that allow housing environments to remain functional despite spatial constraints.

Despite the widespread presence of plantation line settlements in Sri Lanka, limited research has examined the interior spatial transformations occurring within these housing units. This study therefore investigates how residents incrementally transform interior spaces in plantation line housing settlements in the Kegalle District of Sri Lanka. By examining these adaptations, the research aims to contribute to a better understanding of spatial resilience and resident-driven housing transformation in spatially constrained residential environments.

Accordingly, the objective of this study is to investigate how residents incrementally adapt plantation line housing through material and spatial transformations in response to changing household needs, environmental pressures, and spatial constraints. The study addresses the following research questions: (1) How do residents modify and reorganise interior spaces within plantation line housing units over time? (2) What material transformations occur in response to environmental pressures in wet-zone plantation settlements? and (3) How do these adaptations contribute to spatial resilience within spatially constrained housing environments?

# 2. LITERATURE REVIEW

## 2.1 INCREMENTAL HOUSING AND RESIDENT-DRIVEN TRANSFORMATION

Housing in many low-income settlements evolves through gradual processes of adaptation rather than through fixed architectural design. The concept of incremental

housing highlights how residents progressively modify and extend their dwellings in response to spatial constraints and socio-economic needs. Turner (1976) argued that housing should be understood as a dynamic process shaped by residents rather than a completed product delivered by formal planning systems. This perspective emphasizes the agency of residents as active participants in shaping their living environments.

Subsequent studies demonstrate that incremental housing transformations commonly occur in standardized or spatially constrained housing environments where formal design solutions fail to accommodate changing household needs. Recent studies continue to emphasise incremental housing as an effective approach for accommodating changing household needs in resource-constrained contexts, particularly within rapidly urbanising regions of South Asia (Batra, 2021; Wakely & Riley, 2005.). Hamdi (2004) notes that residents frequently introduce extensions, internal partitions, and multifunctional spaces as adaptive responses to limited space and evolving domestic practices. Similarly, Tipple (2000) observes that user-initiated transformations allow households to gradually improve the functionality and usability of their dwellings despite limited financial resources.

These incremental processes can also be understood through the perspective of Open Building theory, which distinguishes between the permanent structural "support" of a building and the adaptable "infill" elements controlled by occupants (Habraken, 1972). Within this framework, the structural shell of a dwelling remains relatively stable, while interior spatial elements evolve through resident-driven modifications. Such a distinction is particularly relevant in plantation housing settlements where the original masonry structures function as long-term supports, while interior partitions and extensions introduced by residents operate as flexible infill systems that adapt to changing household needs.

In plantation housing settlements, similar incremental processes have been observed as residents adapt colonial-era housing units to contemporary living conditions. Plantation line houses were originally designed as compact and repetitive housing units with minimal spatial flexibility (Peebles, 2001). As household sizes increase and domestic practices evolve, residents often introduce informal spatial modifications that enable these housing units to remain functional despite their rigid original design (Perera, 2016). The adaptive nature of incremental housing has also been highlighted through case studies that demonstrate how households progressively expand and modify their dwellings using affordable and locally available resources (SPARC, 2013; Balestra & Göransson, 2009).

## 2.2 SPATIAL ADAPTATION IN LOW-INCOME HOUSING

Spatial adaptation refers to the processes through which occupants modify and reorganize built environments in response to changing functional and social requirements. Within domestic environments, adaptation frequently occurs through interior reconfiguration, temporary partitions, and multifunctional use of limited spaces. Brand (1994) highlights that buildings naturally evolve over time as occupants modify spatial arrangements to accommodate changing needs, suggesting that built environments should be understood as continuously transforming systems.

In low-income housing contexts, spatial adaptation plays a critical role in enabling households to cope with spatial limitations and limited resources. Studies of informal settlements demonstrate that residents often convert single rooms into multifunctional

environments that accommodate sleeping, social interaction, and domestic activities simultaneously (Tipple & Speak, 2009; Hamdi, 2004). Such practices illustrate how spatial flexibility emerges through everyday domestic routines rather than through predetermined architectural design.

Within constrained housing environments, this flexibility can also be understood as a form of spatial elasticity, where a single interior space expands or contracts functionally to accommodate different domestic activities at different times of the day. Through such adaptive practices, limited domestic spaces are capable of supporting multiple household functions without requiring permanent architectural alterations.

In plantation line settlements, the rigid spatial configuration of the original housing design often necessitates internal spatial modifications. Previous research indicates that residents commonly subdivide bedrooms, convert living spaces into sleeping areas, or construct small extensions to accommodate growing household structures (Perera & Nilsson, 2013). Such spatial adaptations illustrate the dynamic relationship between domestic practices and housing environments within spatially constrained residential settings.

## 2.3 SPATIAL RESILIENCE IN THE BUILT ENVIRONMENT

The concept of resilience has become increasingly important in studies of urban systems and the built environment. Initially developed in ecological research, resilience refers to the capacity of a system to absorb disturbances while maintaining its core functions (Holling, 1973). In urban and spatial contexts, resilience is understood as the ability of built environments to adapt to social, economic, and environmental changes (Meerow et al., 2016).

In architectural discourse, spatial resilience refers to the capacity of spatial systems to accommodate evolving user needs while maintaining functionality and habitability. Built environments that support flexibility and incremental transformation are considered more resilient because they allow spaces to adapt to changing social conditions over time (Sharifi & Yamagata, 2016). Similarly, Brand (1994) argues that buildings capable of continuous adaptation achieve greater long-term sustainability.

In highly dense domestic environments, spatial resilience is often closely linked to strategies of territorial regulation and privacy management. Altman (1975) argues that occupants use physical or symbolic boundaries to regulate social interaction and psychological density within shared environments. In constrained housing settings, such boundaries may take the form of lightweight or temporary partitions that allow households to manage privacy without permanently altering the spatial structure of the dwelling.

In low-income housing environments, spatial resilience often emerges through informal and resident-driven spatial practices rather than formal design interventions. Residents introduce incremental spatial modifications to support changing household activities and spatial needs (Hamdi, 2004; Tipple & Speak, 2009). Despite the relevance of spatial resilience to housing environments, limited research has examined how such resilience manifests through interior spatial transformations within plantation housing settlements (Peebles, 2001; Perera, 2016).

### 2.4 RESEARCH GAP

Although existing literature provides valuable insights into incremental housing, spatial adaptation, and resilience in the built environment, limited research specifically examines interior spatial transformations within plantation line housing settlements. Most studies emphasize socio-economic conditions, labor histories, and settlement development patterns rather than the micro-scale spatial adaptations occurring within individual housing units.

This study addresses this gap by examining how residents in plantation line housing settlements incrementally modify their interior environments in response to changing household needs. By mapping spatial transformations and analyzing adaptation patterns within selected case studies, the research aims to reveal how spatial resilience emerges through resident-driven incremental adaptations in spatially constrained housing environments.

## 3. METHODOLOGY

### 3.1 RESEARCH APPROACH

This study adopts a qualitative case study approach to investigate spatial resilience in plantation line housing through resident-driven spatial transformations. Case study methodology is widely used in built environment research to examine spatial phenomena within real-life contexts (Yin, 2018). The study focuses on documenting incremental interior transformations occurring within plantation line housing units and identifying recurring spatial adaptation patterns that enable households to maintain functional living environments within constrained architectural structures.

### 3.2 CASE STUDY SELECTION

Two plantation line housing clusters located in the Beligala area of the Kegalle District, Sri Lanka, were selected as case studies. The settlements lie within the wet-zone climatic region, which significantly influences material and spatial adaptation practices.

A total of 12 housing units were documented across the two clusters, locally known as '*Udaha Laima'* and '*Pahala Laima'*. The housing units were selected through purposive sampling to capture variations in resident-driven modifications while maintaining consistency in housing typology and settlement context.

Linear row housing arrangement

- Identical repetitive housing units
- Limited floor area
- Rigid spatial configurations

Despite their similar original layouts, the housing units demonstrate varying degrees of spatial modification introduced by residents over time. The selection of these two case studies therefore allows a comparative spatial analysis of different adaptation strategies occurring within similar architectural frameworks.

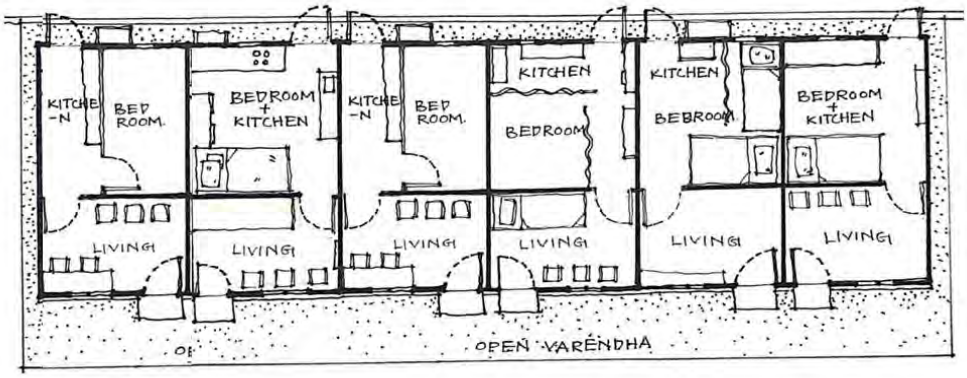



*Figure 1: Typical plantation line housing arrangement showing repetitive linear housing units -Case study 01*

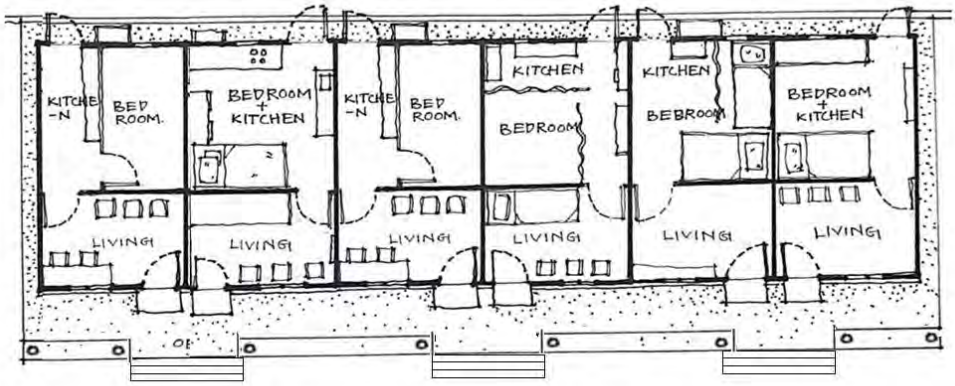



*Figure 2: Typical plantation line housing arrangement showing repetitive linear housing units -Case study 02*

## 3.3 SPATIAL DOCUMENTATION

Field-based spatial documentation was conducted to record both the original spatial configuration of plantation line housing units and the subsequent spatial transformations introduced by residents. Measured sketches and observational drawings were used to document the interior layout of selected housing units. The documentation process involved:

1. Recording spatial dimensions of housing units
2. Identifying functional spaces within the house
3. Mapping interior partitions and modifications
4. Documenting extensions and additional spaces

This process allowed the development of detailed plan drawings representing the existing spatial configuration of the housing units. The collected sketches were later converted into analytical diagrams to facilitate spatial analysis and comparison between the original and modified layouts. Resident narratives were collected through informal conversations conducted during field visits. Notes were recorded to document residents' explanations

regarding spatial modifications, material substitutions, and household practices. Verbal consent was obtained prior to observations and spatial documentation.

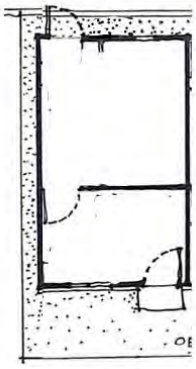


*Figure 3: Original spatial configuration of a plantation line housing unit.*

## 3.4 ADAPTATION MAPPING

To analyse the spatial transformations occurring within the housing units, an adaptation mapping method was employed. Adaptation mapping is a spatial analysis technique used to identify and visualize modifications introduced to build environments over time. In this study, the adaptation mapping process involved comparing the original housing layout with the current spatial configuration observed in the case study units. Spatial modifications were categorized into three primary types:

1. Interior partitioning – introduction of temporary or permanent partitions to divide spaces
2. Functional transformation – changes in the use of existing spaces
3. Incremental extensions – addition of new spaces outside the original housing footprint

These spatial transformations were illustrated through analytical diagrams that highlight the differences between the original and modified layouts.

*Figure 4: Interior spatial adaptation mapping showing resident-driven modifications within the housing unit*

### 3.5 INCREMENTAL TRANSFORMATION ANALYSIS

To understand the process through which spatial modifications evolve over time, the study developed an incremental transformation map that illustrates the sequence of spatial adaptations occurring within the housing units. This diagram represents the gradual transformation of the original housing layout through successive modifications introduced by residents.

The analysis focuses on identifying patterns in spatial transformations, including:
• subdivision of interior spaces
• multifunctional use of limited spaces
• incremental rear extensions for cooking or storage

By mapping these transformations, the study examines how spatial modifications contribute to the emergence of spatial resilience within constrained housing environments.

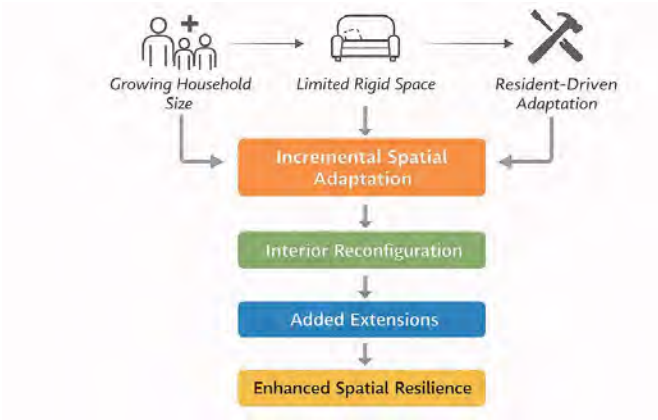



*Figure 5: Spatial adaptation Framework*

### 3.6 COMPARATIVE SPATIAL ANALYSIS

A comparative analysis was conducted between the two selected case studies identify common patterns of spatial adaptation. The analysis focused on comparing:

- types of interior modifications
- patterns of spatial extensions
- functional transformations of interior spaces

This comparison enabled the identification of recurring adaptation strategies used by residents to overcome spatial limitations within plantation housing units.

*Table 1: Comparative analysis of spatial adaptation patterns observed in the selected case studies.*

| Spatial Adaptation Strategy | *"Udaha Laima"* | *"Pahala Laima"* | Spatial Function |
|---|---|---|---|
| **Interior partitioning** | Frequently observed | Frequently observed | Creation of additional sleeping areas and privacy |
| **Kitchen extension** | Common rear extensions | Common rear extensions | Expansion of cooking space and improved ventilation |
| **Storage addition** | Present in several units | Rarely observed | Additional storage for household items |

| Spatial Adaptation Strategy | *"Udaha Laima"* | *"Pahala Laima"* | Spatial Function |
|---|---|---|---|
| **Multifunctional living space** | Widely practiced | Widely practiced | Daytime social space converted to sleeping area |
| **Temporary partitions** | Fabric/plywood partitions used | Fabric partitions occasionally used | Flexible spatial subdivision |
| **Rear utility extensions** | Cooking and washing areas added | Limited rear extensions | Support domestic activities outside main unit |

# 4. RESEARCH FINDINGS

## 4.1 STRUCTURAL CONSTRAINTS AND THE ORIGINAL SPATIAL FRAMEWORK

The Field documentation of the case study units indicates that plantation line houses were originally designed as compact linear domestic structures organized along a front-to-rear spatial sequence. Each unit typically consists of a living space at the front, a sleeping area in the middle, and a small cooking zone toward the rear. Domestic activities such as circulation, resting, cooking, and social interaction occur within a highly compressed spatial environment where functional boundaries are weakly defined.

The linear row configuration of plantation housing clusters imposes a significant structural constraint on spatial transformation. Because housing units share continuous party walls, lateral expansion toward the sides is structurally impossible. The original construction technology of plantation line housing, characterised by granite foundations, load-bearing brick masonry walls, and continuous party-wall construction, provides a durable structural framework but limits opportunities for major spatial reconfiguration. While the masonry shell constrains lateral expansion and structural alterations, lightweight retrofit materials such as fabric partitions, plywood panels, corrugated metal sheets, and reused materials enable residents to introduce flexible extensions and interior modifications. Consequently, spatial adaptation primarily occurs through adaptable infill elements rather than changes to the permanent structural system. This spatial rigidity establishes the underlying framework within which subsequent resident-driven adaptations occur.

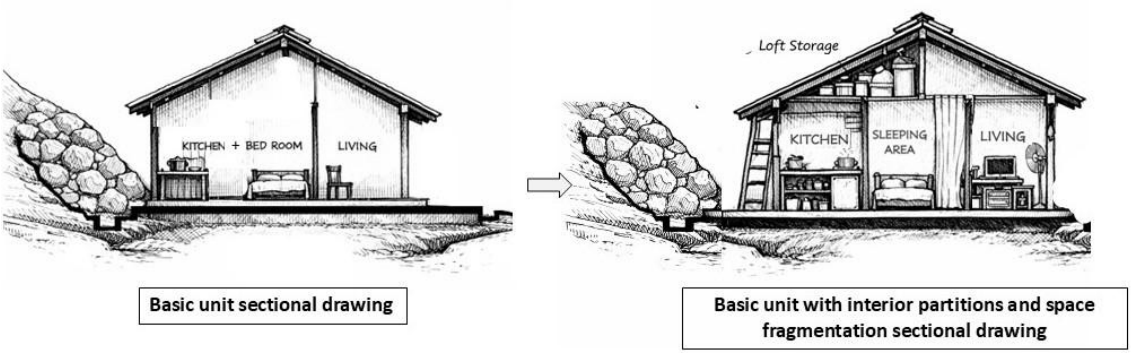



*Figure 6: Transformation and adaptation of spaces in typical unit – sectional drawing*

## 4.2 PATTERN IDENTIFICATION IN SPATIAL ADAPTATION

Comparative analysis of the documented housing units revealed that spatial transformations do not occur randomly but follow recurring patterns shaped by structural constraints, environmental pressures, and everyday domestic practices. Three dominant spatial patterns were identified across the case study settlements.

- Pattern 1 – Rear-ward drift
- Pattern 2 – Vertical storage adaptation
- Pattern 3 – Soft partition logic and ventilation

### 4.2.1 Pattern 1 – Rear-ward Drift: Linear Push of Domestic Functions

One of the most prominent spatial patterns identified is the rear-ward drift of domestic functions, where spatial adaptation occurs along the longitudinal axis due to the constraint of shared party walls preventing lateral expansion. As household sizes increase, interior space becomes increasingly compressed, leading residents to relocate cooking activities to small rear extensions constructed with lightweight or reused materials. Although detailed socio-economic data were not collected, field observations suggest that households with larger family structures tended to introduce more extensive spatial modifications, including partitions and rear extensions, to accommodate increasing domestic demands. This process allows the kitchen to gradually "escape" the interior space, creating additional room for sleeping and domestic activities while generating a progressive outward shift of service functions toward the rear of the dwelling.

This adaptation demonstrates spatial elasticity; whereby domestic functions are reorganised and redistributed beyond the original housing footprint to accommodate changing household needs. The relocation of cooking activities to rear extensions enables the limited interior space to support multiple functions while maintaining the usability of the dwelling.

### 4.2.2 Pattern 2 – Vertical Storage Adaptation: Storage Practices in Constrained Interiors

Another key spatial pattern identified is vertical storage adaptation, where storage functions shift upward due to the extremely limited floor area and absence of designated storage spaces in plantation line houses. Residents commonly use cupboard tops, roof rafters, and upper wall areas to store household items, effectively transforming the upper spatial volume of the house into an informal storage zone. This upward redistribution of storage demonstrates how households adapt vertically within constrained interiors, suggesting that future plantation housing design should consider higher ceiling heights or integrated vertical storage strategies. The upward redistribution of storage functions illustrates spatial resilience within constrained housing environments. By utilizing vertical space, residents adapt existing spatial resources without requiring significant structural alterations, enabling the dwelling to remain functional despite increasing household demands.

### 4.2.3 Pattern 3 – Soft Partition Logic and Ventilation-Based Spatial Boundaries

Material transformations in plantation line housing are strongly influenced by environmental pressures in the wet-zone climate. The humid climatic conditions of the wet zone also influence interior spatial adaptations. Residents frequently prefer

lightweight fabric partitions over rigid walls, as these maintain cross-ventilation and reduce heat and moisture accumulation within the compact housing units Heavy rainfall and damage caused by monkeys often affect traditional clay tile roofs, leading many households to replace them with corrugated metal or asbestos sheets. In this context, frequent roof damage caused by monkeys acts as a biological stressor, encouraging the adoption of more durable and easily repairable roofing materials. These material substitutions also shape spatial adaptation by enabling lightweight partitions, rear extensions, and vertical storage practices, gradually producing hybrid construction systems that combine original colonial structures with resident-driven retrofit elements. The use of fabric curtains and lightweight partitions reflects a form of territorial regulation and privacy management within highly compressed domestic environments. These flexible boundaries allow residents to create temporary private zones for sleeping and personal activities while maintaining airflow and visual connectivity within the dwelling. This adaptation enhances both spatial resilience and spatial elasticity by enabling spaces to accommodate changing functional requirements throughout the day.

*Table 2: Identified spatial adaptation patterns in plantation line housing*

| Spatial Pattern | Spatial Driver / Constraint | Observed Adaptation Strategy | Spatial Outcome | Design Implication |
|---|---|---|---|---|
| **Rear-ward Drift (Linear Push)** | Continuous party walls restrict lateral expansion | Cooking activities relocated to rear through small kitchen extensions using lightweight or reused materials | Progressive outward movement of service spaces toward the rear of the dwelling | Future plantation housing should allow flexible rear expansion zones to accommodate inevitable service space growth |
| **Vertical Sequestration** | Limited floor area and absence of dedicated storage spaces | Use of cupboard tops, roof rafters, and upper wall areas for storing household items | Transformation of upper spatial volume into an informal storage infrastructure | Housing design should incorporate higher ceiling heights and integrated vertical storage systems |
| **Soft Partition Logic & Ventilation Adaptation** | Humid wet-zone climate and need for cross-ventilation | Use of fabric curtains and lightweight partitions instead of rigid walls | Flexible interior subdivision while maintaining airflow and thermal comfort | Interior layouts should support breathable partitions and adaptable spatial boundaries suited to humid climates |

## 4.3 MATERIAL ADAPTATION AND BIOLOGICAL ENVIRONMENTAL PRESSURES

Spatial transformations within plantation line housing are closely linked with material adaptation processes influenced by environmental pressures in the wet-zone climate. Residents reported that heavy rainfall and frequent monkey activity often damage traditional clay tile roofing systems, leading many households to replace them with corrugated metal sheets or asbestos roofing materials.

In this context, monkey interference acts as a biological stressor affecting the durability of the original roofing system. The adoption of metal sheet roofing represents a practical response to this environmental condition, providing a more durable and easily repairable alternative.

Material substitutions also influence spatial organization within the housing units. Lightweight roofing systems enable residents to use roof structures for vertical storage, while lightweight construction materials facilitate the installation of temporary partitions and rear extensions. As a result, plantation line houses gradually evolve into hybrid material systems that combine colonial masonry structures with resident-driven retrofit elements.

### 4.4 SYSTEMATIC ADAPTATION PATTERNS ACROSS CASE STUDY SETTLEMENTS

Comparative analysis of the two case study settlements *Udaha Laima* and *Palleha Laima* reveals a strong convergence in spatial adaptation practices. Despite minor variations in the scale of modifications, the transformation processes observed across both settlements follow the same underlying logic of adaptation.

The spatial patterns identified in this study rear-ward drift, vertical sequestration, and soft partition logic illustrate how plantation housing residents systematically reorganize domestic environments in response to spatial constraints, environmental pressures, and changing household structures.

These patterns demonstrate that spatial transformation in plantation line housing is not the result of isolated household modifications but rather a collective adaptation process shaped by the structural conditions of the housing typology and the everyday practices of its occupants.

## 5. CONCLUSIONS AND RECOMMENDATIONS

This study examined material - space adaptation in plantation line housing through spatial documentation and comparative analysis of two wet-zone settlements in the Kegalle District of Sri Lanka. The findings show that although plantation line houses were originally designed as rigid and spatially minimal worker dwellings, they have evolved into adaptable domestic environments through incremental, resident-driven transformations. Lightweight partitions, multifunctional living spaces, and rear-oriented extensions enable households to reorganize limited interior areas and accommodate changing family structures, reflecting broader patterns of incremental housing adaptation. Environmental pressures in the wet-zone climate have also encouraged material substitutions, particularly the replacement of clay tile roofs with metal sheets, resulting in hybrid construction systems that combine original colonial structures with improvised retrofit elements.

These findings highlight the need for incremental and flexible housing strategies in plantation communities. Future housing design should support adaptable interior layouts, allow rear service extensions, incorporate breathable partition systems for ventilation, and provide sufficient ceiling heights for vertical storage practices observed in existing houses. Recognizing these resident-driven adaptations can help architects develop more resilient and context-responsive plantation housing solutions that enhance spatial flexibility while responding to local environmental conditions The identified adaptation

patterns also demonstrate how spatial resilience emerges through resident-driven modifications. Rear-oriented extensions illustrate spatial elasticity by enabling domestic functions to expand beyond the original housing footprint, while vertical storage practices maximise limited spatial resources within constrained interiors. Similarly, lightweight partitions function as mechanisms of territorial regulation and privacy management, allowing households to negotiate personal space without compromising ventilation. Together, these adaptations highlight the capacity of plantation housing residents to continuously reorganise and transform their living environments in response to changing social and environmental conditions.

The findings suggest that future housing policies should move beyond rigid standardisation and support incremental, adaptable housing models that enhance resilience, affordability, and long-term spatial flexibility.

## 6. REFERENCES.

Batra, B. (2021). Incremental housing development and its implementation in India. *International Journal of Scientific & Engineering Research, 12*(11), 1177–1183.

Brand, S. (1994). *How buildings learn: What happens after they're built*. Penguin Books.

Habraken, N. J. (1972). *Supports: An alternative to mass housing*. Praeger Publishers.

Hamdi, N. (2004). *Small change: About the art of practice and the limits of planning in cities*. Earthscan.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4,* 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning, 147,* 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Peebles, P. (2001). *The plantation Tamils of Ceylon*. Leicester University Press.

Perera, N. (2016). *People's spaces: Coping, familiarizing, creating*. Routledge.

Perera, N., & Nilsson, K. (2013). Suburban transformations in Sri Lanka: From colonial suburb to metropolitan periphery. *Urban Geography, 34*(7), 1011–1032. https://doi.org/10.1080/02723638.2013.778698

Sharifi, A., & Yamagata, Y. (2016). Urban resilience assessment: Multiple dimensions, criteria, and indicators. *Advanced Engineering Informatics, 30*(2), 234–256. https://doi.org/10.1016/j.aei.2016.01.003

Society for the Promotion of Area Resource Centres (SPARC). (2013). *A study of informal incrementality, its impacting factors and supporting systems (2011–2013).* SPARC.

Tipple, A. G. (2000). *Extending themselves: User-initiated transformations of government-built housing in developing countries*. Liverpool University Press.

Tipple, A. G., & Speak, S. (2009). The hidden millions: Homelessness in developing countries. *Urban Studies, 46*(3), 645–668. https://doi.org/10.1177/0042098008100822

Turner, J. F. C. (1976). *Housing by people: Towards autonomy in building environments*. Marion Boyars.

UN-Habitat. (2011). *Cities and climate change: Global report on human settlements 2011*. Earthscan.

Wakely, P., & Riley, E. (2005). *The case for incremental housing*. Cities Alliance.

Herath, H.M.S.P., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Industry readiness for inflation adjusted data driven cost estimation in Sri Lankan construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 924-935. DOI: https://doi.org/10.31705/WCS.2026.68. Available from: https://ciobwcs.com/papers/

# INDUSTRY READINESS FOR INFLATION ADJUSTED DATA DRIVEN COST ESTIMATION IN SRI LANKAN CONSTRUCTION INDUSTRY

**H.M.S.P. Herath[1], K. Thiruchelvam[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Accurate cost estimation at the tendering stage is essential for the financial success of construction projects. However, in the Sri Lankan construction industry, significant discrepancies are often observed between bid price and final contract price, primarily due to economic volatility and limitations in traditional estimation practices. This study aims to examine current cost estimation practices and assess the industry's readiness to adopt inflation adjusted data driven cost estimation models. A mixed method was adopted and a questionnaire survey was used for the data collection, The questionnaire was distributed to 75 construction professionals, and 40 valid responses were received. The questionnaire collected both quantitative and qualitative data, which analysed using descriptive and content analysis techniques. The findings indicate that traditional cost estimation methods are widely used in Sri Lankan construction industry, while the adoption of software-based tools remain limited. The results further reveal that a majority of respondents perceive a considerable difference between bid price and final contract price. Despite this, there is a strong positive perception towards adopting data driven cost estimation models, with most respondents recognising the importance of incorporating inflation adjusted approaches to improve estimation accuracy. However, several challenges were identified, including limitations in historical data availability, economic instability and lack of technical expertise. The study highlights the need to address these challenges to facilitate the adoption of advanced cost estimation approaches. It contributes to both practice and research by providing insights into industry readiness and identifying key areas for future development in the Sri Lankan construction industry.*

***Keywords:*** *Cost Estimation; Data-Driven Cost Estimation; Inflation Adjustment; Construction Industry; Sri Lanka.*

## 1. INTRODUCTION

Cost estimation forms the basis of the financial framework of construction projects from their inception stage (Dehabadi et al., 2017), where it acts as the foundation for assessing

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, herathhmsp.21@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

the financial feasibility of a project and facilitates proper resource planning (Ibrahim & Elshwadfy, 2021). An accurate cost estimate prepared at the tender stage plays a critical role in overall project success and supports various stakeholders in the construction process. Based on the pre-tender estimate, clients can evaluate project viability, secure funding, and establish realistic budgets (Ahlawat & Singh, 2025). For contractors, accurate cost estimation assists in preparing competitive bids, allocating resources effectively, and managing risks associated with cost overruns and market fluctuations (Plebankiewicz, 2018).

Discrepancies between bid price and final contract price represent a persistent and multifaceted challenge in the construction industry (Mbachu & Cross, 2015). These discrepancies arise from a wide range of factors, including scope variations, project delays, and unforeseen site conditions (Ahlawat & Singh, 2025). Such deviations are further intensified by macroeconomic conditions (Nabil, 2024). In countries such as Sri Lanka, where inflation is high and economic fluctuations are frequent, final contract price tend to escalate significantly beyond the estimates made at the tender stage (Fonseka et al., 2024). Projects with longer durations are particularly vulnerable to changes in material prices, labour rates, and statutory levies (Ballesteros-Pérez et al., 2019). When projects extend over several years, even modest annual price increases can accumulate into substantial cost overruns (Welde & Odeck, 2017). This time dependent vulnerability remains a major concern in the Sri Lankan construction industry, where delays in project implementation are common due to funding constraints, political instability, and administrative inefficiencies (Lakruwan & Mudalige, 2025). As project duration increases, the likelihood of significant deviation between final contract price and bid price also increases (Catalão et al., 2021).

Traditional cost estimation methods commonly adopted in the Sri Lankan construction industry are largely based on subjective judgements, which are prone to human errors in calculation (Anireddy, 2024). Furthermore, these traditional approaches are limited in their ability to capture real time market dynamics and inflationary effects, and their limited reliance on historical data reduces their effectiveness in volatile economic conditions. Although Musarat et al. (2024) developed a forecasting model capable of capturing inflation trends and predicting final contract price, the study was conducted in the context of the Malaysian construction industry. Similarly, Jassim et al. (2025) proposed a model incorporating inflation adjustment factors for preliminary cost estimation in Iraq. However, as highlighted by Thiruchelvam and Uduwage (2025), countries face unique challenges when adopting practices from different contexts due to variations in economic, regulatory, and industry conditions.

Despite the growing interest of research on inflation adjusted data driven cost estimation models, there remains a significant gap in relation to the Sri Lankan context. Prior to developing such models tailored to Sri Lanka, it is essential to assess the readiness of the industry to adopt inflation adjusted, data driven cost estimation models. Therefore, this study aims to examine current cost estimation practices in the Sri Lankan construction industry and explore the industry's readiness to adopt data driven cost estimation models to improve the accuracy of final contract price estimation. In this study, inflation adjusted data driven cost estimation refers to the use of historical project cost data and inflation related variables to estimate final contract price. The approach relies on analysing patterns and relationships within available data to generate cost predictions that reflect changing

economic conditions. To achieve the aim of the study, following objectives were formulated.

1. To examine current cost estimation practices in the Sri Lankan construction industry.
2. To examine industry perceptions and challenges associated with adopting inflation adjusted data driven cost estimation models in Sri Lanka.

# 2. LITERATURE REVIEW

## 2.1 COST ESTIMATION IN CONSTRUCTION PROJECTS

The relationship between bid price and final contract price constitutes a fundamental concern in construction project management and economics (Farshidpour et al., 2021). Each of these cost measures serves a distinct purpose throughout project procurement, execution, and completion stages, yet their interconnection determines the financial success and overall viability of construction projects (Dehabadi et al., 2017). The term bid price refers to the total price proposed by a contractor at the tender stage to complete a project, including both direct and indirect costs associated with the project (Uduwage-Don et al., 2023). Whereas the final contract price refers agreed contract sum between the client and contractor after incorporating all approved variations, adjustments, and contractual provisions during the project (Alshibani et al., 2024). However, in practice, the bid price estimated at the tender stage often deviates from the final contract price at the completion stage due to a range of influencing factors.

## 2.2 FACTORS CONTRIBUTING TO COST DEVIATIONS

The difference between bid price and final contract price is widely recognised as a persistent issue in the construction industry. These variances arise from a combination of project specific and external factors that undermine the accuracy of cost estimation and ultimately influence project financial outcomes (Sayed et al., 2020). Project specific factors include scope changes, design modifications, delays in execution, and unforeseen site conditions (Yussef et al., 2018; Gilb, 2012), while external factors include institutional influences and macroeconomic conditions.

In the Sri Lankan context, macroeconomic conditions remain one of the most critical factors contributing to discrepancies between bid price and final contract price (Fonseka et al., 2024). Inflationary pressures, currency depreciation, and fluctuations in interest rates directly affect the assumptions made during the tendering stage (Tembo et al., 2023). Furthermore, the recent economic crisis experienced in Sri Lanka has resulted in significant increases in the prices of key construction inputs such as cement, steel, and fuel. Consequently, bid prices prepared under earlier economic conditions often become outdated and unsustainable as projects progress under changing market conditions (Thilakshan et al., 2023). Additionally, the depreciation of the local currency increases the cost of imported materials, thereby raising overall construction expenditure (Martyshev et al., 2023). Therefore, greater attention is required during cost estimation to address factors contributing to cost deviations. In particular, given the fluctuating nature of the Sri Lankan economy, proper consideration of macroeconomic conditions becomes essential.

### 2.3 LIMITATIONS OF TRADITIONAL COST ESTIMATION METHODS

Traditional cost estimation methods refer to both formal and informal approaches used to forecast construction costs (Anireddy, 2024). Formal methods include techniques such as BOQ based estimating (Agyefi-Mensah & Nani, 2025), elemental estimating (Soutos & Lowe, 2011), and unit rate estimating (Chandra & Polley, 2024), while informal approaches rely primarily on proprietary experience (Anireddy, 2024), expert judgement (Ranadewa et al., 2018). and supplier quotations (Perluka, 2024). Although these methods are widely used in the Sri Lankan construction industry, they present several limitations. Subjective judgements are prone to human error (Anireddy, 2024), while reliance on historical data limits the ability to respond to rapidly changing market conditions (Musarat et al., 2024). Moreover, fluctuations in import duties, exchange rates, and fuel prices introduce significant uncertainty into cost forecasts, particularly when using traditional estimation approaches (Thilakshan et al., 2023). These methods often do not adequately account for inflation related effects, which reduces their reliability in volatile economic environments.

Therefore, transition towards cost estimation models which systematically convert available information into structured estimates that account for project characteristics, complexity, time factors, and external economic variables is essential (Capano et al., 2020). Such predictive modelling reduces financial uncertainty, improves the accuracy of cost planning, and supports proactive cost control throughout the project lifecycle (Jassim et al., 2025).

### 2.4 APPLICATION OF INFLATION ADJUSTED DATA DRIVEN COST ESTIMATION MODELS

Cost estimation models are generally based on the assumption that project costs are correlated with identifiable variables such as project size, material requirements, contract duration, and labor intensity (Kankate & Gurani, 2024). By utilizing historical datasets, statistical models can identify patterns and relationships that may be applied to predict costs for new projects (Farshidpour et al., 2021). Common analytical techniques include cost indexing, factor-based adjustments, and unit rate analysis, where project components are quantified and multiplied by corresponding cost parameters (AlTalhoni et al., 2024). In particular, inflation adjusted models aim to incorporate economic indicators to better reflect future cost conditions and improve prediction reliability (Musarat et al., 2024). Despite these advancements, the application and adoption of inflation adjusted, data driven cost estimation models remain underexplored in the Sri Lankan context.

Given that Sri Lanka frequently experiences cumulative price escalations, especially in long term construction projects, examining industry readiness and identifying potential opportunities for adopting inflation adjusted data driven cost estimation models may provide significant benefits to project stakeholders.

## 3. RESEARCH METHODOLOGY

The study adopted mixed method approach. The target population of this study consists of construction industry professionals, namely quantity surveyors, architects, and engineers, who are involved in cost estimation, tender preparation, and cost management in construction projects within the Sri Lankan construction industry. The sample frame includes construction professionals with a minimum of three years of experience in cost

estimation or project cost management in Sri Lankan construction projects. The minimum experience threshold of three years was considered appropriate as, within the Sri Lankan construction industry, professionals are typically exposed to cost estimation during the early stages of their careers under supervision. This ensures that respondents possess practical familiarity with cost estimation practices while maintaining an adequate and representative sample size. In addition, the study adopted both consultant and contractor perspectives, as these stakeholders are directly involved in cost estimation, tender preparation, and cost management activities, thereby providing comprehensive insights into current estimation practices and the readiness for adopting inflation adjusted, data driven cost estimation models. A purposive sampling technique was employed to capture views from respondents who are aligned with the study objectives and meet the sample frame criteria of having a minimum of three years of experience in cost estimation or project management within the Sri Lankan construction industry. Figure 1 outlines the research design of the study.

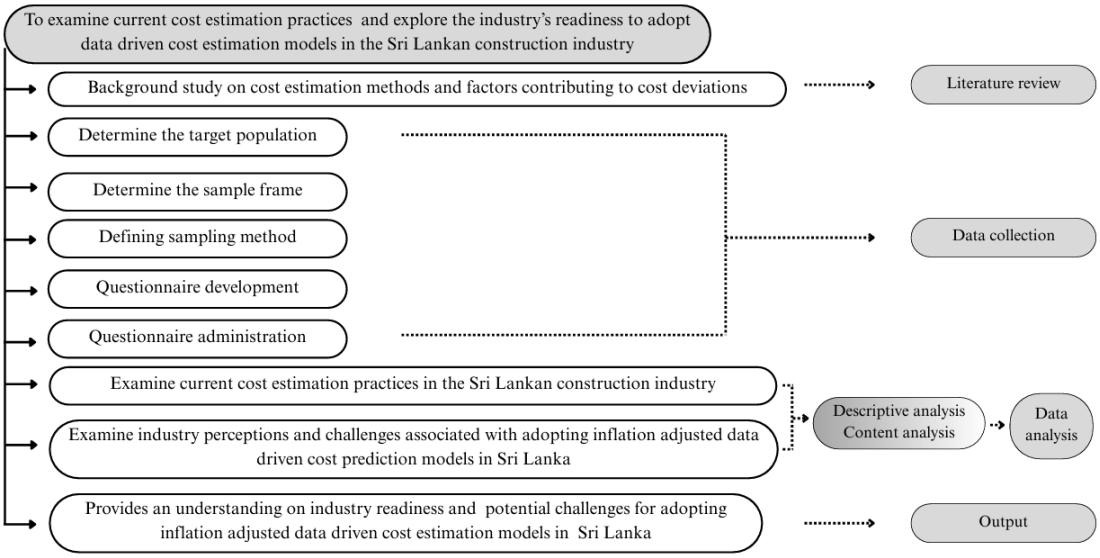



*Figure 1: Research design*

A structured questionnaire was used as the data collection instrument due to its ability to capture the views of a large set of respondents within a relatively short period (Thiruchelvam & Uduwage, 2025). The questionnaire was distributed to 75 construction professionals through online platforms such as email, LinkedIn, and WhatsApp to enhance accessibility for respondents. The collected responses were analysed using both descriptive analysis and content analysis. Descriptive analysis was used to summarise and describe the data related to current cost estimation practices and industry readiness for adopting inflation adjusted data driven cost estimation models in Sri Lanka through frequencies, charts, and mean values. In addition, open ended question was used to collect respondents' views on the challenges associated with adoption of inflation adjusted data driven cost estimation models in Sri Lanka. These responses were analyzed using content analysis, where qualitative data were grouped into key themes representing the challenges associated with adoption.

# 4. RESULTS AND DISCUSSION

## 4.1 RESPONDENTS' DEMOGRAPHIC INFORMATION

The questionnaire was distributed to 75 construction professionals who align with the defined sample frame, and 40 valid responses were received, resulting in a 53% response rate. Taherdoost and Madanchian (2024) highlighted that an average response rate of 51% is considered sufficient for online surveys in business and management-related studies. Since the response rate of this study exceeds the identified threshold, the sample size can be considered adequate for the analysis.

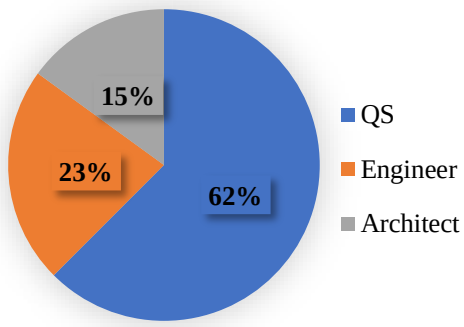



*Figure 1: Respondents' profession*

As presented in Figure 2, data were collected from three categories of construction professionals, namely Quantity Surveyors (QS), Engineers, and Architects, representing 62%, 23%, and 15% of the respondents, respectively. Among these, Quantity Surveyors constitute the majority of respondents. This is justifiable as QS professionals are more directly involved in cost estimation activities compared to engineers and architects, whose involvement in this specific area is relatively limited.

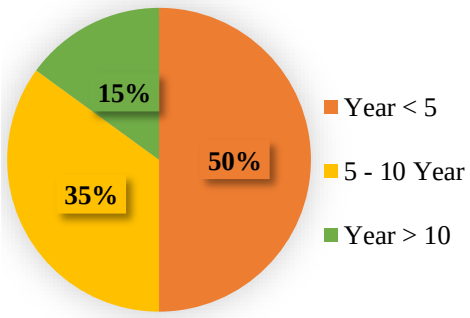



*Figure 2: Respondents' experience*

Figure 3 illustrates the years of experience of the respondents, where all respondents possess at least a degree in a relevant field. Moreover, the demographic analysis indicate that the respondents have a satisfactory level of knowledge and industry experience, enabling them to understand and respond to the questionnaire in a reliable manner.

## 4.2 CURRENT COST ESTIMATION PRACTICES IN THE SRI LANKAN CONSTRUCTION INDUSTRY

Current cost estimation practices followed in the Sri Lankan construction industry at the tendering stage to forecast final contract price were gathered from questionnaire responses and are illustrated in Figure 4.

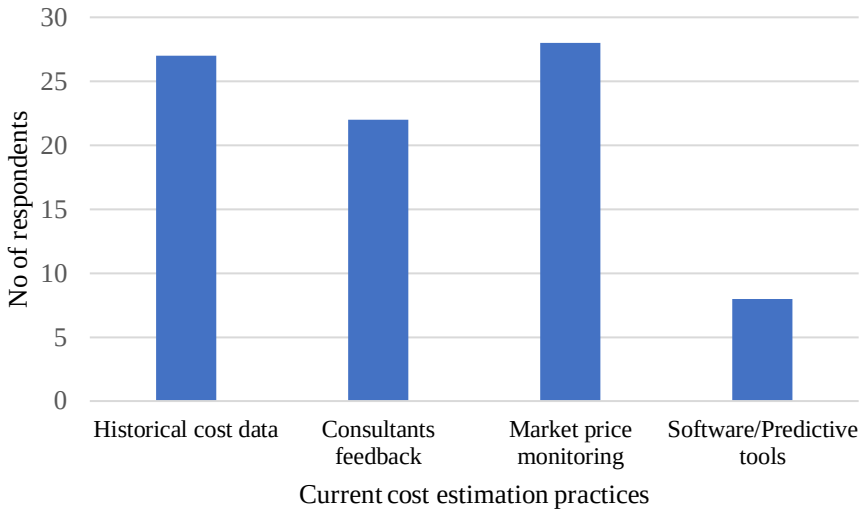



*Figure 3: Current cost estimation practices in the Sri Lankan construction industry*

As indicated in Figure 4, market price monitoring including collecting and regularly updating prices from suppliers, contractors and labour market is identified as most commonly adopted cost estimation practices in Sri Lankan construction industry. This is followed by the use of historical cost data and consultant feedback. These findings indicate that construction industry professionals tend to rely more on experience based approaches and real time market information when preparing cost estimates. In contrast, the use of software or predictive tools remains significantly low, suggesting limited adoption of advanced or data driven approaches in cost estimation when compared to traditional methods such as market price monitoring, historical data utilisation, and consultant based inputs.

Furthermore, respondents were requested to indicate the level of alignment between bid price and final contract price. The results reveal that only 20% of respondents perceived a very close alignment between bid price and final contract price, while the remaining 80% indicated a considerable difference between the two. This suggests that, although traditional estimation methods are widely practised in the Sri Lankan construction industry, they may not adequately capture the factors influencing final contract price.

Overall, the findings highlight that existing cost estimation practices, which are largely based on traditional approaches, show limitations in achieving close alignment with final contract price. This indicates the need to explore the adoption of data driven cost estimation models.

## 4.3 INDUSTRY PERCEPTIONS AND CHALLENGES ASSOCIATED WITH ADOPTING INFLATION ADJUSTED DATA DRIVEN COST ESTIMATION MODELS IN SRI LANKA

Respondents' perceptions regarding the use of data driven cost estimation tools as a method to improve cost estimation accuracy were collected through the questionnaire survey. The findings indicate that nearly 95% of respondents expressed a positive attitude towards the use of data driven cost estimation models in construction cost estimation, while the remaining 5% provided neutral responses, with no respondents indicating disagreement.

Similarly, for the specific question related to the adoption of inflation adjusted data driven cost estimation models in the Sri Lankan construction industry, a consistent trend was observed, where respondents were clearly provided with the definition of the inflation adjusted data driven cost estimation model to ensure informed responses Approximately 98% of respondents indicated that the use of inflation adjusted, data driven cost estimation models is essential for improving cost estimation accuracy, while only 2% expressed disagreement.

These findings suggest that there is a strong positive perception and willingness among industry professionals towards the adoption of inflation adjusted, data driven cost estimation models in the Sri Lankan construction industry

### 4.3.1 Challenges Associated with Adoption of Inflation Adjusted Data Driven Cost Estimation Models in Sri Lanka

Although the findings indicate a positive perception towards adoption, respondents also highlighted several challenges associated with implementing inflation adjusted, data driven cost estimation models in Sri Lanka. These challenges are presented in Figure 5.

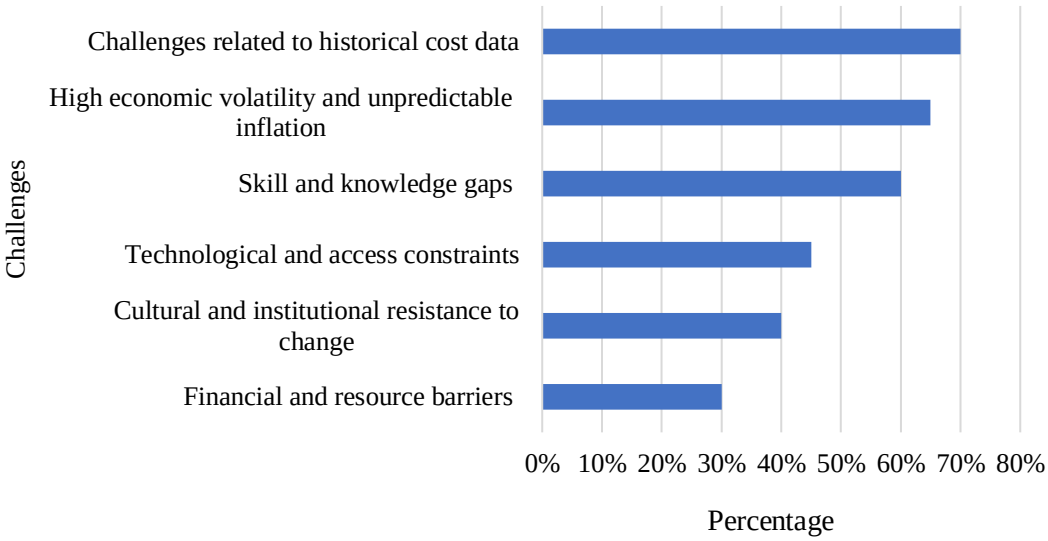



*Figure 5: Challenges associated with adoption of inflation adjusted data driven cost estimation models*

As illustrated in Figure 5, six major challenges were identified by the respondents. Among these, challenges related to historical cost such as data availability and quality were identified as the most critical. Respondents highlighted that fragmented, non digitalised, and inconsistent records limit the ability to develop reliable and robust

models. As noted by AlTalhoni et al. (2024), historical cost data serves as a primary input for cost estimation models. Therefore, the lack of accurate and structured data might become a significant barrier. Further, high economic volatility and unpredictable inflation were identified as another major challenge. Frequent fluctuations and delays in updating official price indices in Sri Lanka can reduce the reliability and stability of cost forecasts. In addition, a lack of skills and knowledge in data analytics, statistics, and machine learning among construction professionals was identified as a key constraint. This limitation affects the ability of industry practitioners to effectively adopt and utilise data driven approaches. Similarly, technological and accessibility constraints were recognised as significant challenges, particularly for small and medium sized firms. The high cost of specialised software and limited digital infrastructure can restrict the adoption of advanced cost estimation tools. Moreover, cultural and institutional resistance to change was highlighted as a challenge, as the Sri Lankan construction industry largely depends on expert judgement in cost estimation. Transitioning from experience based approaches to algorithm based decision making may therefore face resistance. Finally, financial and resource constraints were identified as another barrier, as the initial investment required for system development, validation, training, and maintenance can be substantial, particularly for smaller organisations.

## 4.4 DISCUSSION

The findings of this study provide significant insights into current cost estimation practices and the readiness of the Sri Lankan construction industry to adopt inflation adjusted data driven cost estimation models. As shown in Figure 4, traditional cost estimation methods, particularly market price monitoring and historical cost data usage remain the dominant cost estimation practice in Sri Lanka. This is consistent with Anireddy (2024), who notes that construction cost estimation in developing contexts remains largely judgment-driven due to limited integration of analytical tools and structured data systems. Such reliance on traditional methods may contribute to the observed mismatch between bid prices and final contract prices, where 80% of respondents reported considerable deviations. This indicates that existing approaches may not fully capture dynamic cost variations in volatile market conditions.

In contrast, the limited use of software-based or predictive tools further highlights the relatively low level of technological maturity within the Sri Lankan construction industry. Similar trends have been reported in prior research, which notes that the adoption of digital and predictive cost estimation techniques remains slow in developing construction sectors due to limited digital integration and fragmented data systems (Abu-Khader, 2023). Despite these constraints, the findings reveal a strong conceptual acceptance of inflation adjusted data driven cost estimation models among industry professionals. This suggests a notable awareness - implementation gap. This aligns with existing literature which emphasizes that data driven and inflation adjusted models enhance forecasting reliability by incorporating economic fluctuations (Jassim et al., 2025; Musarat et al., 2024).

Mainly six barriers identified in this study for the adoption of inflation adjusted data driven cost estimation models in Sri Lankan construction industry particularly barriers related to availability and quality of historical cost data, economic instability, and lack of technical skills (Figure 5). Addressing these challenges may support the successful implementation of inflation adjusted, data driven cost estimation models in the Sri Lankan

construction industry and improve the alignment between bid price and final contract price. Based on the findings of this study, industry practitioners may consider developing inflation adjusted, data driven cost estimation models and conducting pilot testing using real construction projects to evaluate their accuracy and applicability. In addition, government and policymakers may facilitate adoption by providing training programmes and financial assistance to enhance industry capacity. Furthermore, this study contributes to the existing body of knowledge by highlighting the need for future research. Subsequent studies may focus on identifying and evaluating suitable strategies to overcome the challenges associated with adopting inflation adjusted, data driven cost estimation models in Sri Lanka.

## 5. CONCLUSIONS

This study examined current cost estimation practices in the Sri Lankan construction industry and evaluated the industry's readiness to adopt inflation adjusted, data driven cost estimation models. The findings reveal that traditional cost estimation practices, particularly market price monitoring, historical data utilisation, and consultant based inputs, remain dominant at the tendering stage. However, these approaches show limitations in achieving close alignment between bid price and final contract price, as highlighted by the significant discrepancies reported by the respondents. Given the limitations of traditional methods, the study identified a strong positive perception among industry professionals towards the adoption of data driven cost estimation models. The majority of respondents acknowledged the importance of incorporating inflation adjusted models to improve cost estimation accuracy, especially in the context of economic volatility in Sri Lanka. However, several challenges were identified that may hinder effective adoption. These include issues related to the availability and quality of historical cost data, high economic uncertainty, limited technical expertise, technological constraints, resistance to change, and financial barriers. Addressing these challenges is important to facilitate the transition towards more advanced cost estimation practices in Sri Lanka. Furthermore, the findings of this study may also be relevant to other developing countries with similar construction industry characteristics. Future research may be extended to identify suitable strategies to overcome the challenges associated with adopting inflation adjusted, data driven cost estimation models in Sri Lanka. Overall, the adoption of such models has the potential to enhance the reliability of cost estimation and improve project financial outcomes.

## 6. REFERENCES

Abu-Khader, W. (2023). Barriers to the adoption of digitalization in the construction industry: Perspectives of owners, contractors, and contractors. *Construction Economics and Building*, *23*(3/4), 87-106. https://doi.org/10.5130/ajceb.v23i3/4.8636

Agyefi-Mensah, S., & Nani, G. (2025). Analysis of historical BOQ data for case-based reasoning in preliminary cost estimating. *African Journal of Applied Research*, *11*(3), 103–128. https://doi.org/10.26437/ajar.v11i3.1160

Ahlawat, S., & Singh, U. P. (2025). Pre-tender cost estimation and bid pricing. In D. Bajaj (Ed.) *Handbook of construction project management* (pp. 347–369). Springer. https://doi.org/10.1007/978-981-96-7631-6_11

Alshibani, A., Hafez, B. E., Hassanain, M. A., Mohammed, A., Al-Osta, M., & Bahraq, A. (2024). Fuzzy logic-based method for forecasting project final cost. *Buildings*, *14*(12), 3738. https://doi.org/10.3390/buildings14123738

AlTalhoni, A., Liu, H., & Abudayyeh, O. (2024). Forecasting construction cost indices: Methods, trends, and influential factors. *Buildings*, *14*(10), 3272. https://doi.org/10.3390/buildings14103272

Anireddy, A. R. (2024). Comparative analysis of traditional vs. modern estimating methods: Pros and cons of different approaches in construction. *International Journal of Science and Research (IJSR)*, *13*(11), 1–5. https://doi.org/10.21275/sr241023231113

Ballesteros-Pérez, P., Sanz-Ablanedo, E., Soetanto, R., González-Cruz, M. C., Larsen, G. D., & Cerezo-Narváez, A. (2019). Duration and cost variability of construction activities: an empirical study. *Journal of Construction Engineering and Management*, *146*(1), 1739. https://doi.org/10.1061/(asce)co.1943-7862.0001739

Capano, C., Hariharan, J., Moud, H., & Asutosh, A. (2020). Construction cost predication model using macro economic indicators. *EPiC Series in Built Environment*, *1*, 373-382. https://doi.org/10.29007/tjbv

Catalão, F. P., Cruz, C. O., & Sarmento, J. M. (2021). The entanglement of time and cost deviations in public projects. *Annals of Public and Cooperative Economics*, *94*(1), 241–272. https://doi.org/10.1111/apce.12364

Chandra, A., & Polley, D. (2024). A comparative analysis on the cost estimation techniques in building construction. *International Research Journal of Engineering and Technology (IRJET)*, *11*(9), 2395–0056. https://www.irjet.net/archives/V11/i9/IRJET-V11I9107.pdf

Dehabadi, M. M. A., Aria, H. A., & Salari, M. (2017). A new model for estimation of project total cost in construction projects. *International Journal of Information and Decision Sciences*, *9*(2), 128. https://doi.org/10.1504/ijids.2017.10005874

Farshidpour, R., Negoro, K., & Tehrani, F. M. (2021). A statistical approach to analyzing engineering estimates and bids. *Stats*, *4*(1), 62–70. https://doi.org/10.3390/stats4010005

Fonseka, W., Withanage, K., & Jayasuriya, D. (2024). Mitigating measures for the escalation of building project costs amid Sri Lanka's economic crisis. In *17th International research conference - FARU*, (pp, 449–458). Faculty of Architecture Research Unit. https://doi.org/10.31705/faru.2024.36

Gilb, T. (2012). Estimation: A paradigm shift towards dynamic design-to-cost and radical management. *INCOSE International Symposium*, *22*(1), 1929–1946. https://doi.org/10.1002/j.2334-5837.2012.tb01447.x

Ibrahim, A. H., & Elshwadfy, L. M. (2021). Assessment of construction project cost estimating accuracy in Egypt. *The Open Civil Engineering Journal*, *15*(1), 290–298. https://doi.org/10.2174/1874149502115010290

Jassim, H. S. H., Hasan, M. F., Altaee, M. J., & Gamil, Y. (2025). A model for preliminary cost estimation in buildings construction projects. *Frontiers in Built Environment*, *11*. 1359777. https://doi.org/10.3389/fbuil.2025.1359777

Kankate, S. V. K. M. S. V., & Gurani, K. B. G. P. K. B. (2024). Development of a prediction model for construction project cost in India: An analytical approach a review. *Journal of Advances in Science and Technology*, *20*(1), 96–99. https://doi.org/10.29070/mmrynp32

Lakruwan, U. I. G. D., & Mudalige, D. M. (2025). A study of the BIM collaboration concept to reduce building construction project delays in Sri Lanka. *Journal of Business and Technology*, *9*(2), 27–46. https://doi.org/10.4038/jbt.v9i2.136

Martyshev, P., Prehn, S., Perekhozhuk, O., & Vakhitov, V. (2023). The effects of domestic currency depreciation on import substitution: New empirical evidence from the Ukrainian pork industry. *Eastern European Economics*, *62*(1), 89–107. https://doi.org/10.1080/00128775.2023.2167721

Mbachu, I., & Cross, C. (2015). Key drivers of discrepancies between initial and final costs of construction projects in New Zealand. *PM World Journal*, *4*(9), 1-13. https://pmworldlibrary.net/wp-content/uploads/2015/09/pmwj38-Sep2015-Mbachu-Cross-cost-discrepancies-construction-projects-new-zealand-second-edition.pdf

Musarat, M. A., Alaloul, W. S., & Liew. (2024). Incorporating inflation rate in construction projects cost: Forecasting model. *Heliyon*, *10*(4), e26037. https://doi.org/10.1016/j.heliyon.2024.e26037

Nabil, A. M. (2024). Impact of cost overruns on infrastructure projects failures and effective cost management to reduce overruns. *Global Journal of Researches in Engineering: J General Engineering*, *24*(2), 2249–4596. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5020982

Perluka, B. Y. (2024). *Reliable procurement cost estimation methodologies: A case study in complex environments* [Master thesis, University of Twente]. https://essay.utwente.nl/fileshare/file/99137/Perluka_MA_BMS.pdf

Plebankiewicz, E. (2018). Model of predicting cost overrun in construction projects. *Sustainability*, *10*(12), 4387. https://doi.org/10.3390/su10124387

Ranadewa, K., Sandanayake, Y., & Siriwardena, M. (2018). Enabling lean among small and medium enterprise (SME) contractors in Sri Lanka. In V.A.González (Ed.) *26th Annual conference of the international group for lean construction*, (pp. 392–401). https://doi.org/10.24928/2018/0428

Sayed, M., Abdel-Hamid, M., & El-Dash, K. (2020). Improving cost estimation in construction projects. *International Journal of Construction Management*, *23*(1), 135–143. https://doi.org/10.1080/15623599.2020.1853657

Soutos, M., & Lowe, D. J. (2011). Elemental cost estimating: Current UK practice and procedure. *Journal of Financial Management of Property and Construction*, *16*(2), 147–162. https://doi.org/10.1108/13664381111153123

Taherdoost, H., & Madanchian, M. (2024). The impact of survey response rates on research validity and reliability. In A. Rahal & M. Adorján (Eds.) *Design and validation of research tools and methodologies* (pp. 177–206). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-1135-6.ch009

Tembo, M., Mwanaumo, E. M., & Kahanji, C. (2023). Impact of tender price variability on economic sustainability of construction sector in developing countries. *International Journal of Development and Economic Sustainability*, *11*(1), 50–80. https://doi.org/10.37745/ijdes.13/vol11n15080

Thilakshan, K., Arsecularatne, B., & Sandanayake, Y. (2023). Impact of economic decisions on building construction material prices in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, and K. A. T. O. Ranadewa (eds) *Proceedings of the 11th World Construction Symposium* (pp. 569–581). CIOB & BEMRU. https://doi.org/10.31705/wcs.2023.47

Thiruchelvam, K., & Uduwage, D.N.L.S (2025). Assessing SDG 7 performance: Identifying relevant KPIs for the Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, and G. A. Tennakoon (eds). *Proceedings of the 13th World Construction Symposium* (pp. 203–215). CIOB & BEMRU. https://doi.org/10.31705/wcs.2025.16

Uduwage-Don, N. L. S., Hadiwattage, C., & Panuwatwanich, K. (2023). Enhancing the responsiveness of bids in public procurement: The case of Sri Lanka. *Public Works Management & Policy*, *29*(3), 332–363. https://doi.org/10.1177/1087724x231191724

Welde, M., & Odeck, J. (2017). Cost escalations in the front-end of projects: Empirical evidence from Norwegian road projects. *Transport Reviews*, *37*(5), 612–630. https://doi.org/10.1080/01441647.2016.1278285

Yussef, A., Gibson, G. E., Asmar, M. E., & Ramsey, D. (2018). Front end engineering design (FEED) for large industrial projects: FEED maturity and its impact on project cost and schedule performance. In *Construction Research Congress 2018* (pp. 1–8). Construction Research Council and the Construction Institute of ASCE. https://doi.org/10.1061/9780784481295.001

Dissanayake, W.M.S.S. and Hirudini, S.M., 2026. Influence of personal space on privacy-related psychological comfort in migratory settlements: A case study of Muththettugala, Kurunegala. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 936-950. DOI: https://doi.org/10.31705/WCS.2026.69. Available from: https://ciobwcs.com/papers/

# INFLUENCE OF PERSONAL SPACE ON PRIVACY-RELATED PSYCHOLOGICAL COMFORT IN MIGRATORY SETTLEMENTS: A CASE STUDY OF MUTHTHETTUGALA, KURUNEGALA

**W.M.S.S. Dissanayake[1] and S.M. Hirudini[2]**

## *ABSTRACT*

*The housing programs designed for migrant communities in Sri Lanka are mostly focused on the physical aspect of housing, ignoring other aspects of living environments, such as privacy and personal space. The proxemics theory of personal space, developed by Hall in 1966, has been found to affect human behaviours. Other studies have found that inadequate privacy-related psychological comfort and personal space can cause negative effects on human psychology. Migratory communities are likely to face these issues, especially since their new living environment would disrupt their previous spatial and social environments. The present study aims to investigate the effect of personal space on the privacy-related psychological well-being of the people living in the selected migrant housing settlement in Kurunegala. A mixed-method approach has been employed to conduct this study, and all 24 households in the selected settlement were surveyed using structured questionnaires consisting of both quantitative and qualitative questions. The results of the study found that the high residential proximity and lack of control over personal space negatively affect the privacy-related psychological comfort of residents of the housing settlement. Though the people adapt to these situations, the lack of privacy causes negative aspects such as increased stress, decreased psychological security, low feelings of belonging, and decreased autonomy, especially for people living in the rural areas of Sri Lanka. The study concludes that the control over personal space has greater significance for the privacy-related psychological well-being of people than the size of the dwelling or the density of the residential area.*

***Keywords:*** *Migratory settlements; Personal space; Privacy; Psychological well-being.*

## 1. INTRODUCTION

Internal migration in Sri Lanka has been influenced by different factors such as urban sprawl, infrastructure development, changes in livelihoods, and environmental pressures. As a solution for that, the government has introduced planned housing schemes to accommodate migrants and displaced people. While these projects meet immediate accommodation needs, they often have high-density residential environments with

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, shashikasarts@gmail.com
[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, mihirih@uom.lk

standardized layouts. Such configurations often prioritize efficiency at the expense of residents' need for privacy, especially the kind experienced through personal space.

The home is where a person lives and feels at ease, supporting their everyday needs and emotional wellness. For folks who move to new areas, it's usually a shift from places they know well to tighter, less flexible living spaces. These changes can seriously impact their ability to control privacy and personal space, which are super important for feeling mentally healthy (Altman, 1975). Researchers keep finding that how you live really affects your mental health as a migrant (Ziersch et al., 2024; WHO, 2025). Yet, there's not much known about how changing residences influences privacy and psychological wellness in migrants, especially in Sri Lanka, where plenty of housing is provided for them.

The purpose of this investigation is to assess the effect of privacy in relation to the personal space of migrants in terms of their psychological well-being. Privacy is an essential element for every individual since it affects the comfort level, security, self-control, and psychological well-being of people. The problem, however, lies in the fact that migration usually involves dramatic shifts in the physical environment and the relationships that a person maintains with others, and as a result, it may negatively affect his or her privacy. Thus, the present research should focus on the importance of privacy and its impact on the psychological well-being of migrants. It is necessary to identify the major aspects of privacy and its relationship with psychological well-being, namely the social and spatial factors that promote psychological well-being and comfort, as well as the role of migration-related environmental changes on this process.

This study focuses on privacy experienced within personal spaces in the selected housing settlement. The scope is limited to spatial and psychological dimensions of housing. Limitations include a restricted sample size, potential recall bias regarding previous privacy conditions, and the subjective nature of privacy-related psychological well-being assessments.

# 2. LITERATURE REVIEW

## 2.1 PERSONAL SPACE AND PRIVACY

Personal space and privacy are central concepts in environmental psychology that affect human behaviour in homes. Proxemics theory, developed by Hall in 1966, defined personal space as a cultural boundary that affects how close we get to other people. It is not only about distance but also encompasses cultural values, identity, and control. In homes, personal spaces exist on different levels, from inside the homes to the neighbourhood or village where one resides.

Another important aspect of environmental psychology in homes is territoriality. Brown and Altman (1983) argued that markers of territory and personalization of spaces increase one's level of control and safety. When one lacks an opportunity to establish or defend one's territory or personal spaces, it affects one's mental well-being negatively.

Altman's theory of privacy regulation (1975) defined privacy as a constantly evolving process of managing one's personal spaces or boundaries. One makes adjustments to the level of involvement in social interactions to achieve an optimal level of detachment and association. When it becomes difficult to manage one's personal spaces in an environment, it can result in stress. Thus, it is not only about detachment but also about

control over one's association or involvement with others. In a highly populated or standardized living environment, such as apartments or condos, one has limited means of protecting one's privacy through barriers or transitional spaces.

## 2.2 THEORETICAL LINKAGES BETWEEN PERSONAL SPACE, PRIVACY, AND PSYCHOLOGICAL WELL-BEING

In this research, psychological well-being is seen as the main dependent variable and represents the general psychological condition of the person. These aspects include feeling comfortable, safe, emotionally balanced and contented with one's living circumstances. While there are some terms mentioned in the literature such as psychological comfort, psychological stability and psychological stress, they have not been taken as distinct independent variables in this research because of their interrelatedness as factors influencing psychological well-being.

In the context of residential environments, proper maintenance of adequate personal space and effective regulation of one's privacy may have some impact on these factors through the process of minimizing any form of social intrusions into one's life, managing one's emotions, and having good control over one's daily activities. Prior studies have already revealed the impact of these two factors on psychological well-being, especially in the context of high-density living and migration (Altman, 1975; Evans et al., 2003; Gifford, 2007). Thus, in this research, the relationship between personal space and privacy as spatial experiences and the psychological well-being of migrants will be investigated. Housing, Density, and Psychological Well-being

One interesting way to divide the relationship between our surroundings and our psychological well-being is the difference between density, or the actual number of people in a space, and crowding, or the feeling that there isn't enough space. Density does not necessarily contribute to stress, but crowding does, especially when a sense of privacy is lacking, and this can contribute to psychological strain in people. Evans (2003) indicates that living in a crowded space for long periods of time can increase stress, hurt cognitive functioning, and reduce emotional well-being. A big part of this is the sense of control when people cannot control their surroundings or their interactions with people in their space, environmental stress increases.

According to Gifford (2007), a lack of privacy can contribute to irritability, withdrawal from social situations, and even more conflicts within the home space. Our satisfaction with our living space is not just based on the physical space, but also on its functionality for our lives and our personal meaning or significance for our well-being (Amerigo & Aragones, 1997). Being able to maintain our own space within our living space is a large contributor to our personal well-being.

## 2.3 MIGRATION AND MIGRATORY COMMUNITIES

Migration is defined as 'the displacement of people or households across a geographic boundary, be it temporary or permanent, for various reasons, including job opportunities, education, family needs, environmental influences or to seek a better life. These displaced people are often required to adapt to new social and physical environment, a different culture etc. During the migration process groups of people often create new communities in their destination area based on their social relationships and neighborhood grouping' (Castles et al., 2020: 10). A migratory community is comprised of those migrants whose

social and domestic lives are affected by the new conditions of housing, relationships and space, while remaining in contact with home to various degrees. Migration is therefore a process of social and physical transformation of communities as well as a geographic displacement (Castles et al., 2020; International Organization for Migration [IOM], 2024; United Nations, 2023).

## 2.4 MIGRATION, RESETTLEMENT, AND SPATIAL DISRUPTION

Migration, especially when state-driven, can transform lifestyles and environments. Place attachment theory provides a mental health perspective on this phenomenon, and the theory further explains the psychological impact of migration. Lewicka (2011) describes place attachment as an emotional bond formed through long-term interaction with familiar environments. People are more likely to cope if there is some spatial continuity in terms of shared architectural elements or settlement form.

Cernea (1997) highlights how migration causes dislocation in terms of social networks, ways of living, and a sense of place, which in turn causes psychological distress. Scudder (2005) highlights how resettlement is a success if it involves rebuilding social and cultural life in a new place, as opposed to simply moving from one place to another. Housing programs are often geared towards achieving uniformity in space, increasing housing densities, and reducing costs. This has been at the expense of flexibility in space. Housing programs that are geared towards efficiency often try to standardize the way homes are laid out, glossing over the way people have been living in the past. This has resulted in a disconnect between the old settlement form and the new housing environment.

However, there are gaps in literature, and one is that there is a lack of studies that examine and compare pre- and post-settlement morphology, or how spaces are arranged before and after migration. Another is that there is a lack of studies that examine how they change, and how they impact psychological outcomes. Lastly, there is a lack of studies on Sri Lankan migratory housing schemes and how they impact mental health. Thus, a case study analysis of the Arayliya Uyana Housing Scheme, which examines both spatial and psychological outcomes, can be a way to address the gap in knowledge. This is because it can examine how spaces are arranged before and after migration, thus providing a comparison and a better understanding of how changes in morphology can impact personal space regulation and psychological outcomes.

## 2.5 CRITICAL SYNTHESIS AND RESEARCH GAP

Personal space, privacy, and mental health are linked. Environmental psychology explains this relationship. These theories explain how a lack of control over spatial arrangements can lead to stress and negative psychological outcomes. Studies on migration highlight social and cultural upsets, and housing studies highlight the limitations of a one-size-fits-all approach to planning.

These are some of the important limitations of the current literature base. Firstly, very little work has been done to compare morphological characteristics prior to migration to those after resettlement; this means comparing the spatial organization of living quarters before and after migration. Secondly, there is an absence of studies on the temporal dimension of such changes in space and the psychological ramifications thereof. Finally, and most importantly for this paper, there has been very little work done on migratory

housing schemes in Sri Lanka and the psychological impact thereof. One such example, which could potentially be used to fill this lacuna, would be the selected Housing Scheme.

## 2.6 PARAMETERS OF THE STUDY

In order to analyse the interconnections between personal space and privacy in relation to psychological well-being, the following parameters have been identified for consideration. The parameters of privacy include spatial distance, connectivity, visual access, spatial depth, and boundary definition, while the parameters of psychological well-being include perceived privacy, environmental control, stress and comfort, social balance, and place attachment, which show the role of spatial design in the two concepts. The study variables and their operational definitions were developed from the environmental psychology literature and translated into measurable questionnaire indicators that could capture residents' perceptions of privacy, spatial control, and psychological comfort.

### 2.6.1 Selected Parameters to Study Personal Space

Selected parameters to study personal space are explained in Table 1.

*Table 1 : Privacy parameters of the study*

| Parameter | Explanation |
|---|---|
| Perceived Control Over Access | The degree to which individuals can regulate entry into their immediate spatial environment; reduced control increases perceived crowding and stress (Altman, 1975; Evans & Lepore, 1993). |
| Visual Privacy Level | The extent to which individuals are protected from unwanted visual exposure within their personal space; reduced visual privacy can increase psychological strain (Altman, 1975; De Macedo et al., 2022). |
| Acoustic Privacy Level | The degree of protection from unwanted sound intrusion; prolonged noise exposure can elevate stress and disrupt psychological restoration (Evans & Johnson, 2000; Basner & McGuire, 2018). |
| Interpersonal Distance | The physical distance maintained between individuals; distances below preferred personal norms may increase discomfort and physiological stress responses (Hall, 1966; Evans & Wener, 2007). |

### 2.6.2 Selected Parameters to Study Privacy-Related Psychological Comfort

Selected parameters to study privacy-related psychological comfort are defined in Table 2.

*Table 2 : Study privacy-related psychological comfort Parameters*

| Parameter | Explanation |
|---|---|
| Cultural Proxemic Alignment | The degree of consistency between culturally preferred interpersonal distances and actual spatial conditions; a mismatch may increase social discomfort and psychological stress (Hall, 1966; Sorokowska et al., 2017). |
| Territorial Definition / Personalization | The presence of clearly defined or personalized micro-territories within the living environment; territorial markers can strengthen feelings of ownership, control, and psychological security (Altman, 1975; Brown et al., 2005). |

# 3. RESEARCH METHODOLOGY

## 3.1 SITE, SAMPLE SELECTION CRITERIA, AND DATA COLLECTION METHOD

For this study, a survey was applied, as all 24 families in the village were targeted, thereby reducing sampling errors in the targeted population. The use of a survey design is applicable in small populations where the objective is not to generalize to a larger population but to gain an in-depth understanding of the population (Yin, 2018, World Health Organization 2025). The mixed format of questions in the questionnaire was applied to ensure that there was a balance between quantitative and qualitative information. The use of mixed methods in a study was recommended as a means to ensure that there was an in-depth understanding of a phenomenon (Creswell, 2014). In small populations, sufficient information can be obtained even from a small sample (Kirsti Malterud et al., 2016).

The study area is located in the Kurunegala District. The area was initially used for the cultivation of coconuts, while later the area was divided into smaller sections by a private enterprise, resulting in the area being used as a residential area. This area was chosen because of the urban expansion that is taking place. The changes that can be observed include improvements to the infrastructure, an increase in the number of houses, and the presence of the highway, all contributing to the increased value of the land.

*Figure 1: Selected site for the study*

## 3.2 DATA ANALYSIS AND ASSESSMENT FRAMEWORK OF VARIABLES

The chosen variables came from environmental psychology theories on privacy, personal space, and psychological well-being. Personal space was measured by the following four variables: control over access, visual privacy, acoustic privacy, and interpersonal distance. The psychological comfort associated with privacy was measured using cultural proxemic congruency and territoriality/personalization (Altman, 1975; Hall, 1966; Brown et al., 2005).

Quantitative data were recorded using a five-point Likert scale and analyzed using Jamovi statistical software. Measures of central tendency and dispersion were obtained to find patterns in participants who had a rural, semi-rural, and urban background. Thematic analysis of qualitative data involved coding together similar responses in relation to privacy, spatial adaptation, and psychological comfort (Creswell, 2014). Integration of results from the two forms of analysis allowed for an in-depth discussion of the personal space-privacy psychological well-being relationship.

### 3.3 SPECIFIC ETHICAL CONSIDERATIONS

No personal data capable of identifying the respondents was gathered, thus, ensuring anonymity among the participants. Considering the sensitive topic of the study concerning privacy and personal space in domestic settings, other steps were undertaken to safeguard the privacy of the individuals, community, and living environment. The study did not involve gathering any exact location addresses, personal photos, detailed house plans, or other similar forms of identifying information to avoid posing certain threats to social psychology. Thus, the characteristics of the settlement were illustrated using maps and analysis. Any form of data gathering and analysis was done only in relation to the purposes of the study. (Belmont Report, 1979; Israel & Hay, 2006; APA, 2017).

## 4. DATA ANALYSIS

### 4.1 ANALYTICAL FRAMEWORK AND DATA SOURCES

This chapter examines privacy via quantitative and qualitative data from all 24 households in the selected migratory settlement. Quantitative data comes from an original survey comprising five-point Likert scales and open-ended questions. Psychological comfort and privacy are positively correlated, that is, high survey scores reflect a high level of comfort and privacy. Jamovi was used to calculate survey means, standard deviations, and test scores for skewness and kurtosis. Shapiro–Wilk was used to test survey normality. Migration patterns were analyzed using Microsoft Excel. Privacy stress was surveyed using constructs from the environmental psychology theories of Altman (1975), Hall (1966), and Evans et al. (2003). Two survey groups were constructed, Personal Space Parameters and Privacy-Related Psychological Comfort Parameters. The former incorporates Interpersonal Distance, Perceived Control Over Access, Visual Privacy, and Acoustic Privacy. The latter includes Territorial Definition/Personalization and Cultural Proxemic Alignment. The absence of normal distribution in the rural-origin sub-groups (Shapiro–Wilk $p < 0.05$, high kurtosis) points to a lack of intragroup variability and the presence of intergroup variability, indicating privacy stress is systematic.

### 4.2 SAMPLE PROFILE: MIGRATION BACKGROUND

#### 4.2.1 Origin Background

The majority of residents come from semi-rural areas (54%), followed by those from rural (25%) and urban (21%) areas. Because residents from rural areas used to live in low density areas that they could organize themselves, they are the most divergent from the compact, organized designs of current settlements. Thus, in this analysis, we expect rural-origin residents will display the most psycho-spatial dislocation in Table 3.

*Table 3 : Distribution of residents by origin background (n = 24)*

| Origin Background | n | % | Spatial Characteristics of Origin |
|---|---|---|---|
| Rural | 6 | 25% | Low density · self-regulated privacy · expansive outdoor space |
| Semi-rural | 13 | 54% | Moderate density · mixed built-natural environment |
| Urban | 5 | 21% | High density · structured housing · reduced open space |
| **Total** | **24** | **100%** | |

## 4.3 REASONS FOR MIGRATION

Migration is primarily purposive and settlement-oriented: permanent residence and employment/education together account for 42% of cases. Notably, privacy was rarely cited as a consideration, suggesting that privacy related psychological well-being was not consciously anticipated before arrival, making subsequent spatial stress potentially more disorienting for residents.

*Table 4 : Stated Reasons for Migration (n = 24)*

| Reason for Migration | n / % | Analytical Category |
|---|---|---|
| Permanent Residence | 5 (21%) | Primary settlement-seeking migrants |
| Employment + Education | 5 (21%) | Dual-purpose economic migrants |
| Convenience | 4 (17%) | Proximity to services/family |
| Marriage / Education alone / Employment alone | 6 (25%) | Social or single-purpose relocation |
| Facilities / Privacy / None | 4 (17%) | Access-based or unspecified relocation |

## 4.4 PSYCHOLOGICAL ANALYSIS OF PREVIOUS SETTLEMENT CONDITIONS

A retrospective analysis establishes the psychological baseline against which current conditions are compared, grounded in Cernea's (1997) concept of spatial dislocation and Lewicka's (2011) place attachment theory.

*Table 5 : Psychological analysis of previous settlement conditions by origin background*

| Parameter | Rural Mean | Semi-rural Mean | Urban Mean | Explanatory Note |
|---|---|---|---|---|
| Interpersonal Distance | Crowding: 2.00<br>Solitude: 3.50 | Crowding: 2.46<br>Solitude: 3.46 | Crowding: 2.20<br>Solitude: 3.40 | Rural: lowest perceived crowding; highest solitude capacity |
| Perceived Control Over Access | 3.00 | 3.38 | 3.60 | Urban control has the highest reverses post-migration |

| Parameter | Rural Mean | Semi-rural Mean | Urban Mean | Explanatory Note |
|---|---|---|---|---|
| Visual Privacy (via calmness) | 4.17 | 3.23 | 2.40 | Rural areas enjoyed substantially higher visual privacy |
| Acoustic Privacy (via stress) | Stress: 1.83 | Stress: 2.77 | Stress: 2.60 | Rural areas had significantly lower acoustic stress |
| Territorial Definition / Personalization | Solitude: 3.50<br>Calmness: 4.17 | Solitude: 3.46<br>Calmness: 3.23 | Solitude: 3.40<br>Calmness: 2.40 | Rural personalization is highest; urban people are accustomed to density |
| Cultural Proxemic Alignment | Calmness: 4.17<br>Stress: 1.83 | Calmness: 3.23<br>Stress: 2.77 | Calmness: 2.40<br>Stress: 2.60 | Rural proxemic alignment strongest and largest post-migration gap |

Three themes emerge from the analysis. The first theme relates to the finding that residents coming from rural areas had the highest emotional calmness score (M = 4.17), the lowest acoustic stress (M = 1.83), and the highest visual privacy score (M = 4.17) in the preceding environment, thereby demonstrating that the psycho-spatial disparity due to migration is higher for this category of respondents. Secondly, Shapiro-Wilk tests of non-normality in the rural population distributions, along with high kurtosis values, imply that the majority of the rural residents had almost similar experiences of high levels of privacy, which means that the change of environment to selected settlement involves a collective, not an individual disturbance. Thirdly, it was found that respondents coming from urban areas had low levels of privacy but low levels of stress as well because of the prior adaptation to urban life; thus, this group's psychological adaptation process is easier.

## 4.5 CURRENT SETTLEMENT CONDITIONS: CONSOLIDATED PARAMETER ANALYSIS

Table 6 presents a consolidated summary of all six study parameters across the three origin sub-groups. Mean scores for each indicator are reported alongside a key interpretive finding per parameter.

*Table 6 : Consolidated analysis of personal space and privacy-related psychological well-being in the current settlement, by origin background*

| Parameter | Indicators | Rural Mean | Semi-rural Mean | Urban Mean | Key Finding |
|---|---|---|---|---|---|
| Interpersonal Distance | Physical Closeness | 4.67 | 4.00 | 3.40 | Spatial adaptation ≠, psychological adaptation; the rural gap is widest |
| | Distance Comfort | 3.50 | 3.85 | 3.80 | |
| | Routine Interruption | 2.50 | 2.23 | 1.80 | |

| Parameter | Indicators | Rural Mean | Semi-rural Mean | Urban Mean | Key Finding |
|---|---|---|---|---|---|
| Perceived Control Over Access | Safety via Control | 4.50 ▲ | 3.92 | 2.80 | Control is the primary predictor of psychological security |
| | Unannounced Entry | 1.17 ▼ | 2.38 ▲ | 1.20 | |
| Visual Privacy | Visual Exposure | 3.17 ▲ | 2.46 | 1.80 | 1:1 correlation confirms visual surveillance triggers identity stress |
| | Self-Consciousness | 3.17 ▲ | 2.54 | 1.80 | |
| Acoustic Privacy | Routine Interruption | 2.50 | 2.23 | 1.80 | Latent stressor; embedded in daily fatigue rather than explicit complaint |
| | Space-Related Stress | 2.33 | 2.46 | 1.40 | |
| Territorial Definition / Personalization | Personal Area | 4.17 | 3.92 | 3.40 | Micro-territory functions as a primary coping resource for spatial stress |
| | Emotional Attachment | 4.83 ▲ | 4.38 | 3.80 | |
| | Psychological Stability | 4.17 | 4.23 | 3.80 | |
| Cultural Proxemic Alignment | Cultural Comfort | 4.17 | 4.23 ▲ | 3.60 | Rural proxemic gap largest; cultural norm violation = persistent background stressor |
| | Cultural Discomfort | 2.83 ▲ | 2.62 | 1.60 | |

From the data provided, there is a clear trend towards experiencing privacy stress due to psychological factors among the first three variables under consideration and depending on the origin of the respondents. Rural residents demonstrate the highest level of physical proximity (M = 4.67) as regards interpersonal distance; however, they feel only a moderate level of psychological comfort (M = 3.50). It can be associated with the theory of exposure stress proposed by Evans and Lepore (1993). As can be observed from distributional characteristics of the obtained scores, there is some adaptation of people to the circumstances rather than the full adjustment. The feeling of control about access proves to be the most important indicator of psychological security. In turn, residents who come from the countryside report the highest levels of feeling safe (M = 4.50) and the lowest number of surprise visitors (M = 1.17). On the contrary, semi-rural dwellers have the highest level of boundary permeability (M = 2.38) and city residents demonstrate the lowest level of self-assurance with regard to the control of access (M = 2.80). It demonstrates the decrease in spatial independence characteristic of learned helplessness according to Evans (2003). Equally, visual privacy reveals a striking correlation between visual exposure and self-consciousness in both rural and urban dwellers (the means for both groups being 3.17 for rural dwellers and 1.80 for urban dwellers). In this regard, one

may conclude that the absence of typical visual barriers such as vegetation, verandas, and setbacks results in continuous identity-related stress as individuals experience permanent psychological surveillance.

Finally, three additional criteria provide insight into how stress associated with privacy transcends physical aspects of living spaces. Acoustic privacy acts as an indirect source of stress, whereby the scores for interruption remain relatively low (from 1.80 to 2.50), but space-related stress continues to exist, especially in the case of semi-rural subjects, who report higher stress scores (2.46) than the frequency of interruptions they endure (2.23). As indicated by Evans and Johnson (2000), chronic exposure to low noise levels can reduce cognitive recovery, even though it goes unnoticed. The highest mean score recorded in the present research concerns territorial definition and personalization of spaces for rural-origin subjects (M = 4.83).

It implies that people cope with a general sense of lacking privacy by fostering attachments to micro-territories, a coping mechanism described by Brown & Perkins (1992). While these attachments help ensure mental balance, they must be regarded as a way of coping with poor spatial arrangements rather than being proof of adequate living spaces. The last category of proxemics, i.e., cultural proxemics, demonstrates an interesting contradiction observed in the group of rural origin, which exhibits both the highest levels of cultural comfort (M = 4.17) and cultural discomfort (M = 2.83). The phenomenon can be explained in accordance with Hall's (1966) notion that deeply rooted spatial norms may play an important role in people's lives regardless of the need to violate them daily.

## 4.6 CROSS-PARAMETER SYNTHESIS

Table 7 integrates findings across all parameters and origin sub-groups to identify overarching patterns.

*Table 7 : Cross-parameter synthesis of privacy and psychological well-being indicators by origin background*

| Parameter | Rural Origin | Semi-rural Origin | Urban Origin | Key Insight |
|---|---|---|---|---|
| Interpersonal Distance | **High stress** | Moderate | Low stress | Physical proximity ≠, psychological comfort; the rural gap is widest |
| Perceived Control Over Access | High security | Moderate | Low security | Control is the strongest predictor of psychological safety |
| Visual Privacy | **High exposure/stress** | Moderate | Low exposure | 1:1 correlation: exposure drives self-consciousness |
| Acoustic Privacy | **Elevated (latent)** | Moderate-high | Low | Normalized background stressor; missed by standard assessments |
| Territorial Definition | Strong attachment | Strong | Moderate | Micro-territories are the primary coping resource |

| Parameter | Rural Origin | Semi-rural Origin | Urban Origin | Key Insight |
|---|---|---|---|---|
| Cultural Proxemic Alignment | **Largest gap** | Moderate gap | Smallest gap | Cultural displacement amplifies spatial stress for rural migrants |

Those of rural origins suffer from the highest psycho-spatial burden. In all five of six criteria, residents with rural origins suffer from the highest levels of privacy stress or the largest discrepancies between past and current criteria, resulting from the large discrepancy between their past spatial environments and the standardized compactness of the selected site. Control, not space, is the key to psychological comfort. The perceived control over access is strong evidence that subjective freedom in the spatial environment is of greater psychological importance than objective factors like living space and residence density. Coping strategies mitigate the effects of poor privacy design. High territorial attachment and high rates of compensatory behavior point to an active coping strategy; yet the fact that stress criteria persist in multiple criteria suggests that the coping process does not negate but mitigates the structural problem. Psychological impacts are structurally differentiated, not randomly determined. The presence of non-normal distribution with higher-than-normal kurtosis among the two subgroups of residents with rural origins reveals the structural differentiation of privacy stress, which suggests that some resident groups face structural disadvantages with regard to spatial design.

# 5. DISCUSSION

The analysis reveals that privacy significantly impacts mental well-being, acting more as a structural influence than a direct benefit. Deterioration of privacy in small resettlement dwellings causes uneven, multi-dimensional harm, particularly affecting those from rural backgrounds the most.

## 5.1 PSYCHO-SPATIAL GAP AND DIFFERENTIAL IMPACT

Rural-origin residents previously enjoyed the highest emotional calmness (M = 4.17), lowest acoustic stress (M = 1.83), and strongest visual privacy conditions sustained by low-density environments, natural buffers, and self-regulated access. The transition to the migratory settlement removes these spatial mediators entirely, producing interpersonal closeness scores of M = 4.67 with only moderate psychological comfort (M = 3.50): Evans and Lepore's (1992) involuntary exposure stress, wherein functional coping masks unresolved strain. Shapiro-Wilk nonnormality and elevated kurtosis confirm this stress is collectively generated (Cernea, 1997), not individually variable. Urban-origin residents, pre-adapted to density, display substantially lower stress throughout, confirming that distress is proportional to the degree of dislocation, not to density itself.

## 5.2 PERCEIVED CONTROL: THE PRINCIPAL MEDIATOR

Perceived control over access is the study's strongest single mediator of psychological security. Rural origin residents achieve the highest safety scores (M = 4.50) through active boundary enforcement (fewest unannounced entries, M = 1.17), while semi-rural residents face chronic privacy dysregulation (Altman, 1975) with the highest intrusion rate (M = 2.38), and urban-origin residents display the lowest control belief (M = 2.80)

consistent with Evans' (2003) learned helplessness model. Across all groups, the evidence is unambiguous: it is the *perception* of control, not objective floor area or density, that determines psychological security.

### 5.3 VISUAL AND ACOUSTIC PRIVACY AS COMPOUNDED STRESSORS

The perfect positive relationship between visual intrusion and self-consciousness (with mean scores of 3.17 for rural and 1.80 for urban) illustrates the point that visual intrusion necessitates constant self-monitoring (Goffman, 1959). This means that the house loses its function as a place of retreat for performance. The intermediate barriers that used to mediate this are architecturally missing. Acoustic distress becomes a hidden form of stress since while scores for interruptions are low (mean scores range from 1.80 to 2.50), among the semi-rural dwellers, scores for space-related stress (mean = 2.46) exceed those for interruptions (mean = 2.23) as found by Evans and Johnson (2000) for low-level chronic noise, which interferes with restoration even before conscious appraisal.

### 5.4 TERRITORIAL COPING AND CULTURAL PROXEMIC MISALIGNMENT

The highest mean score from the survey, emotional attachment to micro-territories among individuals with rural backgrounds (M = 4.83) indicates an intensity of coping strategies, rather than satisfaction: when macroscale privacy is insufficient, residents adapt through territorial personalization (Brown & Perkins, 1992), obtaining actual stability (M = 4.17) through psychological efforts which are not indicative of satisfaction. The cultural proxemics paradox, an individual's comfort (M = 4.17) in combination with the highest level of discomfort (M = 2.83) experienced by people with rural backgrounds, indicates an ongoing struggle with respect to normative spatial practices (Hall, 1966), which creates an unyielding source of discomfort that does not readily get habituated (Sorokowska et al., 2017).

### 5.5 IMPLICATIONS FOR DESIGN AND POLICY

None of the proximity measurements, whether floor area, density, or metric proximity, can serve as an equivalent alternative to a comprehensive assessment of all six factors found in the current study. Proper design of a new settlement requires the integration of visual barriers (zones of transition, border planting), sound mitigation measures, spatial boundaries that re-establish the sense of control, and cultural understanding of personal space distances. These are the psychological prerequisites for restoring well-being in the case of rural origin migrants who, in our findings, were always the least privileged group.

## 6. CONCLUSIONS

In conclusion, this research clearly indicates that privacy in migratory settlements is a structural aspect that contributes to psychological well-being. This is supported by the results obtained in the selected settlement, which indicate that living in close proximity, less visibility/audibility buffering, and spatial control contribute to stress amongst inhabitants, especially among people originating from rural areas. The perception of individual control over personal space proved more significant than even physical aspects like floor area and housing density. Individuals manage spatial stress through territoriality at the micro-level, but this serves as a coping mechanism and does not solve the problem. Moreover, cultural proxemics makes the situation worse for individuals coming from

rural backgrounds. It is imperative that housing policies in Sri Lanka take privacy into consideration while designing houses for migratory populations.

# 7. REFERENCES


Altman, I. (1975). *The environment and social behavior: Privacy, personal space, territory, and crowding.* Brooks/Cole.

Altman, I. (1977). Privacy regulation: culturally universal or culturally specific? *Journal of Social Issues, 33*(3), 66–84. https://doi.org/10.1111/j.1540-4560.1977.tb01883.x

American Psychological Association. (2017). *Ethical principles of psychologists and code of conduct* (2002, amended effective June 1, 2010, and January 1, 2017). https://www.apa.org/ethics/code

Amérigo, M., & Aragonés, J. I. (1997). A theoretical and methodological approach to the study of residential satisfaction. Journal of Environmental Psychology, *17*(1), 47–57. https://doi.org/10.1006/jevp.1996.0038

Basner, M., & McGuire, S. (2018). WHO environmental noise guidelines for the European region: A systematic review on environmental noise and effects on sleep. *International Journal of Environmental Research and Public Health, 15*(3), 519. https://doi.org/10.3390/ijerph15030519

Belmont Report. (1979). *The Belmont Report: Ethical principles and guidelines for the protection of human subjects of research.* National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research. https://www.hhs.gov/ohrp/regulations-and-policy/belmont-report/

Brown, B. B., & Altman, I. (1983). Territoriality, defensible space and residential burglary: An environmental analysis. *Journal of Environmental Psychology*, *3*(3), 203–220. https://doi.org/10.1016/S0272-4944(83)80001-9

Brown, B. B., & Perkins, D. D. (1992). Disruptions in place attachment. In I. Altman & S. M. Low (Eds.), *Place attachment* (pp. 279–304). Plenum Press.

Brown, B. B., Perkins, D. D., & Brown, G. (2005). Place attachment in a revitalizing neighborhood: Individual and block levels of analysis. *Journal of Environmental Psychology*, *25*(3), 259–271. https://doi.org/10.1016/j.jenvp.2005.06.001

Castles, S., de Haas, H., & Miller, M. J. (2020). *The age of migration: International population movements in the modern world* (6th ed.). Red Globe Press.

Cernea, M. M. (1997). The risks and reconstruction model for resettling displaced populations. *World Development*, *25*(10), 1569–1587. https://doi.org/10.1016/S0305-750X(97)00054-5

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). SAGE Publications.

De Macedo, L. S. V., Picoli, F. R., Ferreira, F. L., & Bono, R. (2022). Visual privacy in residential architecture: A systematic review. *Buildings*, *12*(6), 746. https://doi.org/10.3390/buildings12060746

Evans, G. W. (2003). The built environment and mental health. *Journal of Urban Health*, *80*(4), 536–555. https://doi.org/10.1093/jurban/jtg063

Evans, G. W., & Johnson, D. (2000). Stress and open-office noise. *Journal of Applied Psychology*, *85*(5), 779–783. https://doi.org/10.1037/0021-9010.85.5.779

Evans, G. W., & Lepore, S. J. (1993). Household crowding and social support: A quasi-experimental analysis. *Journal of Personality and Social Psychology*, *65*(2), 308–316. https://doi.org/10.1037/0022-3514.65.2.308

Evans, G. W., & Wener, R. E. (2007). Crowding and personal space invasion on the train: Please don't make me sit in the middle. *Journal of Environmental Psychology*, *27*(1), 90–94. https://doi.org/10.1016/j.jenvp.2006.10.002

Gifford, R. (2007). *Environmental psychology: Principles and practice* (4th ed.). Optimal Books.

Goffman, E. (1959). *The presentation of self in everyday life.* Anchor Books.

Hall, E. T. (1966). *The hidden dimension.* Doubleday.

International Organization for Migration. (2024). *World migration report 2024*. IOM. https://www.iom.int/world-migration-report-2024

Israel, M., & Hay, I. (2006). *Research ethics for social scientists.* SAGE Publications.

Lewicka, M. (2011). Place attachment: How far have we come in the last 40 years? *Journal of Environmental Psychology*, *31*(3), 207–230. https://doi.org/10.1016/j.jenvp.2010.10.001

Malterud, K., Siersma, V. D., & Guassora, A. D. (2015). Sample size in qualitative interview studies. *Qualitative Health Research*, *26*(13), 1753–1760. https://doi.org/10.1177/1049732315617444

Scudder, T. (2005). *The future of large dams: Dealing with social, environmental, institutional and political costs* (1st ed.). Earthscan.

Sorokowska, A., Sorokowski, P., Hilpert, P., Cantarero, K., Frackowiak, T., Ahmadi, K., Alghraibeh, A. M., Aryeetey, R., Bertoni, A., Bettache, K., Blumen, S., Boski, P., Butovskaya, M., Castro, F. N., Cetinkaya, H., Cunha, D., David, D., David, O. A., Dileym, F. A., … Pierce, J. D. (2017). Preferred interpersonal distances: A global comparison. *Journal of Cross-Cultural Psychology*, *48*(4), 577–592. https://doi.org/10.1177/0022022117698039

United Nations. (2023). *Annual report 2023: Report of the Secretary-General on the work of the organization.* United Nations. https://www.un.org/en/annualreport2023

World Health Organization. (2025). *WHO results report 2024–2025.* WHO. https://www.who.int/about/accountability/results/who-results-report-2024-2025

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE Publications.

Krishan, V., Senavirtne, L.D.I.P., Gheethanjali, B. and Sivanraj S. 2026. Integrating computer vision into quality assurance of structural concrete in Sri Lankan construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 951-964. DOI: https://doi.org/10.31705/WCS.2026.70. Available from: https://ciobwcs.com/papers/

# INTEGRATING COMPUTER VISION INTO QUALITY ASSURANCE OF STRUCTURAL CONCRETE IN SRI LANKAN CONSTRUCTION INDUSTRY

**V. Krishan[1], L.D.I.P. Seneviratne[2], B. Gheethanjali[3] and S. Sivanraj[4]**

## *ABSTRACT*

*The Sri Lankan construction industry struggles with persistent quality issues in structural concrete works, including cracks, honeycombing, spalling, and misaligned reinforcement, resulted in cost overruns, delays, and safety risks due to inefficient manual inspections. This study investigates the integration of computer vision (CV) technologies leveraging convolutional neural networks (CNNs) and deep learning algorithms into quality management processes to enable proactive, automated defect detection during construction. A literature review identifies CV's efficacy for real-time monitoring and its superiority over traditional methods, while highlighting adoption barriers including data scarcity, high initial costs, skill shortages, and infrastructure limitations specific to Sri Lanka. Semi-structured interviews with ten industry experts reveal strong consensus on CV's potential for accuracy, standardisation, and productivity gains, but they also confirm the sector's incompetence, particularly among small contractors facing a shortage of human and financial resources. Key recommendations include government-incentivised pilot projects, localised datasets, workforce training, awareness programs, and hybrid LLM-mobile applications as scalable entry points. Findings highlight the need for a tailored framework to transition from reactive to predictive quality assurance. By addressing contextual challenges through phased implementation and policy support, CV integration promises enhanced structural integrity, reduced rework, and sustainable development in Sri Lanka's construction landscape. This research provides a roadmap for digital transformation, with implications for similar developing economies.*

***Keywords:*** *Computer Vision; Concrete Defects Construction Industry; Quality Management; Sri Lanka.*

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, krishanv.21@uom.lk.
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isenevi@gmail.com
[3] Temporary Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, gheethanjalib.20@uom.lk
[4] PhD Student, School of Architecture and Built Environment, Deakin University, Australia, S226148384@deakin.edu.au

# 1. INTRODUCTION

The construction industry is a major contributor to the economic and physical development of a developing country, especially Sri Lanka (Madushika & Thayaparan, 2024). However, the Sri Lankan construction sector faces numerous complications, including cost overruns and delays in the project, which are rooted in the quality issues during the construction, as it requires numerous rework and repairs (Madushika & Thayaparan, 2024; Nawade et al., 2022). The common types of quality issues include structural defects including cracks, honeycomb, surface delamination, poor workmanship, water leakage and misalignment of reinforcement (Nawade et al., 2022). Therefore, maintaining the structural quality is the top priority, as the undetected defects cause potential defects on the appearance, durability, functionality, financial returns and safety of structures (Abdelalim et al., 2024; Madushika & Thayaparan, 2024). Madushika & Thayaparan (2024) stated that using the traditional quality management system in Sri Lanka is inefficient, since it fails to achieve early and precise defect detection. Rather than depending on the conventional approaches, it is vital to switch to innovative quality management techniques to improve construction efficiency, ensure sustainability and reduce the cost of reworks through facilitating early defect detection through automated real time monitoring (Wendabona, 2024). The development and adoption of industry-specific Artificial Intelligence (AI) solutions tailored to the unique needs and constraints of the construction industry can help to improve the quality of construction structures (Wijesinghe et al., 2024). Computer Vision (CV), especially those based on convolutional neural networks, has proven to be well-suited for automated early defect detection in concrete structures as it addresses most of the limitations of conventional inspection methods and offers innovative solutions for real-time structural quality monitoring throughout the construction process (Wang et al., 2022). The global construction industry has shown significant attention towards employing CV tools since it enables real-time tracking, improve the efficacy of defect detection, lower long-term maintenance costs and facilitate prompt remedial actions (Abdelalim et al., 2024).While the global literature has extensively investigated CV algorithms and technical architectures for structural defect detection (Jiang & Messner, 2023; Pan et al., 2025), the application of CV within the socio-economic and infrastructural constraints of developing economies, particularly Sri Lanka, remains unexplored. This study addresses that gap by investigating the feasibility, barriers, and adoption strategies for CV integration within Sri Lanka's construction quality management system. Accordingly, this study aims to explore the feasibility of introducing CV technologies into the quality management system for structural concrete in Sri Lanka's construction industry. To achieve this, the study pursues objectives including identifying limitations and challenges in integrating CV applications into construction quality management, assessing Sri Lanka-specific barriers and enablers to CV adoption, and proposing context-specific strategies to facilitate the effective integration of CV technologies into Sri Lankan construction quality management practice.

# 2. LITERATURE REVIEW

## 2.1 COMMON STRUCTURAL DEFECTS IN CONSTRUCTION

Structural defects in construction represent failures to meet functional, performance, statutory, or user requirements of buildings or civil structures, compromising their

integrity and durability (Ekanayake, 2022; Kang et al., 2025). These defects commonly manifest in concrete elements as cracks, segregation, spalling, disintegration, honeycombing, and delamination, while reinforcement misalignment, corrosion of embedded metals, and reinforcing steel further accelerate structural deterioration (Bahreini & Hammad, 2024; Obiora et al., 2022). Similarly, misalignment and bulging in columns, beams, and slabs are often due to inadequate formwork and supervision. Misalignments of doors, window frames, and lintel-frame gaps commonly undermine structural functionality and aesthetics (Dahanayake & Ramachandra, 2015; Olanrewaju & Lee, 2022).

Unaddressed defects escalate from minor issues to major failures, causing structural instability, collapse risks, safety threats, costly rework, time overruns, and reduced project productivity and efficiency (Hussamadin et al., 2023; Karunasena et al., 2025; Obiora et al., 2022). Dahanayake & Ramachandra (2015) emphasise the "doing things right the first time" principle to ensure efficiency, safety, and quality standards in construction. Implementing this requires identifying and preventing defect causes, including incompatible materials, poor workmanship, insufficient supervision, improper installation, mix design flaws, weak management, and maintenance neglect (Dahanayake & Ramachandra, 2015).

Sri Lanka's current quality management system relies on reactive defect detection, addressing issues only when obvious defects necessitate repairs (Dubas & Pasławski, 2018). Traditional quality management relies on manual visual inspections for structural stability assessment, which are inconsistent, subjective, and error-prone while failing to detect early-stage defects (Abdelalim et al., 2024; Hui et al., 2025; Mirbod & Shoar, 2023). Even though traditional quality management techniques help to maintain the quality of structures through rework or repair, it results in a cost overrun (Dahanayake & Ramachandra, 2015). This necessitates a shift to innovative digital solutions in the Sri Lankan construction industry.

## 2.2 COMPUTER VISION AS A TOOL FOR DEFECT DETECTION

CV is a key AI domain that enables autonomous recognition, analysis, and evaluation of visual content in images and videos using extensive training datasets, thereby improving defect detection accuracy and efficiency (Ekanayake, 2022; Ettalibi et al., 2024; Jiang & Messner, 2023). CV tools are widely applied for structural defect assessment due to their efficiency, economy, and precision (Hui et al., 2025; Pan et al., 2025). Structural cracking, honeycombing and surface porosity detection are emerging defects, where the recent hybrid deep learning models exhibited acceptable real-time detection performance (Das et al., 2025).Reinforcement misalignment detection, formwork quality inspection and multi-defect simultaneous classification are still in its infancy and have limited validated models used in the construction site (Pan et al., 2025).Moreover, CV extracts high-dimensional real world data to advise decision making (Zhong et al., 2019). Integration with deep learning (DL) techniques, including advanced CNN architectures, two-stage models, back-propagation networks, and YOLO, enhances concrete defect recognition, enabling image processing, categorisation, detection, and segmentation for precise diagnosis and quality improvement (Ekanayake, 2022; Hui et al., 2025; Wijesinghe et al., 2024). Automated real time monitoring thus advances construction quality control (Wijesinghe et al., 2024).

Image acquisition and dataset preparation constitute the initial step in CV-based defect detection, ensuring sufficient data quantity and quality for effective DL model training (Kang et al., 2025; Zhong et al., 2019). Automated tools, including high-definition or handheld cameras, CCTV, drones, and UAVs capture visual data from construction sites (Gang, 2024; Mirbod & Shoar, 2023; Kang et al., 2025). Kang et al. (2025) and Gang (2024) recommend using smartphone photography with zoom lenses for cost effective, standards compliant imaging without additional equipment. Public datasets provide an alternative for image acquisition to train CV models (Gang, 2024; Munawar et al., 2021). Data augmentation techniques, including rescaling, rotation, shifting, and preprocessing, address high quality image scarcity by expanding datasets, enhancing diversity, noise resistance, and generalisation (Kang et al., 2025; Munawar et al., 2021). Collected images enable CV tasks including retrieval, object detection, semantic segmentation, and categorisation into predefined groups (Nath & Behzadan, 2020). Datasets are then pre-processed and divided into training and testing sets (Gang, 2024; Munawar et al., 2021).

Image processing is an important step to transform images from unprocessed visual input into information that an ML model can interpret (Jiang & Messner, 2023; Gang, 2024). After preprocessing, feature extraction is done to derive vectors for defect classification (Jiang & Messner, 2023). Techniques like Histogram of Oriented Gradients (HOG) or Local Binary Patterns (LBP) analyse structural properties and textures for defect identification (Hui et al., 2025; Mirbod & Shoar, 2023). Gang (2024) recommends replacing these noise-sensitive, feature-based ML methods with deep learning for superior accuracy in real-world construction defect detection. Gang (2024) specifies DL's revolutionary impact on CV applications, particularly defect detection. Convolutional neural networks (CNNs) excel at automatically extracting complex features from raw images, eliminating manual detection needs (Jiang & Messner, 2023; Gang, 2024). CNNs comprise three core layers: convolutional layers for feature extraction, pooling layers to reduce spatial dimensions and computational costs, and fully connected layers that flatten features for optimisation and classification (Pan et al., 2025).

Ekanayake (2022) and Lee et al. (2020) classify the object detection algorithms into two major groups: one-stage and two-stage models, based on their functional output. Two-stage detectors, such as Faster R-CNN, prioritise detection accuracy by first proposing regions of interest before categorising them (Lee et al., 2020; Pan et al., 2025). Conversely, one-stage models, such as YOLO and Single Shot MultiBox Detector (SSD), provide quick, real-time prediction speeds by treating the entire detection task as a regression issue in a single pass (Ekanayake, 2022; Hui et al., 2025). CNN-based models perform with high accuracy and reliability in detecting and classifying concrete defects. Moreover, integrating CNN into frameworks such as R-CNN or U-Net to offer accurate defect detection, localisation, and quantification (Gaur et al., 2023; Madushika & Thayaparan, 2024; Wijesinghe et al., 2024). Pan et al. (2025) identify reporting as the final stage that converts computational output into useful engineering insights.

Utilisation of complex DL algorithms, such as CNN, helps to achieve robust and improved quality assurance through addressing the limitations of traditional quality management across both pre-concreting and post-concreting phases (Ettalibi et al., 2024; Gaur et al., 2023). During the pre-concreting stage, CV-integrated systems based on CNN architectures can provide real-time monitoring of reinforcement alignment, work positioning of the formwork and mix design compliance before concrete is placed (Ekanayake, 2022; Pan et al., 2025). In the post-concreting phase, CV tools can be used

to efficiently detect defects, such as cracks, honeycombing, spalling, and delamination (Abdelalim et al., 2024; Hui et al., 2025). The automated imaging and classification at the documentation and traceability phase provide a documented record of defects with dates and geolocations, enhancing accountability and dispute resolution (Hussamadin et al., 2023). Moreover, it is recommended to integrate CV-based QM systems with BIM or Digital Twins (DT) to enhance system efficiency (Madushika & Thayaparan, 2024). The construction industry can move from a "reactive" quality management approach to a "proactive" and "predictive" approach by incorporating CV into pre- and post-concreting processes, significantly reducing the rework costs and improving structural integrity (Wijesinghe et al., 2024).

## 2.3 CHALLENGES IN ADOPTING CV IN SRI LANKA

Several challenges that hinder the integration of -CV-based defect detection for construction quality management are identified (Ettalibi et al., 2024). The lack of training data and computational resources for creating, training, and implementing sophisticated CV models is the biggest obstacle to the adoption of CV-based systems (Ekanayake, 2022; Jiang & Messner, 2023; Pan et al., 2025). It is essential to expand and maintain the defect database to improve model accuracy, as insufficient annotated data can reduce model accuracy and reliability (Costa et al., 2024; Lee et al., 2020). High DL complexity drives substantial hardware, software, training, consulting, and operational costs (Ekanayake, 2022; Islam et al., 2024; Wijesinghe et al., 2024). Small and medium-sized contractors, who are dominating the Sri Lankan construction industry, have low levels of financial resources needed for making large, up-front investments in technology (Wijesinghe et al., 2024).Furthermore, the period required to achieve a measurable return on investment (ROI) from CV integration is notably prolonged, particularly in developing countries. This extended timeframe often leads organisations to hesitate in adopting CV technologies for quality management purposes (Wijesinghe et al., 2024).

Emuze et al. (2023) highlighted professionals' inadequate technological expertise as a key barrier to adopting CV. Construction professionals are expected to acquire new technological competencies due to the complexity of integrating CV with technologies like BIM (Costa et al., 2024). In addition, the scarcity of skilled AI engineers in the construction sector is a significant challenge in developing customised solutions (Abioye et al., 2021). Moreover, poor digital infrastructure is identified as a major hindrance to the real-time deployment of CV- based tools, since digital infrastructure is still at a primary stage in most Sri Lankan construction sites, with poor connectivity and limited hardware and infrastructure needs (Wendabona, 2024). Finally, the absence of any regulatory standard or government policy framework which encourages the use of digital quality management technologies in construction delays the digitalisation of QM in Sri Lankan construction. Emuze et al. (2023) highlight that, in developing nations, construction firms adopt innovations only when authorities enforce supportive policies (Emuze et al., 2023). Therefore, the authorities need to handle non-technical challenges, particularly costs and establish frameworks for CV integration.

This study mainly focuses on concrete structural defects prevalent in Sri Lankan construction projects, which compromise structural integrity, escalate rework costs and contribute to frequent delays and safety risks (Dahanayake & Ramachandra, 2015). Traditional manual inspections practised in Sri Lanka, which rely on subjective visual assessments, fail to detect early-stage issues efficiently, leading to reactive quality

management (Das et al., 2025). , This study tries to address the drawbacks of the current QM systems and to provide suggestions and recommendations to facilitate CV implementation, mitigating potential risks involved in digitalisation within the unique economic and operational environment of the Sri Lankan construction industry (Abioye et al., 2021; Costa et al., 2024).

## 3. RESEARCH METHODOLOGY

Research methodology is a systematic approach to scientifically solving research problems by defining a comprehensive strategy for conducting investigations (Mendis, 2023). This study aims to evaluate the feasibility of CV technologies and facilitate their integration into quality management practices for concrete structures within the Sri Lankan construction industry. It's important to analyse the practical applicability of CV-integrated tools along with their adaptability, feasibility, and industry capability for CV adoption. A literature review was conducted as the first phase of this study to understand the integration of CV into the QM of concrete structural works and its implications for the construction industry by exploring existing research on CV applications in construction, the challenges faced in defect detection, and current QM practices. Then, 10 semi-structured interviews are conducted to collect insights from construction professionals to identify prevailing trends, challenges, and levels of awareness related to CV technologies and their applications. The interview facilitates assessing both the technological applicability and the practical capability of the Sri Lankan construction industry for the adaptation of CV. The respondent's profile is provided in the Table 1.

*Table 1: Profile of the respondents*

| Code | Organisation type | Designation | Experience |
|---|---|---|---|
| R1 | QS Consultancy Firm | Director | 33 |
| R2 | Contractor Organisation | QMS Engineer | 15 |
| R3 | Consultant Organisation | Structural Engineer | 30 |
| R4 | Education Institute | Researcher and Educator | 7 |
| R5 | Statutory board | Research Material Engineer | 12 |
| R6 | IT System Custom Software Developer | Chief Executive Officer | 3 |
| R7 | Contractor Organisation | Structural Engineer | 20 |
| R8 | Education Institute | PhD Scholar and Lecturer | 8 |
| R9 | Contractor Organisation | Material Engineer | 10 |
| R10 | Education Institute | PhD Scholar and Lecturer | 10 |

As shown in the table, semi-structured interviews were conducted by employing purposive sampling to select 10 expert interviewees currently practising in the construction industry, covering Directors, CEOs, Quantity Surveyors, Structural Engineers, QMS Engineers, Material Engineers and PHD scholars who have done research related to CV and AI tools. Interviewees were selected based on their expertise, experience and sound knowledge of the construction industry and the AI technologies. Contractors (R2, R7 and R9) shared their experience and challenges in the workplace related to on-site QM practice. The consultant respondents (R1, R3 and R5) provided input on technical standards and regulatory compliance. Academic researchers (R4, R8,

R10) were included specifically due to their active research engagement with CV, AI and digital construction technologies, which help to establish technical validation of the feasibility of adoption based on evidence (Ekanayake, 2022). The technology developer, respondent (R6), provided information regarding the cost and approach to be followed to develop an application for CV-based quality management. . The purposive sampling facilitates exploration of complex industry dynamics and ensures representation of the key groups involved in any future CV implementation pathway. (Ekanayake, 2022). Instead of statistical representativeness, sample size in qualitative inquiry is validated by the extent of data saturation, which is when more interviews do not yield new thematic content (Malterud et al., 2016).Data saturation point was found in this sample after interviewing the eight respondents, where the themes of the main dimensions of CV potential, barriers and adoption strategies showed consistent convergence of perspectives across respondents. Therefore, the sample size of 10 respondents is considered to be appropriate to achieve the goal of the study. Moreover, this study adopted a qualitative research approach to analyse the integration of CV in QM for Sri Lankan construction. The NVivo software was used to analyse the collected data using code-based thematic coding, enabling systematic identification of patterns.

## 4. RESEARCH FINDINGS AND DISCUSSION

This section presents and discusses the principal research findings derived from the expert interviews conducted as part of this study. The insights gathered from these interviews provide valuable qualitative evidence, reflecting the perspectives, experiences, and professional judgments of industry practitioners regarding the Importance of integrating computer vision into the quality management of the Sri Lankan construction industry. These findings highlight the benefits of applying CV in construction quality management, identify the challenges associated with its adoption in Sri Lanka, and propose strategies to facilitate its effective integration into construction quality management practices.

### 4.1 POTENTIAL OF CV IN CONSTRUCTION QUALITY MANAGEMENT

The experts were invited to share their perspectives on the potential benefits of integrating CV into construction quality management practices and summarised in Figure 1.

| Name | Files | References |
|---|---|---|
| Potential of CV in construction quality management | 8 | 22 |
| Better than the manual process | 1 | 1 |
| Can facilitate consistent quality monitoring | 1 | 2 |
| Cost of paper is reduced | 1 | 1 |
| CV and 3D models can be used with machine learning | 1 | 1 |
| CV can detect visual defects | 1 | 1 |
| Early defect detection | 2 | 3 |
| Facilitate automated reporting | 1 | 2 |
| Good at verifying materails and workmanship quality | 1 | 1 |
| Improve efficiency and reduce rework | 1 | 1 |
| Reduce Subjectivity | 2 | 3 |
| Strength and design adequacy cannot be verified | 1 | 1 |

*Figure 1: Potential of CV in construction quality management*

The experts identified several potential capabilities of Computer Vision (CV) that could effectively address the limitations of existing quality management practices in the Sri Lankan construction industry. In addition to the general findings, Respondent R2 highlighted that CV can enhance efficiency, particularly when integrated with mobile or drone-based imaging systems. Furthermore, Respondent R6 emphasised that CV has the potential to reduce subjectivity in quality inspections, thereby minimising disputes in decision-making processes. Respondent R4 highlighted that the integration of CV technologies has the potential to create new employment opportunities, driven by the increasing demand for AI specialists. In addition to these features, Table 2 presents a list of key benefits that can be achieved through the integration of CV technologies and the number of respondents agreed.

*Table 2: Key benefits of CV technologies*

| Benefits of CV technologies | The number of Respondents |
|---|---|
| **Accuracy in Defect Detection** | 10 |
| **Consistency and Standardisation of Quality Control Procedures** | 9 |
| **Enhanced Documentation and Traceability** | 9 |
| **Productivity Improvements** | 10 |
| **Improved Efficiency and Reduced Inspection Time** | 10 |
| **Improved Worker Safety** | 10 |
| **Integration with Digital Platforms** | 10 |
| **Lower Project Costs and Reduced Rework** | 7 |
| **Real-Time Monitoring** | 10 |
| **Reduction in Human Error** | 7 |
| **Supports Proactive and Predictive Quality Management** | 10 |

According to the findings presented in the Table 2, all respondents emphasised that maintaining high accuracy in defect detection is mandatory for CV systems. However, R1 noted that human verification is essential, as CV tools cannot independently handle complex problem-solving tasks, and emphasised the need for workforce discipline to enhance efficiency and reduce inspection time. Similarly, R1, R9, and R10 acknowledged that human intervention is crucial in quality inspection processes. R8 reinforced this perspective, stating that *"CV technologies should be seen as a support tool rather than a replacement for engineers, and their successful use in Sri Lanka will depend on gradual adoption, strong leadership commitment, localised datasets, and integration with existing quality management practices to build trust and demonstrate long-term value." Further, R1 emphasised the necessity to train these systems to* replicate the thoughtful analysis of an experienced QA engineer. Further, R1 also highlighted that training data should be cautiously selected and entered into CV models to ensure that CV models can "imagine and visualise" structural conditions similar to an expert. This approach enables the models to examine complex situations, spot defect patterns, and produce clear, insightful results rather than simple mechanical outputs. R1 also noted that CV models will gradually minimize the need for manual checks on routine tasks, while maintaining human decision

for complex scenarios. This automation perspective is reinforced by R6, who recommended integrating CV with robotics to enable greater automation and promoted using analytical algorithms instead of statistical machine learning approaches.

## 4.2 CHALLENGES IN ADOPTING CV

Despite the abundant benefits, certain challenges remain inevitable. The identified challenges are summarised Table 3.

*Table 3: Common barriers to the adoption of CV*

| Common Barriers to the Adoption of CV | Number of Participants |
|---|---|
| **Unavailability of Datasets** | 10 |
| **Challenges in data management and privacy** | 8 |
| **Insufficient digital infrastructure on construction sites** | 9 |
| **Adverse environmental conditions** | 7 |
| **High Initial Cost** | 8 |
| **Difficulties in integration with existing workflows** | 7 |
| **Scarcity of skilled AI professionals** | 9 |
| **Lack of standards and regulatory support** | 8 |

Experts also provided practical recommendations to address the primary cost barriers hindering the adoption of CV technologies. To mitigate data insufficiency, R2, R6, and R8 suggested developing and maintaining localised datasets tailored for CV model training, enabling context-specific defect recognition in concrete structures while reducing reliance on foreign datasets ill-suited to local materials and environmental conditions. For data security concerns raised by 8 respondents, experts encouraged secure cloud storage solutions backed by robust contractual agreements and data management protocols, ensuring compliance with Sri Lankan data protection regulations while enabling access across project teams. Furthermore, R8 identified organisational resistance to change as a key factor delaying technology integration, which also contributes to workflow integration challenges, as noted by seven respondents. To address this, R2 encouraged programming CV tools for seamless alignment with existing quality assurance procedures, thereby minimising operational disruptions during adoption. Complementing this approach, R6 proposed that initiating implementation with simple mobile applications as a low-risk entry point.

In addition to the barriers, the substantial cost associated with CV integration is a major obstacle to its implementation. Figure 2 illustrates the important cost barriers impeding CV adoption.

| Name | Files | References |
|---|---|---|
| Cost barriers that hinders the implementation of CV | 4 | 4 |
| Graphics Processing Unit (GPU) cost is high | 1 | 1 |
| High purchasing cost | 1 | 1 |
| High upfront investment in hardware, software, training and system integration | 2 | 2 |

*Figure 2: Cost barriers for the implementation of CV*

The barriers depicted in Figure 2 mainly concern initial implementation costs, as experts emphasised that ongoing integration expenses exert minimal influence. R6 offered a detailed breakdown of CV model development and maintenance costs, supported by specific figures. According to R6, "*deploying CV models capable of detecting defects across a 8-storey building in a single scan incurs a monthly recurring charge of approximately $10,000. Data collection costs approximately $9,000, while model development costs $6,000, yielding a total initial development cost of $15,000. Monthly maintenance thereafter is estimated at $10,000.*" Professionals were also invited to offer recommendations for overcoming these cost barriers. Accordingly, respondents R2 and R8 proposed conducting pilot projects and implementing them in phases, supported by government incentives.

## 4.3 SUGGESTIONS TO FACILITATE THE ADOPTION OF CV

The experts were requested to provide suitable recommendations to overcome these barriers and to improve the CV for construction quality management. Accordingly, R1 highlights that the "CV *cannot stand alone, should be integrated with other systems*" Further, R2 defended his answer by stating "*early defect detection can be achieved, especially when integrated with mobile or drone-based imaging systems*"

Finally, industry experts were requested to evaluate the preparedness of the Sri Lankan construction industry for adopting CV technologies in quality management. The majority declare that the industry remains unprepared for CV tool implementation, with R10 particularly emphasising the numerous restrictions prevalent in Sri Lanka. Conversely, R3 contended that the industry is prepared to adopt CV technologies, a view that contradicts the dominant expert perspective. Respondents R2 and R4 took a balanced position, describing the industry as partially ready and R2 substantiated this by observing that larger contractors are increasingly embracing digital tools, while smaller contractors struggle with cost and skill limitations. R6 similarly asserted that the industry is not equipped for large-scale CV models. Furthermore, participants were invited to offer recommendations for integrating CV technologies into the Sri Lankan construction industry, particularly within quality management processes. Figure 3 summarises the key suggestions provided by the experts.

| Name | Files | References |
|---|---|---|
| Suggestions to adopt CV tools in Sri Lankan Construction QM | 1 | 1 |
| Conduct awareness and training programmes | 4 | 5 |
| Implement specification, requirements and standards for digital implemtations | 2 | 3 |
| Improve site-level digital facilities | 1 | 1 |
| Increase the number of construction projects | 1 | 1 |
| Initiatives should be taken by government authorities or third party testing organisations | 1 | 1 |
| Phased adoption and collaboration with tech providers or universities to create loacal data sets | 2 | 2 |
| Start with small technologies tailored for Sri Lankan context | 2 | 2 |

*Figure 3: Suggestions to adopt CV technologies in the Sri Lankan construction*

The suggestions outlined in Figure 3 reveal a strong expert expectation on conducting awareness programs and workforce training to facilitate CV adoption, as R1, R2, and R3 emphasised their critical role. R8 provided comprehensive strategies by mentioning that "*To support adoption, the industry should start with small pilot projects, invest in training*

*and upskilling, encourage collaboration between industry and universities, improve site-level digital readiness, and develop national guidelines or standards (even roadmaps) to support the use of AI-based tools in construction quality management."* Complementing this, R3 suggested collaboration with international contractors to enable pilot projects that expose local professionals to AI tools, while R9 preferred government initiative, stating, "*The first step should be taken by the research authorities to make it a standard*." Further, R2 emphasised that "*Phased adoption and collaborations with tech providers, create local datasets for CV models*" to address dataset scarcity. Similarly, R6 recommended to commence with accessible mobile applications tailored to the Sri Lankan context, proposing LLM-based solutions that minimise CV dependency. Further, mentioned that "*such applications would particularly benefit small-scale contractors, given their relatively low development cost of approximately $4,000 and a monthly maintenance fee of $100*."

The results of this study revealed that, according to expert respondents, the CV-based tools have potential for improving quality management processes in the construction industry in Sri Lanka. However, the implementation of efficient CV-based QM tools is dependent on the specific features of the Sri Lankan construction industry, such as data availability, the cost of data, the skills of the working population and infrastructure. The results indicate that the transition to CV in Sri Lanka is likely to be a gradual process, rather than one of overnight, blanket deployment.

## 5. CONCLUSIONS AND RECOMMENDATIONS

The findings from this study affirm the transformative potential of CV technologies in elevating quality management practices for concrete structural works within the Sri Lankan construction industry. CV addresses critical limitations of traditional manual inspections, including subjectivity, inefficiency, and high rework costs, by enabling accurate, real-time defect detection. However, persistent barriers, including data scarcity, high initial implementation expenses, skill shortages, and infrastructural constraints, render the industry largely unprepared for widespread adoption, as highlighted by most expert respondents. While larger contractors show partial readiness through digital tool adoption, smaller firms face disproportionate challenges, underscoring the need for context-specific adoption. A multi-phased framework is recommended to facilitate CV integration. In order to adopt this framework, awareness programs should be established on CV in construction by the government and professional organisations. In addition, it's recommended to collaborate with universities and the industry to introduce AI/CV-related modules into construction engineering curricula. Furthermore, government-funded pilot projects should be launched to build confidence among private contractors regarding the ROI, since uncertain ROI is a significant hindrance to the adoption of CV. Developing localised datasets and LLM-hybrid mobile applications is proposed as a practical solution that facilitates small-scale contractors, gradually scaling to full CV systems aligned with existing workflows. Moreover, regulatory standards should be established, public-private partnerships for secure cloud infrastructure should be promoted, and BIM-CV integration should be encouraged to ensure sustainability.

This study contributes to the academic field by providing a detailed analysis of the feasibility of the CV adoption for quality management in the Sri Lankan construction industry. Moreover, it discusses the state of readiness in Sri Lanka and a framework to implement a phased approach. The study was conducted with 10 expert interviewees

using purposive sampling, which provides valuable insights but might not represent the broader spectrum of views and experiences in the Sri Lankan construction industry, which becomes a limitation of this study. Further research should be conducted to investigate the technical performance of CV models trained with the locally developed Sri Lankan concrete defect datasets. Studies quantifying the cost-benefit ratio of the usage of CV in Sri Lankan construction projects would add weight to the business case for the industry to take up CV. The Proposed strategies and future research have the potential to change Sri Lanka's quality management paradigms from reactive to proactive, promoting structural safety and economic efficiency.

## 6. REFERENCES

Abdelalim, A. M., Shalaby, Y., Ebrahim, G. A., & Badawy, M. (2024). An Article Review on Vision-Based Defect Detection Technologies for Reinforced Concrete Bridges. *Annals of Civil Engineering and Management*, *1*(1), 01–17. https://doi.org/10.33140/ACEM.01.01.08

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Davila Delgado, J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*, 103299. https://doi.org/10.1016/j.jobe.2021.103299

Bahreini, F., & Hammad, A. (2024). Developing an ontology for concrete surface defects to enhance inspection, diagnosis and repair information modelling. Infrastructures, *9*(12), 220. https://doi.org/10.3390/infrastructures9120220

Costa, M. D. D., Costa, M. R. R., & Thayaparan, M. (2024). The impacts of computer vision technology in construction: Investigating applications and challenges. In Proceedings of the 12th World Construction Symposium (p. 1025). https://doi.org/DOI:10.31705/wcs.2024.81

Dahanayake, B. M. Y., & Ramachandra, T. (2015). Assessment on Defects Occurrence and Rework Costs in Housing Construction Sector in Sri Lanka. *6"' International Conference on Structural Engineering and Construction Management 2015*. http://dl.lib.mrt.ac.lk/handle/123/11715

Das, S. K., Yogi, B., Majumdar, R., Ghosh, P., & Roy, S. (2025). Real-time detection and localization of honeycomb defects in concrete pillars using hybrid deep learning models. *Scientific Reports*, *15*(1), 22536. https://doi.org/10.1038/s41598-025-06971-1

Dubas, S., & Pasławski, J. (2018). Methods of construction quality issues elimination with use of modern technology. *MATEC Web of Conferences*, *222*, 01001. https://doi.org/10.1051/matecconf/201822201001

Ekanayake, B. (2022). A deep learning-based building defects detection tool for sustainability monitoring. *Proceedings of 10th World Construction Symposium 2022*, 2–13. https://doi.org/10.31705/WCS.2022.1

Emuze, F., Sherratt, F., & Soeiro, A. (Eds). (2023). *Digital Transformation of Health and Safety in Construction (CIBW099W123): Book of Proceedings*. FEUP. https://doi.org/10.24840/978-972-752-309-2

Ettalibi, A., Elouadi, A., & Mansour, A. (2024). AI and Computer Vision-based Real-time Quality Control: A Review of Industrial Applications. *Procedia Computer Science*, *231*, 212–220. https://doi.org/10.1016/j.procs.2023.12.195

Gang, L. (2023). A Review of Computer Vision Applications in Concrete Crack Identification. *International Journal of Research in Engineering and Science (IJRES)*, 11(4), 188–195. https://www.ijres.org/papers/Volume-11/Issue-4/1104188195.pdf

Gaur, A., Kishore, K., Jain, R., Pandey, A., Singh, P., Wagri, N. K., & Roy-Chowdhury, A. B. (2023). A novel approach for industrial concrete defect identification based on image processing and deep convolutional neural networks. *Case Studies in Construction Materials*, *19*, e02392. https://doi.org/10.1016/j.cscm.2023.e02392

Hui, L., Ibrahim, A., & Hindi, R. (2025). Computer Vision-Based Concrete Crack Identification Using MobileNetV2 Neural Network and Adaptive Thresholding. *Infrastructures*, *10*(2), 42. https://doi.org/10.3390/infrastructures10020042

Hussamadin, R., Jansson, G., & Mukkavaara, J. (2023). Digital Quality Control System—A Tool for Reliable On-Site Inspection and Documentation. *Buildings*, *13*(2), 358. https://doi.org/10.3390/buildings13020358

Islam, M., Raisul, Zamil, M., Zakir Hossain, Rayed, M., Eshmam, Kabir, M., Mohsin, Mridha, M. F., Nishimura, S., & Shin, J. (2024). Deep Learning and Computer Vision Techniques for Enhanced Quality Control in Manufacturing Processes. *IEEE Access*, *12*, 121449–121479. https://doi.org/10.1109/ACCESS.2024.3453664

Jiang, Z., & Messner, J. I. (2023). Computer Vision Applications In Construction And Asset Management Phases: A Literature Review. *Journal of Information Technology in Construction*, *28*, 176–199. https://doi.org/10.36680/j.itcon.2023.009

Kang, S., Kim, S., & Kim, S. (2025). Automatic detection and classification process for concrete defects in deteriorating buildings based on image data. *Journal of Asian Architecture and Building Engineering*, *24*(4), 2773–2787. https://doi.org/10.1080/13467581.2024.2373832

Karunasena, G., Gurmu, A., Shooshtarian, S., Udawatta, N., Ranthika Perera, C. S., & Maqsood, T. (2025). Effect of construction defects on construction and demolition waste management in building construction: A systematic literature review. *Integrated Environmental Assessment and Management*, *21*(2), 233–244. https://doi.org/10.1093/inteam/vjae026

Lee, K., Hong, G., Sael, L., Lee, S., & Kim, H. Y. (2020). MultiDefectNet: Multi-Class Defect Detection of Building Façade Based on Deep Convolutional Neural Network. *Sustainability*, *12*(22), 9785. https://doi.org/10.3390/su12229785

Madushika, H., & Thayaparan, M. (2024). Applicability of Digital Twin Technology for Quality Management in the Sri Lankan Construction Industry. *FARU Proceedings*. https://doi.org/10.31705/faru.2024.46

Malterud, K., Siersma, V. D., & Guassora, A. D. (2016). Sample size in qualitative interview studies: guided by information power. *Qualitative health research*, 26(13), 1753-1760. https://doi.org/10.1177/1049732315617444

Mendis, A. (2023). Inclusion of marginalised communities during post-disaster context in Sri Lanka: What methodology? *World Construction Symposium*, *1*, 582–594. https://ciobwcs.com/2023/papers/

Mirbod, M., & Shoar, M. (2023). Intelligent concrete surface cracks detection using computer vision, pattern recognition, and artificial neural networks. *Procedia Computer Science*, *217*, 52–61. https://doi.org/10.1016/j.procs.2022.12.201

Munawar, H. S., Ullah, F., Heravi, A., Thaheem, M. J., & Maqsoom, A. (2021). Inspecting Buildings Using Drones and Computer Vision: A Machine Learning Approach to Detect Cracks and Damages. *Drones*, *6*(1), 5. https://doi.org/10.3390/drones6010005

Nath, N. D., & Behzadan, A. H. (2020). Deep convolutional networks for construction object detection under different visual conditions. *Frontiers in Built Environment*, *6*, 97. https://doi.org/10.3389/fbuil.2020.00097

Nawade, P. P., Kosamkar, V., & Raut, S. (2022). Reducing defects in project construction. International Journal of Advances in Engineering and Management, 4(6), 1452–1455. https://doi.org/10.35629/5252-040614521455

Obiora, C. O., Ezeokoli, F. O., Belonwu, C. C., & Okeke, F. N. (2022). Defects in concrete elements: A study of residential buildings of 30 years and above in Onitsha Metropolis, Anambra State, Nigeria. *Journal of Building Construction and Planning Research*, *10*(3), 102–123. https://doi.org/10.4236/jbcpr.2022.103005

Olanrewaju, A., & Lee, H. J. A. (2022). Analysis of the poor-quality in building elements: Providers' perspectives. *Frontiers in Engineering and Built Environment*, *2*(2), 81–94. https://doi.org/10.1108/FEBE-10-2021-0048

Pan, X., Yang, T. T. Y., Li, J., Ventura, C., Málaga-Chuquitaype, C., Li, C., Su, R. K. L., & Brzev, S. (2025). A review of recent advances in data-driven computer vision methods for structural damage evaluation: Algorithms, applications, challenges, and future opportunities. *Archives of Computational Methods in Engineering*. https://doi.org/10.1007/s11831-025-10279-8

Wang, W., Su, C., & Fu, D. (2022). Automatic detection of defects in concrete structures based on deep learning. *Structures*, *43*, 192–199. https://doi.org/10.1016/j.istruc.2022.06.042

Wendabona, P. M. (2024). Safety detection system: A technological leap in Sri Lanka's construction safety. *Journal of Research Technology and Engineering*, 5(1), 13–26. https://www.jrte.org/wp-content/uploads/2024/01/Safety-Detection-System-A-Technological-Leap-in-Sri-Lankas-Construction-Safety.pdf

Wijesinghe, L., Jayasooriya, S., & Nilupulee, M. (2024, September 26). *AI-Driven Innovation in Cost Estimation and Quality Control in Sri Lankan Construction Projects*. 17th International Research Conference. https://ir.kdu.ac.lk/handle/345/8751

Zhong, B., Wu, H., Ding, L., Love, P. E., Li, H., Luo, H., & Jiao, L. (2019). Mapping computer vision research in construction: Developments, knowledge gaps and implications for research. *Automation in Construction*, *107*, 102919. https://doi.org/10.1016/j.autcon.2019.102919

Yang, P., Lim, B.T.H., & Oo, B.L., 2026. Integrating life cycle assessment and emissions trading scheme in the Australian construction sector: A preliminary study. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 965-978. DOI: https://doi.org/10.31705/WCS.2026.71. Available from: https://ciobwcs.com/papers/

# INTEGRATING LIFE CYCLE ASSESSMENT AND EMISSIONS TRADING SCHEME IN THE AUSTRALIAN CONSTRUCTION SECTOR: A PRELIMINARY STUDY

**Pengqi Yang[1], Benson Teck Heng Lim[2] and Bee Lan Oo[3]**

## *ABSTRACT*

*Construction carbon mitigation is increasingly moving beyond operational energy, with growing attention directed towards embodied carbon in materials. Life cycle assessment (LCA) offers a means to quantify these emissions, yet its uptake is constrained by data limitations, varied organisational capability, and fragmented decision-making processes. Carbon pricing under an emissions trading scheme (ETS) faces similar adoption barriers. In the absence of a workable accounting interface, ETS-derived carbon costs rarely enter project-level engineering and procurement trade-offs. This exploratory study examines the feasibility of embedding ETS logic within an LCA framework, and clarifies the conditions under which such integration could operate in practice. Semi-structured interviews were conducted with five industry practitioners, and the data were analysed using thematic analysis. The results indicate that participants generally valued the LCA–ETS integration, particularly when concrete carbon information is available in time to inform procurement choices. Key implementation barriers include weak policy and verification credibility, immature early-stage information, and delivery-side workflow frictions. Key enabling conditions include stable policy signals, minimum data and verification standards, and an accounting interface that can be embedded into routine procurement decision-making. The study offers preliminary, project-grounded insights into the conditions under which LCA–ETS integration may become workable in construction project delivery.*

***Keywords:*** *Australia; Barriers; Construction Decarbonisation; Emissions Trading Scheme (ETS); Life Cycle Assessment (LCA).*

## 1. INTRODUCTION

The construction sector drives global energy use and carbon emissions across extraction, manufacturing, transport, construction and end-of-life treatment (Intergovernmental Panel on Climate Change [IPCC], 2023). A narrow focus on operational efficiency, such as heating, ventilation and air conditioning (HVAC) and lighting systems, often overlooks the embodied carbon committed during material production and construction, before

[1] PhD Candidate, School of Built Environment, University of New South Wales, Australia, pengqi.yang@unsw.edu.au
[2] Associate Professor, School of Built Environment, University of New South Wales, Australia, b.lim@unsw.edu.au
[3] Associate Professor, School of Built Environment, University of New South Wales, Australia, bee.oo@unsw.edu.au

buildings enter the operational phase. Early design decisions and material choices lock in embodied carbon, and embodied carbon is therefore too large to treat as secondary in building decarbonisation efforts (Ibn-Mohammed et al., 2013). Life cycle assessment (LCA) offers a promising approach to quantify whole-of-life carbon emissions and identify carbon hotspots (Abd Rashid & Yusoff, 2015). In theory, it converts low-carbon intent into comparable design options, yet in practice it is often framed as a compliance pathway and/or a means of earning rating points (Athena Sustainable Materials Institute, 2014). Data limitations, time and cost, and time pressure within procurement and planning phases constrain the applicability of LCA in practice (Scherz et al., 2022). Additionally, project stakeholders' responsibilities often blur within multi-actor project delivery systems, meaning LCA rarely enters the core decision loop (Ristimäki & Junnila, 2015). In practice, carbon results are rarely priced into project budgets or embedded in tender evaluation and contractual accountability, so they have limited leverage over procurement trade-offs (Subal et al., 2024). Thus, when LCA-based carbon results are given lower priority than other decision criteria, the gap between LCA calculation and project decision-making can widen (Subal et al., 2024). More fundamentally, the challenge is not just better datasets or faster calculation tools, but the legitimacy and governance of carbon metrics, including which calculations are treated as decision-relevant and under what boundaries, procedures and verification rules (Jordan & Bleischwitz, 2020). Market-based instruments such as emissions trading schemes (ETSs) offer a different lever. These schemes convert emissions into an explicit cost and attempt to reweight decisions through price signals (Zhang & Wei, 2010). However, applying ETS logic to the construction sector is more challenging because a substantial share of project-related emissions sits upstream in multi-tier material supply chains where carbon data is fragmented and difficult to trace consistently (Pittri et al., 2026). A price signal only changes choices when measurement, reporting and verification (MRV) is robust enough to sustain credible and comparable emissions accounting (European Commission, n.d.). Standard ETS design therefore assumes that emissions within the scope of the scheme can be monitored and verified, and that a clearly defined legal entity is accountable for compliance obligations such as emissions reporting and allowance surrender (World Bank & International Carbon Action Partnership [ICAP], 2021). In project-based delivery, this assumption weakens because traditional contracting and procurement fragment responsibilities between design and construction teams, limiting contractors' ability to influence design-stage choices (Nawi et al., 2014). Information asymmetry across project participants further constrains how carbon information travels into tender evaluation, contracting terms, and procurement decisions (Ivić & Cerić, 2023).

In the context of the Australian construction sector, these constraints are even stronger. Unlike jurisdictions with established compliance carbon markets such as the EU ETS, the Korea ETS, and California's Cap-and-Trade Program (Narassimhan et al., 2018), Australia lacks a national ETS covering the building value chain. Policy volatility has also made firms more sensitive to long-run certainty. This raises a practical question about whether the construction sector would accept an integrated framework that uses LCA as the accounting base for an ETS carbon-price obligation. The more difficult question is what minimum conditions would make such integration implementable. Although LCA and ETS are well developed in the literature, they are rarely examined as an integrated framework in construction project delivery. In this setting, carbon accounting outputs would need to be translated through agreed rules and systems into allocations of cost, risk and accountability across project stakeholders who do not share incentives. Feasibility of

such integration is therefore not primarily about agreeing with decarbonisation in principle (Giesekam et al., 2016; World Bank & ICAP, 2021). Instead, it depends on whether this integration can survive routine procurement, programme pressure, and contested responsibility boundaries across the project life cycle. This challenge is further sharpened in Australia by the absence of a building-sector ETS and the reliance on facility-based constraints under the Safeguard Mechanism (covering facilities emitting >100,000 $tCO_2$-e/year), which do not map neatly onto project-level procurement decisions (Department of Climate Change, Energy, the Environment and Water [DCCEEW], 2025).

This study addresses this interface gap through an exploratory qualitative design. Using semi-structured interviews and thematic analysis, it identifies the key constraints and enabling conditions that shape whether LCA–ETS integration can operate in routine construction project delivery. The two research questions are:

Q1: How do construction practitioners perceive value and feasibility of LCA–ETS integration?

Q2: What barriers and enabling conditions shape the practical implementation of LCA–ETS integration?

This paper provides preliminary empirical evidence from the Australian construction sector, where a national ETS is absent. While prior research has examined LCA usability and ETS governance as separate domains, these two mechanisms have rarely been studied as an integrated framework within construction project delivery. The study contributes by linking LCA-derived carbon information with ETS compliance logic at the project level, and by identifying the specific conditions under which such integration is perceived as workable by practitioners. This project-level integration perspective, situated in a jurisdiction without a building-sector ETS, offers a distinct analytical contribution that extends beyond established findings on LCA adoption barriers or ETS design principles that were considered in isolation.

# 2. LITERATURE REVIEW

## 2.1 DECARBONISATION: STRATEGIC DRIVERS AND ADOPTION TRIGGERS

Research on construction decarbonisation often frames adoption drivers in terms of governance and decision usability (Jordan & Bleischwitz, 2020; Scherz et al., 2022; Schmidt et al., 2020; Subal et al., 2024). Carbon performance is more likely to shape routine project decisions when it can be presented in a legible form and compared across options within organisational decision processes. Operational energy has attracted sustained attention, largely because it is easier to measure and benchmark, and can be more readily incorporated into established disclosure and governance arrangements (DCCEEW, 2024). As operational efficiency improves and electricity grids decarbonise, several studies suggest that embodied emissions in materials and upstream supply chains become increasingly salient within whole life carbon footprints (Giesekam et al., 2016; IPCC, 2023). However, the literature indicates that embodied carbon management often lacks stable market incentives, and is therefore more commonly advanced through voluntary actions, client requirements, Environmental, Social, and Governance (ESG) reporting expectations, and rating-based incentives rather than direct price constraints (IPCC, 2023; Green Building Council of Australia [GBCA] & thinkstep-anz, 2021;

Infrastructure Australia [IA], 2024). This implies that adoption triggers may not be determined by technical feasibility alone (Kibert, 2016; United Nations Environment Programme [UNEP] & Global Alliance for Buildings and Construction [GlobalABC], 2023). They may also be shaped by institutional arrangements, including the indicators legitimised for disclosure and comparison and the practices that are rewarded and become embedded over time.

The Australian context reflects many of these dynamics, particularly through disclosure schemes and inconsistent approaches to embodied carbon (Clean Energy Regulator, 2026; DCCEEW, 2025; New South Wales Department of Planning and Environment [NSW DPE], 2026; IA, 2024). While the National Australian Built Environment Rating System (NABERS) and the Commercial Building Disclosure scheme have strengthened transparency around operational performance, requirements addressing embodied carbon remain comparatively limited and inconsistent (DCCEEW, 2024; GBCA & thinkstep-anz, 2021). In parallel, coverage under the Safeguard Mechanism is concentrated on large facilities, which means that many construction-related actors do not face a direct carbon price signal at the project level (DCCEEW, 2025; IPCC, 2023). For non-covered actors, uptake is often shaped by non-price drivers, particularly investors' expectations and the incentives embedded within voluntary rating systems (IA, 2024). Recent state level measures also suggest that regulatory triggers can emerge in more targeted forms, as illustrated by mandatory embodied emissions disclosure for selected projects in New South Wales (NSW DPE, 2026). At the same time, Fouché and Crawford (2015) noted continuing uncertainty in methods and data used for embodied carbon assessment, and suggested that uneven organisational capability may remain a practical constraint on consistent implementation (Marsh et al., 2023). Overall, decarbonisation adoption triggers in the Australian construction sector appear increasingly policy oriented, and whether these signals extend beyond disclosure and translate into routine project decisions is likely to depend on whether sector capability and implementation conditions can support uptake at scale (IPCC, 2023; IA, 2024).

## 2.2 LCA CAPABILITY, DECISION USABILITY AND BARRIERS IN PROJECT DELIVERY

Studies on LCA delivery in construction projects show that producing credible results depends on reliable information being available across design, procurement, and construction (Marsh et al., 2023; Scherz et al., 2022; Waldman et al., 2020; Pittri et al., 2026). Marsh et al. (2023) pointed out that when harmonised rules and structured protocols are limited, context such as system boundaries, data provenance and quality indicators may not be recorded in a consistent way. This can make verification and comparisons more difficult. At the product level, Waldman et al. (2020) noted that Environmental Product Declarations (EPDs) do not always report uncertainty and other key fields in a uniform manner. This can reduce alignment across projects and increase the labour required for interpretation and checking (Waldman et al., 2020). Evidence in the Australian context provides a concrete example. Crawford and Stephan (2022) reported substantial variations in cut-off rules for concrete EPDs. Such variations require additional calibration at the building scale and add to the interpretive load when results are compared. Taken together, the literature often characterises these issues as challenges of comparability and interpretability, which may limit the extent to which LCA outputs

could inform routine project decisions (Waldman et al., 2020; Crawford & Stephan, 2022).

On workflow integration, building information modelling (BIM) is widely regarded as useful for quantity take-off, yet BIM and LCA linkage still often relies on manual mapping. Studies typically attribute this to limited machine-readable data and interoperability frictions across software tools, which can constrain automated integration in routine delivery settings (Parece et al., 2025; Pittri et al., 2026). International studies also report a high intent but low adoption pattern, suggesting a persistent gap between professional endorsement and everyday application (Moncaster et al., 2019). Additionally, the investment required for rigorous data management may be perceived as a cost burden if economic incentives are weak, which could dampen organisational willingness to adopt more advanced practices (IPCC, 2023). Policy measures such as mandatory disclosure in New South Wales aim to improve transparency, but they may also introduce adaptation costs as stakeholders adjust to new reporting requirements (NSW DPE, 2026). Across these studies, the practical issue is not simply about producing compliant figures; it is about producing outputs that are comparable, interpretable and workable within procurement and decision-making workflows (Waldman et al., 2020; Parece et al., 2025).

## 2.3 ETS LOGIC AND IMPLEMENTATION PREREQUISITES IN THE CONSTRUCTION SECTOR

Many studies describe ETS as an institutional arrangement rather than a simple 'price on emissions' that reshapes how organisations weigh trade-offs and make decisions (Schmalensee & Stavins, 2017). Reviews also suggest that the influence of an ETS is not determined by price levels alone. It depends heavily on three institutional foundations. First, monitoring, reporting and verification (MRV) needs to support consistent boundary setting and verifiable data sources. Second, compliance responsibility needs to sit with actors who hold budget and decision authority. Third, the rules need to be credible and predictable enough to support medium- to long-term choices (World Bank & ICAP, 2021). From this perspective, the 're-weighting' effect of an ETS can be seen as a process of institutionalisation, with outcomes closely shaped, and often constrained, by factors such as rule clarity, verification feasibility, and clear allocation of responsibility (Narassimhan et al., 2018; Schmalensee & Stavins, 2017; World Bank & ICAP, 2021).

Against this institutional framing, Narassimhan et al. (2018) noted that, in the construction sector, discussion tends to focus on practical implementation conditions and sources of friction, particularly around MRV, responsibility allocation and cost pass-through, which often become more complicated in this sector. On the one hand, construction-related emissions are distributed across multi-tier material supply chains and multiple project stages. This makes boundary definition and cross-actor data transfer more difficult, and increases challenges for verification and comparability. Studies suggest that LCA results become harder to trace and less robust to comparison across projects if key assumptions, dataset details, or process documentation are not recorded transparently (De Wolf et al., 2017; Marsh et al., 2023; Röck et al., 2020). On the other hand, project-based delivery and contract chains can fragment control and accountability. If compliance obligations are not assigned to entities with budget and decision authority, carbon costs are unlikely to be embedded consistently in procurement evaluation or contractual responsibilities. World Bank and ICAP (2021) describe this as a practical

implementation challenge when ETS compliance logics are mapped onto construction project governance structures. In Australia, this is reinforced by the current policy architecture: regulatory information and industry analyses generally noted that there is currently no ETS framework at the national level that directly covers the construction value chain, and existing constraints remain largely facility oriented. This makes procurement-side exposure to carbon costs comparatively indirect (Clean Energy Regulator, 2026; KPMG, 2023). Relatedly, LCA research more often focuses on establishing clearer emissions boundaries and measurement bases for buildings, while also emphasising that cross-stage data transfer and transparent reporting of key methodological assumptions and traceability can materially affect whether results are verifiable and comparable (Röck et al., 2020; Marsh et al., 2023). At the sector discourse level, recent reviews suggest that ETS-related discussion and practice in the construction sector remains relatively limited and often leans towards operational emissions; incorporating embodied carbon into implementable institutional arrangements still faces challenges around measurement, allowance allocation and feasibility (Liu & Loo, 2026). While some studies have begun to monetise whole-life emissions using carbon prices and apply this in economic appraisal or procurement incentives (Schmidt et al., 2020; Scherz et al., 2023), work on building a replicable and verifiable LCA–ETS interface for the construction sector context remains fragmented. This study aims to address these gaps by investigating, in the Australian construction sector, the drivers and barriers shaping stakeholders' willingness to adopt an LCA-informed ETS approach, and by identifying the governance and delivery conditions under which carbon information can be embedded into routine procurement and decision-making processes.

Two constructs are central to this exploratory study. Value refers to the perceived benefits that practitioners associate with LCA–ETS integration, including improved carbon transparency, enhanced comparability of design alternatives, and alignment with regulatory and market expectations. This definition was informed by Subal et al. (2024) and Schmidt et al. (2020). Feasibility refers to the perceived practicality of implementing such integration at the project level, encompassing data availability, verification credibility, cost implications, institutional support, and compatibility with existing procurement and delivery processes (Narassimhan et al., 2018; World Bank & ICAP, 2021). These constructs are treated as practitioner-assessed judgements shaped by role, organisational context, and project conditions, rather than as objective or fixed properties of the integration itself.

At the project level, LCA–ETS integration could take the form of using life cycle carbon assessment outputs as a quantified basis for estimating project-related carbon liabilities, comparing design and material alternatives on a carbon-cost basis (Schmidt et al., 2020), identifying high-emission processes or supply chain segments (Röck et al., 2020), and informing whether carbon costs, allowances, or offset obligations should be incorporated into procurement evaluation and contractual terms (Liu & Loo, 2026; Scherz et al., 2023). Such integration would likely require an accounting interface capable of translating LCA outputs into units compatible with ETS compliance logic—such as verified tonnes of $CO_2$-equivalent linked to defined system boundaries—and embedding these within routine project decision points including tender evaluation, design review, and material procurement (World Bank & ICAP, 2021).

# 3. RESEARCH METHOD

This study adopted an exploratory qualitative design to address the research questions. The focus was on how feasibility judgements are formed in practice and what implementation conditions practitioners see as necessary, rather than on estimating the prevalence of views in the wider population. The study therefore aimed to surface the practical logics and condition sets that shape feasibility judgements, rather than to quantify attitudes. A qualitative approach was used to capture practitioners' decision logics and feasibility judgements under real project constraints. Data was collected through semi-structured interviews. Interviewees were recruited through purposive sampling to target decision-critical roles across the construction value chain. The final sample comprised five senior practitioners: a project manager, a sustainability consultant, a cost manager, and two developers from organisations of different scales. Recruitment was constrained by the time pressure faced by senior staff, the commercial sensitivity of procurement and carbon-related decision processes, and, in several cases, internal approval requirements and confidentiality obligations. Given these constraints, the study prioritised experienced practitioners who could provide role-specific and information-rich insights. Consistent with purposive sampling in exploratory qualitative research, participant selection prioritised information richness and relevance to the research questions over representativeness (Patton, 2015). The intent was not to achieve theoretical saturation or population-level generalisability, but to surface the practical logics and condition sets through which feasibility is assessed in role-specific project contexts.

The interview guide questions were developed relative to the research questions, covering decarbonisation drivers, LCA and ETS implementation conditions, policy trust, and practical requirements for integration. During the interviews, follow-up questions were tailored to role-specific examples and project contexts. The interviews lasted approximately 30 minutes each and were conducted online or in person. With informed consent, interviews were audio-recorded, transcribed verbatim, and de-identified prior to analysis. Ethics approval was obtained through the university human research ethics process, and confidentiality and informed consent procedures were followed throughout. The thematic analysis followed Braun and Clarke's (2006) six phases of familiarisation, initial coding, theme development, theme review, theme definition and reporting, and was performed using the NVivo software. Coding began with a small set of deductive categories aligned to the research questions and was iteratively refined as recurring ideas emerged. Themes were compared across participants and roles to identify recurring patterns and role-based contrasts, while retaining the context of each interview. Rigour was supported through an audit trail of coding decisions, iterative refinement of the codebook, checks for disconfirming evidence, and the use of exemplar quotations to support key interpretations.

# 4. RESULTS AND DISCUSSION

## 4.1 PROFILE OF INTERVIEWEES AND ROLE-BASED CONTEXT

Table 1 summarises the profiles of the five interviewees. They work in cost management, property development, project management, and sustainability consulting roles, covering decision and delivery points that are central to LCA–ETS integration across the construction value chain. All interviewees have had at least eight years of industry experience, and three of them have had over fifteen years of experience. Accordingly, the

interviews reflect practitioners' practical judgements and trade-offs drawn from real project delivery contexts. This sample was assembled deliberately to address the research questions through different role lenses. For example, the developer participants focused on investment decisions and strategic trade-offs, while the cost manager emphasised how carbon performance information can be translated into cost planning, budgeting, and contractual language. These role-critical accounts help clarify how practitioners assess the perceived value and feasibility of LCA–ETS integration, and which barriers and enabling conditions shape its practical implementation.

*Table 1: Profile of Interviewees*

| ID | Professional role | Organisation type | Years of experience | Key focus |
|---|---|---|---|---|
| I1 | Cost Manager | Large quantity surveying consultancy firm | ≥15 | Carbon performance integration into cost planning and budgeting |
| I2 | Developer Representative | A large-scale property development firm | ≥15 | Institutional logic, ESG strategy, and macro-level policy compliance |
| I3 | Developer Representative | A small-to-medium sized property development firm | ≥12 | Economic sensitivity, incentives, and implementation constraints |
| I4 | Project Manager | Major building contractor (Tier 1) | ≥15 | Delivery interface frictions and cross-stakeholder workflow coordination |
| I5 | Sustainability Consultant | Specialist environmental/sustainability consultancy firm | ≥8 | LCA methodological rigour, data quality, and decision-support usability |

## 4.2 PERCEIVED VALUE AND FEASIBILITY APPRAISAL OF LCA–ETS INTEGRATION

When the interviewees discussed the value of LCA–ETS integration, they focused less on broad environmental ideas and commented more on its applicability in project decision-making. Value was primarily framed in terms of early visibility of carbon information, support for option comparisons, and usefulness in budgeting and risk conversations. In these budgeting and risk conversations, carbon pricing was seen to matter mainly when it could be translated into established costing routines. Interviewee I2 rarely framed decisions in terms of a 'carbon price'; carbon-related costs were typically treated as secondary to programme certainty, procurement sequencing, and downside risk. Interviewee I3 stated a similar view explicitly: "If you don't force me to use it, I won't. Why would I use it? My margin is already tight." Overall, the interviewees point to a conditional view of the value of LCA–ETS integration: carbon information needs to be quantifiable, benchmarkable, and defensible, and able to appear as a clear line item within budget and contract language, before it is likely to shift project trade-offs. This aligns with research showing that LCA evidence influences decisions most strongly when it is decision-relevant within organisational routines, rather than existing only as reporting output (Subal et al., 2024). This routine-based view is consistent with LCA-based carbon

quantification often being driven by regulation, client requirements, and ESG disclosure under weak incentives, rather than by stable project-level price constraints (IPCC, 2023; GBCA & thinkstep-anz, 2021; IA, 2024). In Australia, project actors' exposure to an explicit carbon cost signal is often indirect, because major compliance obligations are largely structured around facility-level coverage rather than project procurement (DCCEEW, 2025; Clean Energy Regulator, 2026). Against this backdrop, the interviewees specified that the value of integration in practice depends on whether carbon information can be expressed in cost and risk language, and can function as a priced, comparable basis for decisions.

Alongside recognising potential value, interviewees set a higher bar for feasibility. Feasibility was first framed around policy stability, consistency of implementation, and the credibility of verification. Interviewee I2 positioned compliance as the baseline driver and indicated that developers tend to wait for mandatory rules rather than pursue voluntary adoption. While prior research commonly emphasises technical and informational conditions, such as boundary definition, data comparability, and workflow integration (e.g., Waldman et al., 2020; Crawford & Stephan, 2022; Marsh et al., 2023), the interviewees suggest that a key prerequisite is whether carbon assessment outputs are trusted and reliable, rather than whether they can be calculated. The interviewees suggested that 'value' and 'feasibility' are assessed through usability in project decision-making. Integration was considered feasible in practice only when carbon information can be expressed in cost, risk, and contractual terms and relied upon as a defensible basis for choices.

### 4.3 BARRIERS AND ENABLING CONDITIONS SHAPING THE IMPLEMENTATION OF LCA–ETS INTEGRATION

Regulatory triggers and compliance deadlines were a shared starting point among the interviewees, framing carbon-related requirements as a baseline compliance task rather than an optional initiative. Beyond regulation, client requirements were described as a direct project-level instruction that legitimises allocating budget and adjusting scope; for example, I1 noted: "The main trigger was the client's internal targets" (I1, interview). Against this backdrop, the interview results indicate that implementation of LCA–ETS integration is constrained by three interrelated issues: unstable outputs driven by low information maturity in early stages, delivery-side workflow and resourcing frictions, and responsibility and risk concerns linked to weak verification credibility. On the information side, interviewees emphasised that underdeveloped early design and unclear material specifications force teams to rely on assumptions, undermining accuracy and defensibility. Interviewee I1 captured this clearly: "If the design doesn't show it, I have to make assumptions, and those assumptions can be incorrect." When carbon information is delayed, it often arrives too late to shape procurement and other key decisions where carbon impacts are largely fixed. Next, delivery-side barriers were commonly described as operational frictions rather than ideological resistance. An example given by Interviewee I5 is that reconciling inconsistent certificates and managing supplier documentation is labour-intensive under time pressure, yet their project teams are rarely resourced for this workload. Third, responsibility and risk concerns were amplified where verification credibility was perceived as weak. Interviewee I2 noted that when carbon assessment outputs cannot be independently verified, relying on them in procurement or contractual settings increases accountability and commercial exposure. As a result,

participants were reluctant to treat such outputs as decision-binding, even when calculations could be produced.

The results suggest that institutional and risk-related barriers were more pronounced from the developers' perspectives. Policy settings were treated as parameters shaping investment logic, and shifts in rule stability were seen as changing strategic judgement. Interviewee I2 specifically distinguished mandatory and voluntary regimes, framing compliance as the primary driver for action. Where supply-chain carbon data are opaque or boundaries are unstable, risk was seen as concentrating on parties with final reputational and contractual exposure. Overall, the interviewees assessed implementability in terms of defensible accountability and credible verification, with less emphasis on whether carbon assessment outputs can be produced. This is consistent with prior findings that inconsistent boundaries and disclosure in supply chains reduce comparability and weaken decision usability (Waldman et al., 2020; Crawford & Stephan, 2022; Marsh et al., 2023). Limited workflow integration often means that data handling remains manual and feedback loops are slower (Parece et al., 2025). Uneven capability and resourcing constraints therefore remain practical barriers in Australia (Fouché & Crawford, 2015). Most interviewees added that a key prerequisite for integration is trust in verification and clarity of responsibility. Even if carbon assessment outputs can be produced, inconsistent verification and unstable rules can make them too risky to rely on (Schmalensee & Stavins, 2017; Narassimhan et al., 2018).

In terms of enabling conditions, interviewees converged on MRV and data standardisation as the minimum requirements for integration. They emphasised that consistent rules, clear baselines, and third-party verification are necessary for carbon assessment outputs to be comparable and defensible. Interviewee I5 noted that if LCA data is used for compliance, project teams would need "standardised baselines" and "approved datasets or verified EPDs", and that "third-party verification would also be important". Operationally, strengthening LCA influence was framed as front-end embedding: clarifying scope and targets early, and using cross-disciplinary workshops so LCA becomes a design input rather than being "added at the end" (Interviewee I5). It appears that developers placed greater weight on institutional supports and risk buffering. Interviewee I2 highlighted the need for financial support and more mature, validated tools to sustain early-stage integration. He further noted that longer defect liability periods increase the potential liability risks associated with adopting new solutions. As a result, developers tend to prefer proven, established systems unless low-carbon alternatives can demonstrate reliability and are cost-acceptable (Interviewee I2). These conditions align with the broader literature that ETS influence is dependent not only on price levels, but also on MRV that supports verifiable boundaries, clear responsibility assigned to actors with decision authority, and predictable rules (Schmalensee & Stavins, 2017; World Bank & ICAP, 2021). Overall, the interview findings suggest that implementation hinges on three conditions: (i) early-stage information being decision-ready; (ii) delivery teams having the capacity to absorb additional documentation and verification work; and (iii) MRV and responsibility arrangements being credible enough to reduce accountability risk.

## 5. CONCLUSIONS

This study draws on five semi-structured interviews with Australian construction practitioners to provide preliminary insights into how LCA–ETS integration is perceived

and what conditions may shape its implementation in routine project delivery. Its contribution is not in identifying individual barriers, such as compliance-driven adoption or distrust of early-stage data, which are documented in prior LCA and ETS literature. Rather, it lies in examining how these factors interact at the project level when LCA and ETS are considered as an integrated framework, and in surfacing the specific institutional and delivery conditions under which such integration is perceived as workable in a jurisdiction without a building-sector ETS. Within this exploratory study, compliance-related requirements were described as a relatively stable and credible trigger for action. Carbon price signals, by contrast, appeared uneven and indirect, and tended to shape decisions only when they could be translated into established routines such as cost planning, material selection, and risk appraisal. Taken together, these findings indicate that feasibility judgements are shaped not only by attitudes, but also by whether integration can be executed within everyday project systems. Minimum MRV foundations, interoperable data and workflows, and clearer responsibility allocation need to be in place; otherwise, carbon evidence may struggle to be incorporated into routine procurement processes and approval points. From this perspective, LCA–ETS integration is better treated not as a simple add-on or pricing overlay, but as a socio-technical shift that is likely to require coordinated change across data governance and organisational processes. The implication for practice is that integration efforts need to focus on making requirements workable in projects. Priorities include establishing minimum data and verification standards, creating workflow interfaces that align with procurement governance, and clarifying roles and responsibilities across project teams. Such measures could reduce accountability risk and make implementation more repeatable. For research, the study offers an empirical foundation for subsequent construct operationalisation. It supports survey development that treats capability, trust, and responsibility allocation as testable mechanisms rather than background context.

This research is exploratory in nature and is intended to map how the feasibility of LCA–ETS integration is interpreted and reasoned through by practitioners in the Australian construction sector. The study is limited by its small sample size and exploratory design. The findings should therefore be interpreted as analytically indicative rather than statistically generalisable, and future research should extend the sample to test whether these patterns hold across a wider range of organisational types and project contexts. Despite this limitation, the study allows role-based interpretation and careful tracing of how feasibility is reasoned through in practice. Future work can extend this study through an exploratory sequential mixed-methods design. This is planned in the next stage of this study to quantify the impacts of the key factors identified in this exploratory study on practitioners' perceptions of feasibility and implementation likelihood. In parallel, project case studies can be used to assess the practicality and cost implications of embedding an LCA–ETS accounting interface into procurement decision-making.

## 6. REFERENCES

Abd Rashid, A. F., & Yusoff, S. (2015). A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews, 45*, 244–248. https://doi.org/10.1016/j.rser.2015.01.043

Athena Sustainable Materials Institute. (2014). *Athena guide to whole-building LCA in green building programs*. Athena Sustainable Materials Institute. https://www.athenasmi.org/wp-content/uploads/2014/03/Athena_Guide_to_Whole-Building_LCA_in_Green_Building_Programs_March-2014.pdf

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Clean Energy Regulator. (2026). *Safeguard mechanism*. Clean Energy Regulator. https://cer.gov.au/schemes/safeguard-mechanism

Crawford, R. H., & Stephan, A. (2022). Comparison of embodied greenhouse gas emissions data from environmental product declarations and the EPiC database: Implications for material selection. In P. Izadpanahi & F. Perugia (Eds.), *Architectural science and user experience: How can design enhance the quality of life? Proceedings of the 55th International Conference of the Architectural Science Association 2022* (pp. 177–188). Architectural Science Association. https://archscience.org/paper/comparison-of-embodied-greenhouse-gas-emissions-data-from-environmental-product-declarations-and-the-epic-database-implications-for-material-selection/

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

Department of Climate Change, Energy, the Environment and Water. (2024). *About the program*. Commercial Building Disclosure. https://www.cbd.gov.au/about-cbd-program/administration/about-program

Department of Climate Change, Energy, the Environment and Water. (2026, April 14). *Safeguard mechanism*. Department of Climate Change, Energy, the Environment and Water. https://www.dcceew.gov.au/climate-change/emissions-reporting/national-greenhouse-energy-reporting-scheme/safeguard-mechanism

European Commission. (n.d.). *Monitoring, reporting and verification (MRV) – EU ETS*. European Commission. Retrieved May 03, 2026, from https://climate.ec.europa.eu/eu-action/carbon-markets/eu-emissions-trading-system-eu-ets/monitoring-reporting-and-verification_en

Fouché, M., & Crawford, R. H. (2015). The Australian construction industry's approach to embodied carbon assessment: A scoping study. In R. H. Crawford & A. Stephan (Eds.), *Living and learning: Research for a better built environment: 49th International Conference of the Architectural Science Association 2015* (pp. 578–587). The Architectural Science Association. https://www.unsw.edu.au/content/dam/pdfs/ada/built-environment/low-carbon-living-crc/resources/asa2015_monique_fouche.pdf

Giesekam, J., Barrett, J. R., & Taylor, P. (2016). Construction sector views on low-carbon building materials. *Building Research & Information, 44*(4), 423–444. https://doi.org/10.1080/09613218.2016.1086872

Green Building Council of Australia, & thinkstep-anz. (2021, August 20). *Embodied carbon & embodied energy in Australia's buildings: A national benchmarking study*. Green Building Council of Australia. https://new.gbca.org.au/news/gbca-news/gbca-and-thinkstep-release-embodied-carbon-report/

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational versus embodied emissions in buildings: A review of current trends. *Energy and Buildings, 66*, 232–245. https://doi.org/10.1016/j.enbuild.2013.07.026

Infrastructure Australia. (2024, July 15). *Embodied carbon projections for Australian infrastructure and buildings*. Infrastructure Australia. https://www.infrastructureaustralia.gov.au/reports/embodied-carbon-projections-australian-infrastructure-and-buildings

Intergovernmental Panel on Climate Change. (2023). *Climate change 2022: Mitigation of climate change. Contribution of working group iii to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

Ivić, I., & Cerić, A. (2023). Risks caused by information asymmetry in construction projects: A systematic literature review. *Sustainability, 15*(13), 9979. https://doi.org/10.3390/su15139979

Jordan, N. D., & Bleischwitz, R. (2020). Legitimating the governance of embodied emissions as a building block for sustainable energy transitions. *Global Transitions, 2*, 37–46. https://doi.org/10.1016/j.glt.2020.01.002

Kibert, C. J. (2016). *Sustainable construction: Green building design and delivery* (4th ed.). John Wiley & Sons. https://www.wiley.com/en-gb/Sustainable%2BConstruction%3A%2BGreen%2BBuilding%2BDesign%2Band%2BDelivery%2C%2B4th%2BEdition-p-9781119055327

KPMG. (2023, October 4). *Tackling embodied carbon within Australia's construction and infrastructure sector*. KPMG. https://kpmg.com/au/en/insights/economics-geopolitics/embodied-carbon-management-construction-infrastructure-sector.html

Liu, Y., & Loo, B. P. Y. (2026). Carbon trading in the construction industry: A systematic review and a vigorous impact assessment framework to facilitate implementation. *Environmental Impact Assessment Review, 118*, 108271. https://doi.org/10.1016/j.eiar.2025.108271

Marsh, E., Allen, S., & Hattam, L. (2023). Tackling uncertainty in life cycle assessments for the built environment: A review. *Building and Environment, 231*, 109941. https://doi.org/10.1016/j.buildenv.2022.109941

Moncaster, A., Rasmussen, F. N., Malmqvist, T., Houlihan Wiberg, A., & Birgisdottir, H. (2019). Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-disciplinary building projects. *Journal of Cleaner Production, 235*, 378–393. https://doi.org/10.1016/j.jclepro.2019.06.233

Narassimhan, E., Gallagher, K. S., Koester, S., & Rivera Alejo, J. (2018). Carbon pricing in practice: A review of existing emissions trading systems. *Climate Policy, 18*(8), 967–991. https://doi.org/10.1080/14693062.2018.1467827

Nawi, M. N. M., Baluch, N., & Bahaudin, A. Y. (2014). Impact of fragmentation issue in construction industry: An overview. *MATEC Web of Conferences, 15*, 01009. https://doi.org/10.1051/matecconf/20141501009

New South Wales Department of Planning and Environment. (2026). *Embodied emissions technical note*. NSW Government. https://www.planning.nsw.gov.au/sites/default/files/2023-09/embodied-emissions-technical-note.pdf

Parece, S., Resende, R., & Rato, V. (2025). Current trends and challenges in BIM–LCA integration. In L. M. M. Domingos & M. J. Sousa (Eds.), *Swarm intelligence applications for the cities of the future* (1st ed., pp. 187–218). CRC Press. https://doi.org/10.1201/9781032656786-11

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE Publications. https://books.google.com/books?vid=ISBN9781412972123

Pittri, H., Godawatte, G. A. G. R., & Forster, A. M. (2026). Embodied carbon tracking in the construction supply chain: Phenomenological insights into challenges and strategies. *Construction Innovation: Information, Process, Management, Ahead-of-Print*. https://doi.org/10.1108/CI-09-2025-0389

Ristimäki, M., & Junnila, S. (2015). Sustainable urban development calls for responsibility through life cycle management. *Sustainability, 7*(9), 12539–12563. https://doi.org/10.3390/su70912539

Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings: The hidden challenge for effective climate change mitigation. *Applied Energy, 258*, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Scherz, M., Wieser, A. A., Passer, A., & Kreiner, H. (2022). Implementation of life cycle assessment (LCA) in the procurement process of buildings: A systematic literature review. *Sustainability, 14*(24), 16967. https://doi.org/10.3390/su142416967

Scherz, M., Kreiner, H., & Passer, A. (2023). Sustainable procurement for carbon neutrality of buildings: A life cycle assessment (LCA)-based bonus/malus system to consider external cost in the bid price. *Developments in the Built Environment, 14*, 100161. https://doi.org/10.1016/j.dibe.2023.100161

Schmalensee, R., & Stavins, R. N. (2017). The design of environmental markets: What have we learned from experience with cap and trade? *Oxford Review of Economic Policy, 33*(4), 572–588. https://doi.org/10.1093/oxrep/grx040

Schmidt, M., Crawford, R. H., & Warren-Myers, G. (2020). Integrating life-cycle GHG emissions into a building's economic evaluation. *Buildings and Cities, 1*(1), 361–378. https://doi.org/10.5334/bc.36

Subal, L., Braunschweig, A., & Hellweg, S. (2024). The relevance of life cycle assessment to decision-making in companies and public authorities. *Journal of Cleaner Production, 435*, 140520. https://doi.org/10.1016/j.jclepro.2023.140520

United Nations Environment Programme, & Global Alliance for Buildings and Construction. (2023). *Global status report for buildings and construction*. United Nations Environment Programme. https://www.unep.org/resources/report/global-status-report-buildings-and-construction

Waldman, B., Huang, M., & Simonen, K. (2020). Embodied carbon in construction materials: A framework for quantifying data quality in EPDs. *Buildings and Cities*, *1*(1), 625–636. https://doi.org/10.5334/bc.31

World Bank, & International Carbon Action Partnership. (2021). *Emissions trading in practice: A handbook on design and implementation* (2nd ed.). World Bank Group. https://openknowledge.worldbank.org/entities/publication/fe7cd64d-ec21-566f-86f9-9351d6e3e2e0

Zhang, Y.-J., & Wei, Y.-M. (2010). An overview of current research on EU ETS: Evidence from its operating mechanism and economic effect. *Applied Energy*, *87*(6), 1804–1814. https://doi.org/10.1016/j.apenergy.2009.12.019

Amandi, K.P.S., Hettiarachchi, A.A. and Nawagamuwa, U.P., 2026. Integrating material performance and pedestrian experience in Sri Lanka: A review of bio-based wood-clay composites in landscape architecture. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 979-992. DOI: https://doi.org/10.31705/WCS.2026.72. Available from: https://ciobwcs.com/papers/

# INTEGRATING MATERIAL PERFORMANCE AND PEDESTRIAN EXPERIENCE IN SRI LANKA: A REVIEW OF BIO-BASED WOOD-CLAY COMPOSITES IN LANDSCAPE ARCHITECTURE

**K.P.S. Amandi[1], A.A. Hettiarachchi[2] and U.P. Nawagamuwa[3]**

## *ABSTRACT*

*Assessing the urban potential of bio-based materials requires a transdisciplinary evaluation framework that bridges the mechanical durability of civil engineering with the sensory microclimatic and aesthetic goals of Landscape Architecture. Using a systematic literature review following the PRISMA 2020 guidelines, this study synthesizes global knowledge on wood-clay composites (WCC) as low-impact pedestrian paving systems. Peer-reviewed studies published between 2010 and 2025 were analysed to synthesize knowledge on material properties and composition, mechanical and thermal behaviour, and aesthetic and sensory qualities. Findings indicate that appropriate incorporation of sawdust enhances porosity, reduces thermal conductivity, and maintains structural stability. Thereby offering a dual benefit of environmental adaptation and pedestrian comfort. Surface attributes such as texture, roughness, and visual coherence were identified as critical mediators of walking satisfaction and safety perception. Despite these advances, gaps persist in integrating multi-dimensional evaluation frameworks that link structural performance, microclimate adaptation, and human-centered design, particularly in real urban contexts. The study proposes a Multi-Dimensional Pedestrian Pavement Framework (MDPPF)**, emphasizing the interplay of** material properties, thermal and hydrological behaviour, and sensory-aesthetic parameters to inform evidence-based landscape architectural decision-making. Future research should prioritize field-based validation, pedestrian-centered design interventions, and low-energy bio-based material stabilization strategies to foster paving systems that simultaneously advance walkability, urban thermal regulation, and aesthetic quality. This review contributes to a transdisciplinary understanding of sustainable paving, bridging technical feasibility with human experience and urban design excellence, and offers conceptual pathways for integrating bio-based composites into pedestrian-oriented landscapes.*

***Keywords:*** *Landscape Architecture; Material Performance; Regenerative Design; Sustainable Paving; Wood-clay composites (WCC).*

[1] PhD Candidate, Department of Architecture, University of Moratuwa, Sri Lanka, amandikps.25@uom.lk
[2] Professor, Department of Architecture, University of Moratuwa, Sri Lanka, anishkah@uom.lk
[3] Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka, udeni@uom.lk

# 1. INTRODUCTION

Sustainability and climate adaptation have become central challenges within contemporary construction and urban development. That requires systematic changes in product design and societal consumption patterns (Huisingh et al., 2015). In landscape architectural discourse, the ground surface is not merely a technical layer but a spatial and experiential element that contributes to placemaking, visual coherence, and public realm quality. It encompasses thermal comfort, tactile feedback, visual rhythm, and the emotional response evoked by material expression for paving (Fonseca et al., 2025).

Pedestrian walkability is compromised by thermal discomfort and aesthetic monotony in urban environments. Pavement surface temperatures reach as high as 48-67 °C under high solar exposure (Santamouris et al., 2012). Standard Walkability Indexes ignore surface temperature, which is a primary deterrent in tropical climates like Sri Lanka. High solar radiation, monsoon rainfall, and humidity significantly influence pavement performance and pedestrian comfort. Advanced paving solutions, such as high albedo, permeable, and heat handling materials, have demonstrated effectiveness in mitigating urban heat island (UHI) in developed countries (Lin et al., 2013).

While most of the current literature covers concrete and natural stone, there is a significant gap in bio-composites such as WCC. WCC has emerged as a promising paving material that uses waste wood and natural clay. Substantial quantities of wood waste end up in landfills, limiting reuse and recycling opportunities (Falk, 2002). Converting wood waste into manufactured composites enhances material performance and aligns with sustainability, enabling versatile applications (Maier, 2021). In addition, the utilization of wood waste in WCC supports circular economy principles by reducing material disposal while creating value-added products for sustainable urban infrastructure.

The aim is to review and synthesize existing knowledge on WCC through a multidisciplinary approach that bridges material science, structural performance, and landscape design principles. This research undertakes a conceptual evaluation of WCC within climate-responsive and pedestrian-centered landscape architectural frameworks. The study examines their environmental responsiveness, thermal and mechanical characteristics, and their implications for pedestrian-scale spatial experience, thereby assessing their suitability for sustainable landscape applications.

Research objectives (RO) are based on,

- RO 1- Establish a multi-dimensional landscape evaluation framework for pedestrian paving systems using a systematic, PRISMA-compliant literature review strategy
- RO 2- Review the existing knowledge of composition, material properties, and manufacturing methods of WCC.
- RO 3- Examine how pavement aesthetics and sensory qualities have been conceptualized and assessed within landscape architectural theory and practice.
- RO 4- Identify knowledge gaps, technical limitations, and research opportunities for multidisciplinary applications.

# 2. METHODOLOGY

## 2.1 RESEARCH APPROACH

This study builds a systematic literature review, following the 'PRISMA 2020' guidelines, to synthesize knowledge on bio-based WCC as sustainable paving materials. The review integrates materials science, sustainability considerations, and landscape architectural perspectives on paving materials to provide a comprehensive understanding of existing research directions and to understand knowledge gaps.

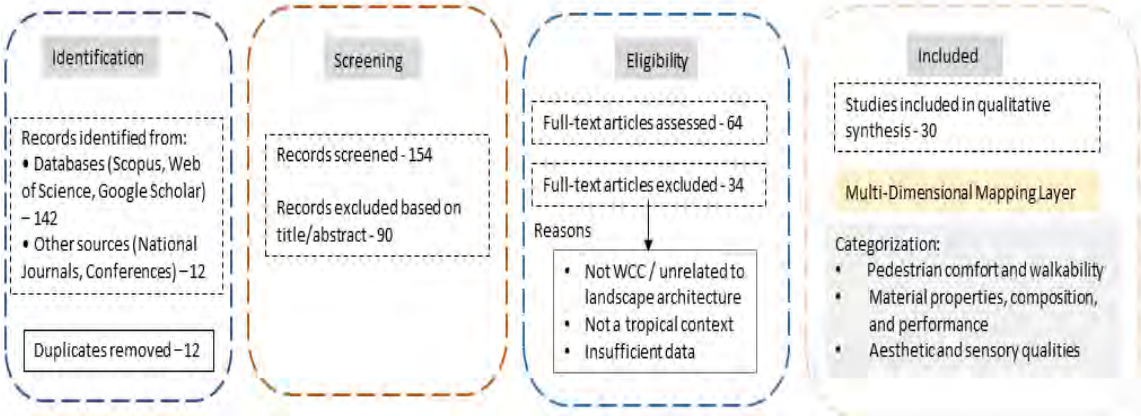



*Figure 1: PRISMA 2020 flow diagram adapted for the systematic review*

*Note: During the initial title and abstract screening, 90 records were excluded due to lack of relevance. Of these, 54 studies focused on WCC applications for heavy vehicular loads or structural masonry walls, while 36 examined non-clay polymer-based systems (Wood-Plastic Composites), which did not align with the focus of the study on pedestrian landscape paving.*

## 2.2 SEARCH STRATEGY

Given the niche focus of WCC relevant to landscape architecture aspects, the literature search included Scopus and Web of Science, Google Scholar, peer-reviewed national journals, and relevant conference proceedings to ensure a comprehensive coverage of all available studies. In order to ensure methodological reproducibility, the exact search string used in the primary search was formulated based on the following keywords:

(ALL("wood-clay composite*") OR ALL("sawdust-clay") OR ALL("bio-brick*")) AND ALL("paving" OR "pavement*" OR "walkability" OR "landscape architecture" OR "urban design")

## 2.3 ARTICLE SELECTION CRITERIA

The articles were selected according to the criteria mentioned in Table 1 to ensure quality, relevance, and alignment with the research objectives.

*Table 1: Selection criteria with rationale*

| Inclusion | Exclusion | Rationale |
|---|---|---|
| Peer-reviewed articles published in English | Non-English publications | Ensures scientific rigor and accessibility, avoids translation errors |

| Inclusion | Exclusion | Rationale |
|---|---|---|
| Published between 2010 and 2025 | Published before 2010 | To capture advances in mineral-bonding stabilizers and ecological urban drainage, earlier studies (pre-2010) mainly treated WCC as high-temperature fired industrial blocks, overlooking newer ambient-cured, low-carbon methods and user-experience factors important in modern landscape design. |
| Focus on WCC, wood waste, or clay-based paving, paving materials, durability, and pedestrian comfort | Studies unrelated to WCC paving, landscape architecture, or urban walkability | Ensures relevance to the research topic and ROs |
| Studies evaluating material properties, sustainability, aesthetic qualities, or pedestrian comfort | Conference abstracts only | Ensures sufficient detail for systematic analysis and thematic synthesis |

*(Source: Compiled by author)*

### 2.4 DATA EXTRACTION AND ANALYSIS

Data were extracted from each selected study, including details on author(s) and year, country or region, material composition (wood and clay), manufacturing methods, sustainability and performance, and aesthetic or pedestrian comfort assessments. The thematic synthesis was structured into three main codes directly linked to the research objectives:

- Pedestrian comfort, walkability indices, and tactile baselines, derived from established environmental psychology frameworks
- Material composition, properties, and manufacturing performance (including fired vs. ambient-stabilized pathways)
- Aesthetic qualities and sensory indicators

The results were interpreted within the framework of landscape architectural principles and sustainable urban design, complemented by insights from engineering knowledge.

## 3. RESULTS AND DISCUSSION

### 3.1 PEDESTRIAN COMFORT AND WALKABILITY

Walkability is defined as the degree to which a built environment supports and encourages people to move, socialize, and spend time comfortably within a particular area (Rafiemanzelat et al., 2017). Several studies review strategies designed to enhance pedestrian safety and comfort in urban fabric. It highlights key design interventions such as expanding sidewalks, creating pedestrian-only zones, and integrating green spaces into urban layouts (Seferoğlu & Allahverdiyev, 2025).

In addition, research on campus landscapes emphasizes that four core factors shape pedestrian comfort and walkability (Harun & Nashar, 2017) which are comfort, connectivity, safety, and accessibility. These factors stress the importance of climate-responsive streetscapes, adequate shading, continuous pedestrian networks, and safe crossings to enhance mobility and overall well-being. Under streetscape physical elements, pavement plays a fundamental role in determining pedestrian comfort and walkability.

Different urban landscape qualities are categorized into three main categories (Salem et al., 2022), which are safety and security, comfort, and level of interest. Adequate lighting, traffic calming measures, separation from vehicles, clear wayfinding, unobstructed visibility, durable materials, and well-maintained, non-slip paving collectively enhance pedestrian safety and security (Salem et al., 2022). Indicators like 'comfort' and 'interest' root back to restorative environment theories, suggesting pedestrians subconsciously seek spaces that minimize psychological fatigue (Kaplan, 1995). Consequently, features like greenery and clear wayfinding act as essential environmental affordances that reduce cognitive load, rather than merely serving aesthetic functions (Kaaronen, 2017).

Comfort is increased by continuous, connected sidewalks and environmental affordances for all users. Thermal regulation through shade-providing trees, which ensures a pedestrian-friendly environment across different seasons (Vasilikou & Nikolopoulou, 2020).The presence of greenery, particularly street trees, improves visual preference, softens harsh urban features, and creates a sense of enclosure and restorative potential. In turn, encourages longer and more frequent walking trips (Scopelliti et al., 2019). Integrating these qualities in urban landscapes creates an environment that supports pedestrian movement and enhances the walking experience. It also promotes sustainable and walkable streetscapes (Hadavi et al., 2015).

## 3.2 MATERIAL PROPERTIES, COMPOSITION AND MANUFACTURING PERFORMANCE

Scholars have demonstrated that pore-forming organic waste, such as sawdust, fly ash, rice husk, and sugarcane bagasse, increases porosity and reduces bulk density. That is a potential to enhance thermal insulation (Benjeddou, 2025; Dondi et al., 2010; Faria et al., 2012). Sawdust content of 10% achieve compressive strength of 21.2 MPa while maintaining a permeability coefficient of 0.0556 m/s. That condition is suitable for paving of light-weight traffic and pedestrians. Also, scholars found that small additions of sawdust (1%) improved tensile and shear strength and reduced swelling potential of clay by 20% to 32% (Abu Zeid, 2020). It suggests that the mechanical threshold varies with the indentation application.

The base clay used across these studies is typically characterized by high concentrations of silica ($SiO_2$) and alumina ($Al2O_3$), reporting levels 50.47% and 19.14%, respectively (Shafiquzzaman et al., 2022). This profile is suitable for brick manufacturing due to its stability during firing. Raw sawdust is enriched with cellulose and organic matter. This acts as a combustible pore-forming agent during firing that increases porosity from 7.4% to as high as 56.7% at a 20% sawdust mixing ratio. Sawdust ash functions as a chemical stabilizer. It possesses a lower specific gravity compared to clay.

While raw sawdust is valued for its ability to reduce thermal conductivity and bulk density, dropping from 2090 kg/m3 to ~1398 kg/m3 in fired bricks (Benjeddou, 2025). It

inherently compromises mechanical strength as the organic fibres create voids. This differs from ash-stabilized systems, where, at low concentrations (4%), the chemical integration actually boosts California Bearing Ratio (CBR) values by over 103%. Sawdust particle sizes also affect the properties of paving. Table 2 categorizes the effects of different gradations on the structural and functional performance of WCC.

*Table 2: Particle size performance grid*

| Category | Particle Size | Primary Material Application | Impact on Mechanical Strength | Impact on Physical/Functional Properties |
|---|---|---|---|---|
| Fine | 0.5 mm (Shafiquzzaman et al., 2022)<br>212-300 µm (Jannat et al., 2021)<br><600 µm ash (Butt et al., 2016) | Fired permeable bricks<br>Unfired clay blocks<br>Subgrade stabilization | 21.2 MPa at 10% sawdust (Shafiquzzaman et al., 2022)<br>4.09 MPa at 2.5% (Jannat et al., 2021)<br>+26% Unconfined Compressive Strength (UCS) at 4% Sawdust ash (Butt et al., 2016) | Higher Porosity, absorption, and permeability<br>↓ Density<br>Swelling reduction (Abu Zeid, 2020) |
| Medium | 0.75-1.0 mm (Shafiquzzaman et al., 2022)<br>425-600 µm (Jannat et al., 2021) | Permeable pavement units<br>Lightweight fired bricks<br>Optimized unfired blocks | **Optimal strength-porosity balance**<br>4.74 MPa UCS (Jannat et al., 2021)<br>21.2 MPa at 10% Sawdust (Shafiquzzaman et al., 2022) | Controlled porosity<br>Moderate permeability<br>Improved thermal performance (Benjeddou, 2025) |
| Coarse | 1.5 mm (Shafiquzzaman et al., 2022)<br>1.18-2.00 mm (Jannat et al., 2021) | Experimental permeable blocks | Strength reduction<br>10.2 MPa (1.5 mm) (Shafiquzzaman et al., 2022)<br>3.90 MPa at 2.5% (Jannat et al., 2021) | Excessive porosity<br>Highest permeability<br>Reduced structural integrity |

*Note: Locally available Sri Lankan timber wastes may exhibit different physical, chemical, and hygroscopic behaviours compared to species such as Deodar (*Cedrus deodara*) or Kail (*Pinus wallichiana*) used in previous studies.*

## 3.3 AESTHETIC AND SENSORY QUALITIES

Aesthetic and sensory qualities extend beyond functional safety to influence emotional comfort and a sense of place. Material selection for the particular landscape should balance functionality, aesthetics, and heritage preservation (da Silva & Pereira, 2022). Pedestrian comfort involves emotional responses to paving materials and the quality of the walking environment. A Pilot Study introduced paving attributes in Braga (Silva et al., 2025). The study evaluated five primary surface parameters (Table 3).

*Table 3: Paving attribute measuring parameters*

| Parameter | Description | Measuring method |
|---|---|---|
| Roughness | Surface unevenness | 3m straightedge + laser sensor |
| Friction | Slip resistance | British Pendulum Tester (BPT) |
| Texture | Surface depth and drainage capacity | Laser profilometer (ETD value) |
| Heat retention | Surface temperature and thermal comfort | Infrared thermometer |
| Maintenance | Cracks, damage, wear | Visual inspection |

*Source: Silva et al. (2025)*

Tactile and visual attributes such as texture, roughness, and surface regularity were highly rated (M = 4.79). That indicates smooth, stable, and visually uniform pavements enhance walking satisfaction (Silva et al., 2025). Computational texture analysis shows that physical texture features influence perceived aesthetic qualities, indicating that material properties can shape emotional and perceptual responses to surfaces (Liu et al., 2015). Surface colour and reflectivity affect visual and thermal perception, and influence how pedestrians experience urban landscapes (Rosso et al., 2016). Pedestrians often walk barefoot or in thin-soled sandals in cultural landscapes in the Sri Lankan context. Low thermal effusivity of WCC is a major sensory advantage over asphalt.

Moderate slip risks are presented by the Portuguese pavement, which combines aesthetic and historical value (Benson et al., 2023). The selection of walkability paving materials is directly related to the UHI (Kasim et al., 2018). The albedo value in paving materials is the primary factor in mitigating the effects of UHI. Several researchers have proven colours and textures of paving play an important role in reducing the temperature (Kasim et al., 2018). During the monsoon, algal growth diminishes visual appeal and slippery surfaces, posing a safety risk for pedestrians. Conditions that encourage algal colonization include high light exposure, neutral pH, nutrient availability, and low electrical conductivity and total dissolved solids (Munyai et al., 2019).

The Ancol Art Market study examined landscape hardscape aesthetics using a descriptive-analytical approach. Variables included building, site structure, and pavement (Adhitya et al., 2020) analyzed through form, texture, and colour. Aesthetic indicators (Adhitya et al., 2020), including unity, symmetry, balance, harmony, and contrast. The findings of these studies can inform the development of improved landscape design strategies and optimize site aesthetics through the identified parameters and indicators. These aesthetic principles are particularly relevant for evaluating pedestrian paving systems, where surface expression directly influences user perception and spatial experience. In the context of WCC, such indicators provide a useful lens to assess how material texture, colour variation, and surface consistency contribute to visual coherence and landscape identity.

# 4. INTEGRATED SYNTHESIS AND RESEARCH GAPS

## 4.1 INTEGRATED SYNTHESIS

Analysis of Sections 3.1-3.3 suggests that pedestrian walkability is not solely a function of design geometry but is critically mediated by the properties of the materials employed.

Existing walkability frameworks identify comfort, safety, accessibility, and connectivity as core determinants (Rafiemanzelat et al., 2017; Salem et al., 2022). This review demonstrates that these dimensions are directly influenced by the physicochemical and mechanical behaviour of paving materials. There is a need for an integrated, climate-responsive framework that explicitly addresses tropical environmental pressures characteristic of Sri Lanka.

Empirical evidence shows 10% sawdust replacement achieves approximately 21.2 MPa compressive strength in fired systems. It maintains permeability near 0.0556 m/s (Shafiquzzaman et al., 2022), fulfilling structural requirements for pedestrian and light-load applications. However, reliance on high-temperature firing (850-900°C) increases carbon footprint and requires specialized laboratory conditions, limiting scalability in the resource-constrained construction sector in Sri Lanka. Reductions in density from 2090 kg/m³ to approximately 1398 kg/m³ (Benjeddou, 2025) enhance thermal regulation, contributing to UHI mitigation, as highlighted by Kasim et al. (2018).

Pavement surface temperatures frequently exceed pedestrian comfort thresholds, intensifying heat stress and discouraging walkability in dense urban areas such as Colombo. Therefore, the reduced thermal conductivity associated with lightweight WCC should be positioned as a climate-adaptive requirement rather than an optional sustainability feature. Contents exceeding 15-20% or particle sizes above 1.5 mm result in significant strength loss (~10.2 MPa). Therefore, environmental benefits achieved through increased porosity must be balanced against mechanical stability. The optimal performance window can be summarized as follows.

*Table 4: Comparative performance of WCC mix ratios*

| Study | Optimal Mix | Processing / Methodology | Key Result |
|---|---|---|---|
| Shafiquzzaman et al. (2022) | 10% sawdust (0.5–1.0 mm) | Sieved soil (0.5 mm), mix with sawdust, mold (70×70×50 mm), air/oven dry, fire 900°C | 21.2 MPa compressive strength; 0.0556 m/s permeability |
| Butt et al. (2023) | 4% sawdust ash | -Sawdust (deodar and kail wood) is air-dried and burnt at room temperature.<br>-Ash sieved through a 600-micron sieve to remove deleterious materials. | 103% increase in CBR |
| Abu Zeid (2020) | 1% sawdust | Air-dried samples; sawdust mixed directly with clay at optimum water content and compacted at Maximum dry density; no firing of blocks | 30% increase in tensile strength, Shear strength >20%, Swelling potential ↓ 20–32% |
| Jannat et al. (2021) | 2.5% sawdust | -Dry blending of raw clay powder and sawdust particles | Best mechanical performance for unfired blocks. |

| Study | Optimal Mix | Processing / Methodology | Key Result |
|---|---|---|---|
| | (425–600 µm) | -Addition of water to the workable paste<br>-Molding into prisms (40×40×160 mm). Cured for 21 days (room temp.) and dried for 28 days before testing. | Density: ~1781 to ~1422 kg/m³<br>Capillary water absorption: increases with sawdust percentage<br>Linear shrinkage: decreases with increasing sawdust |
| Benjeddou (2025) | 4% sawdust | -Dry mixing of clay and sawdust<br>-Water added for a workable paste<br>-Moulding into plates (270×270×40 mm)<br>-Drying (staged 40–110 °C)<br>-Firing in kiln (total cycle ~23 h)<br>-Heat to 850 °C, hold 4 h – Controlled cool-down | ~4% sawdust: threshold where lightweight behaviour and thermal insulation improvements become significant while avoiding extreme porosity that may compromise mechanical function.<br>2–6% range balances improved insulation with manageable density changes |

Hygroscopic behaviour is critical under high relative humidity (>80%) and monsoon conditions in Sri Lanka. Although 1% sawdust reduced swelling by 20-32% in unfired systems (Abu Zeid, 2020), its effectiveness under prolonged wet-dry cycles remains uncertain and requires tropical durability testing. Biological resilience is also a concern. The organic content of sawdust may increase fungal or algal growth in warm, humid environments. While firing reduces this risk, the long-term performance of unfired systems needs further investigation.

Experience metrics can be strengthened by linking measurable surface properties to human perception. Particle size influences perceived texture, where finer particles create smoother impressions while coarser particles produce rougher, more natural qualities. Visual texture attributes such as coarseness and contrast influence aesthetic responses to surfaces (Liu et al., 2015). Surface treatments can further enhance these qualities. Sanding or polishing wood-chip aggregates may reveal grain patterns and improve visual coherence. Research also shows that appropriate surface roughness and coherent material design can improve pedestrian comfort, perceived safety, and the overall experience of walkable environments (Adhitya et al., 2020; Silva et al., 2025).

## 4.2 PROPOSED MULTI-DIMENSIONAL PEDESTRIAN PAVEMENT FRAMEWORK (MDPPF)

The proposed MDPPF is a comprehensive design system that integrates material composition, thermal and hydrological behaviour, and sensory perception to guide the development of user-centric, bio-based paving materials for creating walkable, healthy cities in tropical environments (Figure 2). Sustainable pedestrian pavements should be evaluated across several interrelated dimensions. User experience and visual quality must also be considered from a landscape architectural perspective. The MDPPF recognizes potential trade-offs between key properties of WCC pavements while higher organic content can enhance porosity, permeability, and pedestrian thermal comfort, it may

reduce structural durability. Therefore, MDPPF encourages a site-responsive balance of material composition based on landscape use, prioritizing durability in high-traffic areas and porosity in low-traffic environments.

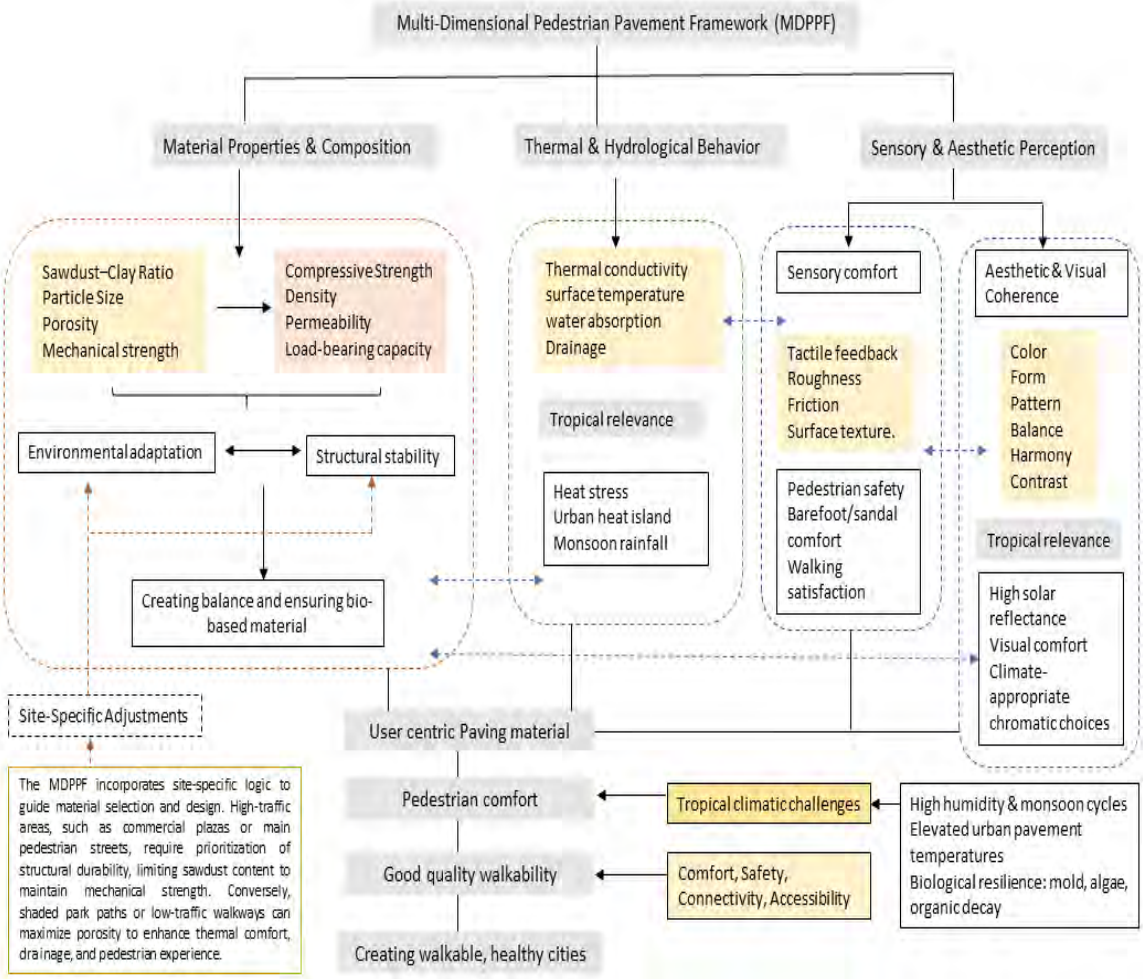



*Figure 2: Conceptual diagram of MDPPF*

## 4.3 IDENTIFIED RESEARCH GAPS

Identified research gaps under the three categories (indicated in Section 2.4) have been listed below.

*Table 5: Key research gaps*

| Thematic Domain | Identified Gap | Landscape Architectural Concern | Implication for Urban Design & Public Realm |
|---|---|---|---|
| Pedestrian Comfort & Walkability | Limited field-based validation in real pedestrian environments | Pavement performance under high humidity (>80%), monsoon rainfall, intense solar exposure, and barefoot/sandal walking remains untested | Uncertainty in long-term walkability, spatial resilience, and public realm performance |

| Thematic Domain | Identified Gap | Landscape Architectural Concern | Implication for Urban Design & Public Realm |
|---|---|---|---|
| Material Properties, Composition and Performance | Weak integration of microclimate performance and pedestrian comfort | Surface temperature and thermal perception rarely correlated with pedestrian experience | Limits the design of climate-responsive, thermally adaptive, and heat-mitigating streetscapes in dense urban areas such as Colombo |
| | Absence of a performance-based walkability material framework | No multi-criteria evaluation tool integrating structural stability, hygroscopic response, thermal behaviour, and sensory experience | Designers lack evidence-based material selection criteria for pedestrian pavements |
| | Laboratory-focused evaluation detached from site context | Mechanical properties assessed without accounting for monsoon wet–dry cycles, biological exposure, or landscape use patterns | Difficult translation into implementable urban design strategies and long-term maintenance planning |
| Aesthetic and Sensory Qualities | Fragmented evaluation of structural and aesthetic qualities | Texture, colour, and spatial rhythm are not linked with moisture behaviour, thermal comfort, or weathering patterns | Constrains holistic streetscape design and climate-sensitive place-making strategies |
| | Limited guidance on preferred pavement colours in tropical climates | Chromatic selection is not evaluated against solar reflectance, glare control, thermal absorption, or visual harmony | Weak evidence-based design for visual coherence and pedestrian experience in urban landscapes |

# 5. CONCLUSIONS AND IMPLICATIONS

## 5.1 SCHOLARLY AND PRACTICAL IMPLICATIONS

The MDPPF developed in this study provides a practical, evidence-based framework for urban designers working in hot and humid tropical environments. Rather than focusing solely on structural performance, it encourages a more holistic approach to material selection by considering both technical and sensory factors, such as how particle size distribution can influence thermal performance and pedestrian comfort. From a practical perspective, the framework supports circular economy principles by promoting the use of sawmill waste as a sustainable material for urban infrastructure. In the Sri Lankan context, this offers a low-carbon alternative for managing timber industry residues while creating value-added construction products. For policymakers, the adoption of WCC standards could contribute to municipal solid waste reduction targets by encouraging the local reuse and valorisations of wood waste streams.

Furthermore, the MDPPF bridges the traditional divide between laboratory-based material testing and real-world urban design applications by integrating engineering

performance indicators with environmental and user-experience criteria. This enables designers and decision-makers to evaluate paving materials not only for their mechanical suitability but also for their contribution to pedestrian comfort, thermal adaptation, and aesthetic quality in public spaces. As a result, the framework provides a pathway for translating material science research into practical landscape architectural and urban design interventions that respond to the challenges of tropical urban environments.

### 5.2 LIMITATIONS OF THE CURRENT REVIEW

Although this review provides a strong theoretical foundation, several limitations should be acknowledged. The analysis is limited to English-language academic publications published between 2010 and 2025, which may have excluded relevant non-indexed technical reports and local studies. In addition, most existing evidence is based on laboratory experiments, resulting in limited understanding of the long-term performance of WCC under real tropical conditions, including prolonged weathering, monsoonal wet–dry cycles, high humidity, and biological growth such as algae in pedestrian environments.

### 5.3 FUTURE RESEARCH DIRECTIONS

To further optimize climate-responsive materials and enhance pedestrian walkability in tropical environments, subsequent studies should prioritize the following areas:

- Conduct long-term, multi-season field studies to assess the performance of ambient-cured stabilized pavements under actual pedestrian use.
- Explore low-energy stabilization approaches, including bio-based binders and low-temperature thermal treatments, to improve moisture resistance and durability.
- Examine how different pavement textures and layout patterns influence pedestrian perceptions, comfort, and movement behavior in tropical public spaces.

## 6. REFERENCES

Adhitya, M. V., Manan, R. H., & Aini Besila, Q. (2020). Evaluation of aesthetic aspects in the landscape hardscape elements of the Ancol Art Market area in Jakarta Indonesia. *International Journal of Engineering Research & Technology (IJERT), 9*(5), 330-336. https://www.ijert.org/evaluation-of-aesthetic-aspects-in-the-landscape-hardscape-elements-of-the-ancol-art-market-area-in-jakarta-indonesia

Benjeddou, O. (2025). Experimental investigation of the impact of wood sawdust incorporation on the physical and thermal properties of fired clay bricks. *Scientific Reports*, *15*(1), 30855. https://doi.org/10.1038/s41598-025-00365-z

Benson, J., Wickham, C., Rowan, T., & Taylor, D. (2023). Predicting the degradation of slip resistance in paving materials. *Wear*, *512*, 204520. https://doi.org/10.1016/j.wear.2022.204520

Butt, E. W., Baker, J. C. A., Bezerra, F. G. S., Von Randow, C., Aguiar, A. P. D., & Spracklen, D. V. (2023). Amazon deforestation causes strong regional warming. *Proceedings of the National Academy of Sciences*, *120*(45), e2309123120. https://doi.org/10.1073/pnas.2309123120

da Silva, C. M., & Pereira, S. (2022). Walking on geodiversity: The artistic stone-paved sidewalks of Lisbon (Portugal) and their heritage value. *Geoheritage*, *14*(3), 98. https://doi.org/10.1007/s12371-022-00733-5

Dondi, M., Guarini, G., Raimondo, M., Zanelli, C., Fabbriche, D. D., & Agostini, A. (2010). Recycling the insoluble residue from titania slag dissolution (tionite) in clay bricks. *Ceramics International*, *36*(8), 2461–2467. https://doi.org/10.1016/J.CERAMINT.2010.08.007

Falk, B. (2002). Wood-framed building deconstruction: A source of lumber for construction? *Forest Products Journal*, *52*(3), 8-15. https://research.fs.usda.gov/treesearch/8885

Faria, K. C. P., Gurgel, R. F., & Holanda, J. N. F. (2012). Recycling of sugarcane bagasse ash waste in the production of clay bricks. *Journal of Environmental Management*, *101*, 7–12. https://doi.org/10.1016/j.jenvman.2012.01.032

Fonseca, F., Rodrigues, A., & Silva, H. (2025). Pedestrian perceptions of sidewalk paving attributes: Insights from a pilot study in Braga. *Infrastructures*, *10*(4), 79. https://doi.org/10.3390/infrastructures10040079

Hadavi, S., Kaplan, R., & Hunter, M. C. R. (2015). Environmental affordances: A practical approach for design of nearby outdoor settings in urban residential areas. *Landscape and Urban Planning*, *134*, 19–32. https://doi.org/10.1016/j.landurbplan.2014.10.001

Harun, N. Z., & Nashar, A. (2017). Developing a framework for streetscape design to promote walkability in Malaysian campus. *Advance Science Letters*, *23*(4), 2761–2765. https://doi.org/10.1166/asl.2017.7616

Huisingh, D., Zhang, Z., Moore, J. C., Qiao, Q., & Li, Q. (2015). Recent advances in carbon emissions reduction: Policies, technologies, monitoring, assessment and modeling. *Journal of Cleaner Production*, *103*, 1–12. https://doi.org/10.1016/j.jclepro.2015.04.098

Jannat, N., Al-Mufti, R. L., Hussien, A., Abdullah, B., & Cotgrave, A. (2021). Influence of sawdust particle sizes on the physico-mechanical properties of unfired clay blocks. *Designs*, *5*(3), 57. https://doi.org/10.3390/designs5030057

Kaaronen, R. O. (2017). Affording sustainability: Adopting a theory of affordances as a guiding heuristic for environmental policy. *Frontiers in Psychology*, *8*, 1974. https://doi.org/10.3389/fpsyg.2017.01974

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kasim, Z., Shahidan, M. F., & Yusof, Y. (2018). Use of landscape environmental setting for pedestrian to enhance campus walkability and healthy lifestyle. *WIT Transactions on Ecology and the Environment*, *215*, 219–232. https://doi.org/10.2495/EID180201

Lin, J. D., Hsu, C. Y., Paramitha, P. A., & Lee, J. C. (2013). The study of pavement surface temperature behavior of different permeable pavement materials during summer time. *Advanced Materials Research*, 723, 711–718. https://doi.org/10.4028/www.scientific.net/AMR.723.711

Liu, J., Lughofer, E., & Zeng, X. (2015). Aesthetic perception of visual textures: A holistic exploration using texture analysis, psychological experiment, and perception modeling. *Frontiers in Computational Neuroscience*, 9, 134. https://doi.org/10.3389/fncom.2015.00134

Maier, D. (2021). Building materials made of wood waste a solution to achieve the sustainable development goals. *Materials*, *14*(24), 7638. https://doi.org/10.3390/ma14247638

Munyai, T. R., Sonqishe, T., & Gumbo, J. R. (2019). Algae colonisation of brick pavement at the University of Venda: A potential slippery hazard. *Jamba: Journal of Disaster Risk Studies*, *11*(2), 689. https://doi.org/10.4102/jamba.v11i2.689

Rafiemanzelat, R., Emadi, M. I., & Kamali, A. J. (2017). City sustainability: The influence of walkability on built environments. *Transportation Research Procedia*, *24*, 97–104. https://doi.org/10.1016/j.trpro.2017.05.074

Rosso, F., Pisello, A. L., Cotana, F., & Ferrero, M. (2016). On the thermal and visual pedestrians' perception about cool natural stones for urban paving: A field survey in summer conditions. *Building and Environment*, *107*, 198–214. https://doi.org/10.1016/j.buildenv.2016.07.028

Salem, D., Khalifa, S. I., & Tarek, S. (2022). Using landscape qualities to enhance walkability in two types of Egyptian urban communities. *Civil Engineering and Architecture*, *10*(5), 1798–1813. https://doi.org/10.13189/cea.2022.100508

Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Giannopoulou, K., Vasilakopoulou, K., & Kardomateas, T. (2012). Using cool paving materials to improve microclimate of urban areas: Design realization and results of the Flisvos project. *Building and Environment*, *53*, 128–136. https://doi.org/10.1016/j.buildenv.2012.01.022

Scopelliti, M., Carrus, G., & Bonaiuto, M. (2019). Is it really nature that restores people? A comparison with historical sites with high restorative potential. *Frontiers in Psychology*, *9*, 2742. https://doi.org/10.3389/fpsyg.2018.02742

Seferoğlu, M. T., & Allahverdiyev, J. (2025). Pedestrian safety and sustainable urban planning: A literature review on walkable city design. In A. Reis (Ed.), *Proceedings of the International Conference of Contemporary Affairs in Architecture and Urbanism-ICCAUA* (Vol. 8, pp. 142–155). Cihan University Press. https://doi.org/10.38027/iccaua2025tr0038

Shafiquzzaman, M., Alqarawi, S. M. A., Haider, H., Rafiquzzaman, M., Almoshaogeh, M., Alharbi, F., & EL-Ghoul, Y. (2022). Sawdust recycling in the development of permeable clay paving bricks: Optimizing mixing ratio and particle size. *Sustainability*, 14(18), 11115. https://doi.org/10.3390/su141811115

Silva, H., Fonseca, F., Rodrigues, A., & Palha, C. (2025). Engineering-based evaluation of sidewalk pavement materials: Implications for pedestrian safety and comfort. *International Journal of Pavement Research and Technology*, *18*(1), 89–102. https://doi.org/10.1007/s42947-025-00588-3

Vasilikou, C., & Nikolopoulou, M. (2020). Outdoor thermal comfort for pedestrians in movement: Thermal walks in complex urban morphology. *International Journal of Biometeorology*, *64*(2), 277–291. https://doi.org/10.1007/s00484-019-01782-2

Abu Zeid, M. M. (2020). Influence of the sawdust on the behavior of clay soils. *American Journal of Materials Engineering and Technology*, 8(1), 1–8. https://doi.org/10.12691/materials-8-1-1

Subhasingha H.D. and Disaratna P.A.P.V.D.S., 2026. Integration of post occupancy evaluation into government office buildings to enhance user satisfaction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 993-1007. DOI: https://doi.org/10.31705/WCS.2026.73. Available from: https://ciobwcs.com/papers/

# INTEGRATION OF POST OCCUPANCY EVALUATION INTO GOVERNMENT OFFICE BUILDINGS TO ENHANCE USER SATISFACTION

**H.D. Subhasingha[1] and P.A.P.V.D.S. Disaratna[2]**

## *ABSTRACT*

*Shortcomings in project delivery in government office buildings lead to occupant dissatisfaction. Post Occupancy Evaluation (POE) presents a valuable yet underutilised approach in government office buildings, especially in developing countries. Therefore, this research aims to investigate the integration of POE into government office buildings to enhance user satisfaction in Sri Lanka. Qualitative research choice was adopted, comprising a phase of semi-structured interviews with 16 experts from the industry. Empirical data were analysed using manual content analysis. The findings indicate that user satisfaction in Sri Lankan government office buildings is influenced by a context-specific combination of factors, with thermal comfort remaining consistently important while accessibility and building design emerged as particularly relevant considerations affecting the user satisfaction of government office buildings. The findings provide practical, context-sensitive guidance for developing countries to enhance the performance and user satisfaction of government office buildings, supporting more informed, evidence-based design and management decisions.*

***Keywords:*** *Government office building; POE; Sri Lanka.*

## 1. INTRODUCTION

People spend a substantial proportion of their daily lives indoors, with studies indicating that individuals remain within enclosed environments for nearly 90% of their time (Mannan & Al-Ghamdi, 2021). The extended duration of building occupancy demonstrates that building performance functions as a fundamental element which determines occupant health and comfort and their complete life experience (González-Lezcano, 2023). Building conditions and operational efficiency determine health outcomes as well-designed spaces promote well-being while poorly functioning areas create discomfort which leads to reduced satisfaction and decreased productivity and negative effects on user experience (Fissore et al., 2023; Zhang et al., 2022). Specifically, office employees spend one-third of their waking hours within office environments and consequently, occupant satisfaction in these spaces is a key factor influencing productivity, job performance, and overall workplace experience (Quevedo et al., 2025).

[1] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, himashasubasinghe3@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, vijithad@uom.lk

The immediate surroundings of office workers have a measurable impact on cognitive function and task performance (Zhang et al., 2022). Beyond short-term effects, studies suggest that prolonged exposure to suboptimal building conditions can contribute to chronic health challenges, reinforcing the role of quality of the building as a fundamental determinant of both occupant well-being and long-term organizational success (Zhang et al., 2022). In comparative assessments, private offices generally demonstrate superior quality and maintenance standards, while government offices are frequently associated with lower levels of upkeep and overall condition (Zhao et al., 2024).

With regards to Sri Lanka, particularly the government buildings in Sri Lanka are confronted with issues relating to inadequate interior design, poor management, and maintenance practices (Subhasingha et al., 2026). Furthermore, the Sick Building Syndrome has been identified as a common concern in office buildings in Sri Lanka (Subhasingha et al., 2025). Several barriers hinder the resolution of issues pertaining to the government buildings, where lack of and knowledge poses as a major setback (Subhasingha et al., 2026).

As an intervention, the feedback provided by the occupants of a building is a crucial source of information to enable the technical and structural functions to be tailored to the well-being of end users (Lolli et al., 2022). The construction industry benefits from multiple feedback mechanisms such as construction company feedback forms, customer relationship management software, Building Information Modelling software, and inspection and reporting software (Cusumano et al., 2024; Ford & Gosling, 2024; Lin et al., 2016; Venturini & Benito, 2015). Among these mechanisms, POE stands out as a prominent feedback technique with the ability to gather effective and comprehensive feedback from the occupants (Preiser, 2002). This thorough assessment involves a multifaceted analysis, which provides information on gaps between anticipated design performance and actual performance in operation, especially with respect to occupant comfort and functional utility (Zhao et al., 2024).

Globally, POE has gained significant awareness as an assessment tool for building user satisfaction (Albuainain et al., 2021), while in Sri Lanka, very few studies have been undertaken regarding POE. Particularly in government office buildings, existing research mainly evaluates building performance in terms of technical efficiency, energy use, or physical conditions, while insufficient emphasis has been placed on how POE can be integrated as a continuous management tool to enhance user satisfaction among public-sector office occupants. Notably, the occupant experiences vary across different countries, reflecting contrasts in context, culture, and building practices, which necessitate a context-specific investigation (Ruth et al., 2025). Therefore, this study aims to investigate the integration of POE into government office buildings to enhance user satisfaction in Sri Lanka. In attending to this aim, the following objectives are put forward to 1. identify the factors affecting user satisfaction in government office buildings in Sri Lanka, 2. identify the benefits of POE in government office buildings in Sri Lanka, and to 3. investigate how to adopt the benefits of POE in government office buildings to enhance user satisfaction in Sri Lanka. Hereinafter, the paper comprises a comprehensive literature review, research methodology section, findings, discussions, followed by conclusions and recommendations.

# 2. LITERATURE REVIEW

## 2.1 FACTORS AFFECTING USER SATISFACTION IN GOVERNMENT OFFICE BUILDINGS

Public offices play an effective and fundamental role in any country since they pursue the national values of serving the citizens and residents in the country (Albuainain et al., 2021; Pirabath et al., 2019). Nevertheless, several researchers observed significant differences in job satisfaction, productivity, performance, behaviour, motives, and commitment between employees in public offices compared to private offices (Albuainain et al., 2021). Recent occupant-centred research has further expanded the understanding of user satisfaction beyond traditional indoor environmental quality indicators. Candido et al. (2018) argue that occupant experience should be viewed as a multidimensional concept incorporating workplace functionality, perceived productivity, health, well-being, and organisational performance. According to Wijaya et al. (2020) it had appeared that, in many countries the condition and maintenance of government office buildings have been unsatisfactory with various issues arising which can impact the performance of buildings and user satisfaction (Dahal & Dahal, 2020). Moreover, researchers have highlighted that inadequate maintenance leads to the deterioration of building interior, which in turn degrades the quality of indoor environments experienced by occupants (Li, 2025). Such deterioration can negatively influence occupants' comfort, perceptions of the workplace, and overall satisfaction with the building environment (Kadhim & Altaie, 2023). Therefore, improving maintenance practices in government buildings is essential not only for effective building management but also for enhancing occupant satisfaction and the overall workplace experience (Albuainain et al., 2021). User satisfaction and building performance are closely linked, with several key factors influencing both aspects (Pestana et al., 2021). Moreover, Khalil and Nawawi (2009) reported that past studies demonstrate a strong correlation of 74% between performance criteria and occupant satisfaction in public buildings. Numerous studies have identified a plethora of factors which affects user satisfaction in a building space. Accordingly, thermal comfort, spatial comfort, Indoor Air Quality (IAQ), building design and fenestration appear as the most cited factors out of the 16 identified factors (Bengi & Toprakli, 2020; Frontczak & Wargocki, 2011; Halicioglu et al., 2023; Mindeel et al., 2024; Pestana et al., 2021). Moreover, visual comfort, acoustic comfort, hygiene, and lighting comfort remain moderately cited factors (Davoodi et al., 2020; Li et al., 2018; Pirabath et al., 2019; Wargocki et al., 2012). However, accessibility, building aesthetics, and outdoor climate variations emerge as the least cited factors which affect user satisfaction (Norazman et al., 2023; Preiser, 2002).

Although thermal comfort, IAQ, and spatial comfort are consistently identified as dominant determinants of occupant satisfaction in office buildings (Frontczak & Wargocki, 2011; Pestana et al., 2021; Mindeel et al., 2024), there is no clear consensus regarding the relative importance of these factors across different building contexts. Studies conducted in developed countries often emphasise indoor environmental quality indicators such as thermal comfort, air quality, and energy performance as primary determinants of occupant satisfaction (Frontczak & Wargocki, 2011; Li et al., 2018; Zhao et al., 2024). In contrast, research undertaken in developing countries has highlighted the influence of building condition, maintenance practices, and operational challenges on user satisfaction (Albuainain et al., 2021; Dahal & Dahal, 2020). Furthermore, relatively

limited attention has been paid to accessibility and inclusivity within government office buildings despite their importance in accommodating diverse user groups and ensuring equitable access to public services (Pirabath et al., 2019; Norazman et al., 2023). These variations suggest that factors affecting user satisfaction are highly context-dependent and cannot be universally generalised, thereby necessitating investigation within the Sri Lankan government office building sector.

## 2.2 POE AND ITS BENEFITS

Preiser (2002) defined, "post-occupancy evaluation is the process of evaluating buildings systematically and rigorously after they have been built and occupied for some time." POE directly assesses the factors influencing user satisfaction to investigate the relationship between occupants' comfort and well-being and the building's performance (Kasi & Kaliluthin, 2024) utilising both subjective approaches, such as occupant surveys, interviews, expert walkthroughs, and objective physical measurements, including on-site assessments (Hamida & Hassanain, 2020; Lolli et al., 2022). Hence POE delivers numerous benefits to achieve a comprehensive understanding of the user satisfaction and building performance (Bae & Martin, 2023). Research indicates that POE primarily facilitates innovation by identifying and replacing dysfunctional building features while providing a robust feedback loop for iterative design improvement (Aliyu et al., 2016; Bengi & Toprakli, 2020; Preiser, 2002). By generating empirical data to support behavioural adjustments and optimizing life-cycle performance, these evaluations refine pre-design programming and minimize the recurrence of design errors (Hadjri & Crozier, 2009). Furthermore, POE serves as a strategic organizational tool that reduces long-term operating costs, streamlines resource allocation, and informs the development of rigorous design standards and policy frameworks (Aliyu et al., 2016). It also acts as a communicative bridge between stakeholders, ensuring building quality is monitored against established benchmarks (Li et al., 2018). Ultimately, by identifying emerging user needs and enhancing occupant satisfaction through participatory evaluation, POE effectively balances budgetary constraints with owner requirements to maximize space utilization and design quality (Roberts & Edwards, 2022).

The successful integration of POE is contingent upon several enablers including organizational, technical, and managerial enablers. Strong management support is essential for allocating resources, setting up evaluation policies, and ensuring POE findings are employed within facility management practices, as the absence of institutional commitment results in the underutilisation of POE outcomes (Murguía et al., 2020). Furthermore, stakeholder engagement is another critical enabler facilitating the active participation of several key stakeholders throughout the evaluation process to improve the reliability of the outcomes (Preiser, 1995). Alongside these, having access to precise data collection techniques allows for systematic data collection and analysis to conduct effective POEs (Uşma & Ölçer, 2024). Moreover, the organisation culture, communication networks, and knowledge sharing platforms act as enabling mechanisms that support the successful application of POE recommendations (Rane et al., 2023).

Despite the widely acknowledged benefits of POE, its practical implementation remains limited in many developing countries. Consequently, a disconnection exists between the theoretical value of POE and its practical application. While the literature extensively discusses the benefits of POE, comparatively few studies have examined how these benefits can be operationalised to address specific user satisfaction issues within

government office buildings. This gap highlights the need for research that moves beyond identifying POE benefits towards understanding how they can be translated into practical interventions.

### 2.3 IMPORTANCE OF USING POE TO ENHANCE USER SATISFACTION IN DEVELOPING COUNTRIES

POE has become well-regarded as a strategy for increasing occupant satisfaction by systematically understanding how well their building is meeting their needs (Li et al., 2018). Candido et al. (2018) highlights that effective workplace assessment should capture users' experiences, perceptions, and behavioural responses rather than relying solely on technical performance indicators. By addressing occupant perceptions, POE provides a transparent account of occupants' experience living or working in a building (Aliyu et al., 2016). This feedback assists industry stakeholders in recognising the gap between designed performance and actual user experience, leading to sustained and actionable upgrades that enhance comfort, productivity, and well-being (Hamida & Hassanain, 2020). Recent studies have noted that incorporating POE feedback improves user satisfaction and contributes to sustainability by reducing rework and operational inefficiency by incorporating POE feedback into future design and management strategies (Lolli et al., 2022). In developed nations, POE has become an institutionalised practice, representing common means to collect user feedback, assess building performance, and inform policy development (Preiser, 2002). The formal use of POE within those contexts has led to incremental improvements in the quality of design, user satisfaction, and sustainability benefits (Li et al., 2018). In contrast, many developing countries have limited POE adoption and have yet to realise its full potential, mainly due to a lack of awareness, technical expertise, and financial resources restricting its wider implementation (Roberts & Edwards, 2022). In addition, scholars have noted that developing countries still struggle to systematically understand user feedback and develop and learn from the experience of POE (Aliyu et al., 2016). Consequently, buildings in these regions are often delivered without a structured evaluation of their effectiveness in meeting user needs, cultural relevance, or long-term sustainability (Albuainain et al., 2021).

Recent POE studies have increasingly emphasised occupant-centred approaches, sustainability performance, and evidence-based facility management. Nevertheless, most studies examine either factors affecting user satisfaction or the benefits of POE in isolation. Limited research has investigated the relationship between these two dimensions, particularly within government office buildings in developing countries. Furthermore, the Sri Lankan context remains underexplored despite the unique climatic, organisational, and operational characteristics of government facilities. Therefore, a knowledge gap exists regarding how POE benefits can be systematically utilised to address user satisfaction factors and improve building performance in Sri Lankan government office buildings.

## 3. METHODOLOGY

This study adopted the qualitative research choice due to the exploratory nature of the study and the need to obtain in-depth insights into the relationships between user satisfaction factors and POE enablers (Yin, 2018). In this research, the qualitative approach enabled the exploration of professional perspectives on the relevance of factors

identified through the literature and facilitated a deeper understanding of how POE enablers could be linked to these factors within the context of Sri Lankan government office buildings. Semi-structured interviews were employed as the primary data collection method, as this format allows researchers to follow a set of guiding questions while maintaining flexibility to probe deeper into participants' responses and capture detailed expert insights (Kallio et al., 2016). Following the arguments of Campbell et al. (2020), purposive sampling was used to select participants deliberately for the interview phases to ensure that respondents possessed the required expertise and contextual knowledge. Participants were required to have more than ten years of industry experience, and more than three years of experience POE to ensure an informed understanding of the context of Sri Lankan government office buildings as revealed in Table 1. The interview guide was developed based on the literature review and structured around the three research objectives. The first set of questions focused on validating and refining factors affecting user satisfaction in government office buildings identified from the literature. The second set explored the applicability and significance of POE benefits within the Sri Lankan government office context. The final set examined how POE benefits could be utilised to address user satisfaction issues and improve building performance. Open-ended questions were employed to encourage participants to elaborate on their professional experiences and provide context-specific insights. The data obtained from the interviews were subsequently analysed using manual content analysis, which enabled the systematic identification, categorisation, and interpretation of recurring themes and relationships within the collected qualitative data (Castro et al., 2020). The analysis was undertaken in three stages. First, factors affecting user satisfaction and POE benefits identified through the literature review were used as preliminary coding categories. Second, interview transcripts were manually coded to identify statements confirming, modifying, merging, or introducing new factors and benefits. Third, cross-case comparisons were conducted across the 16 interviews to identify recurring patterns and establish relationships between user satisfaction factors and POE benefits. Factors repeatedly endorsed by participants were retained, while overlapping factors were consolidated into broader categories. New themes emerging from the interviews, such as safety, building amenities, benchmarking, and adaptation to local work culture, were incorporated into the final output. The resulting thematic structure was then used to develop the linkage matrix presented in Table 3. Through this process, the factors affecting user satisfaction and the benefits of POE were further refined and the potential linkages between these elements were established.

*Table 1: Expert selection criteria*

| **Expert ID** | **Designation** | **Experience in the Built Environment** | | **Experience in POE** | **Educational Qualifications in the Built Environment** | | **Professional Qualifications in the Built Environment** |
|---|---|---|---|---|---|---|---|
| | | **10-20 years** | **> 20 years** | **> 3 years** | **BSc** | **Postgraduate** | |
| I1 | Managing Director | | ✓ | ✓ | ✓ | ✓ | ✓ |
| I2 | Architect | | ✓ | ✓ | ✓ | ✓ | ✓ |
| I3 | Planning Engineer | | ✓ | ✓ | ✓ | ✓ | ✓ |

| Expert ID | Designation | Experience in the Built Environment | | Experience in POE | Educational Qualifications in the Built Environment | | Professional Qualifications in the Built Environment |
|---|---|---|---|---|---|---|---|
| | | 10-20 years | > 20 years | > 3 years | BSc | Postgraduate | |
| I4 | Maintenance Engineer | ✓ | | ✓ | ✓ | | ✓ |
| I5 | Senior Cost Manager | | ✓ | ✓ | ✓ | | ✓ |
| I6 | Facilities Manager | | ✓ | ✓ | ✓ | ✓ | |
| I7 | Architect | | ✓ | ✓ | ✓ | | |
| I8 | Facilities Manager | | ✓ | ✓ | ✓ | ✓ | |
| I9 | Professor | | ✓ | ✓ | ✓ | ✓ | |
| I10 | Facilities Manager | ✓ | | ✓ | ✓ | ✓ | |
| I11 | Senior Architect | ✓ | | ✓ | ✓ | | ✓ |
| I12 | Senior Quantity Surveyor | | ✓ | ✓ | ✓ | | ✓ |
| I13 | Senior Lecturer | ✓ | | ✓ | ✓ | ✓ | ✓ |
| I14 | Project Manager | ✓ | | ✓ | ✓ | | ✓ |
| I15 | Project Manager | ✓ | | ✓ | ✓ | | |
| I16 | Civil Engineer | ✓ | | ✓ | ✓ | ✓ | ✓ |

# 4. ANALYSIS AND FINDINGS

## 4.1 IMPORTANT FACTORS AFFECTING USER SATISFACTION IN GOVERNMENT OFFICE BUILDINGS IN SRI LANKA

In total, 16 factors affecting user satisfaction in office buildings were identified through the literature review. During the expert interviews, the list of factors was further refined to 13 factors to better reflect its relevance to Sri Lankan government office buildings, particularly within a tropical climate context. The outcomes of this interview phase are presented in Table 2. The content analysis generated three overarching themes: Indoor Environmental Quality, Functional and Spatial Performance, and User-Centred Building Design. Within these themes, thirteen categories representing factors affecting user satisfaction were identified. Table 2 presents the refined categories derived from the coding process. Thermal comfort emerged as the most crucial factor, with all respondents emphasizing its importance in Sri Lanka's tropical climate, particularly in densely occupied government buildings where discomfort is immediately noticeable. Equally,

visual comfort and acoustic comfort were identified as other related parameters attached to productivity. IAQ was another unanimously important factor, with respondents linking it directly to health outcomes and work performance. Moreover, accessibility was identified as a critical requirement to the public government buildings, making it both an ethical and legal obligation to accommodate diverse users, including individuals with disabilities. Additionally, building design and ergonomics were emphasized for their importance in ensuring space efficiency and supporting worker health, as poor design can hinder workflow while inadequate ergonomic conditions may lead to long-term physical issues among employees. Expert interviews facilitated the refinement of factors identified in the literature through the elimination, consolidation, and reclassification of several elements. Outdoor climate variations and fenestration were considered less significant when adequate thermal comfort is maintained, while lighting comfort was combined with visual comfort. The study used technical parameters to create broader thermal comfort categories instead of using them as separate elements. The interviews discovered safety measures and building amenities as practical needs, which previous studies did not extensively cover, highlighting user-centred aspects often overlooked in theoretical frameworks.

*Table 2: Factors affecting user satisfaction*

| Factors Identified from the Literature Review | Refined Factors after Expert Interviews |
|---|---|
| Thermal Comfort | |
| Radiant Temperature Asymmetry | Thermal Comfort |
| Thermal Zone Size | |
| Visual Comfort | Visual Comfort |
| Lighting Comfort | |
| Acoustic Comfort | Acoustic Comfort |
| IAQ | IAQ |
| Accessibility | Accessibility |
| Building Design | Building Design |
| Furniture Ergonomics | Furniture Ergonomics |
| Privacy | Privacy |
| Spatial Comfort | Spatial Comfort |
| Building Aesthetic | Building Aesthetic |
| Hygiene | Indoor Hygiene |
| Fenestration | Safety |
| Outdoor Climate and Seasonal Changes | Building Ergonomics |

## 4.2 BENEFITS OF POE IN GOVERNMENT OFFICE BUILDINGS IN SRI LANKA

The literature review revealed multiple benefits in the application of POE in building management. Strikingly, all experts interviewed confirmed the applicability of these enablers to government office buildings in Sri Lanka as depicted in Table 3. The agreement found among professionals with academic and industry bent provides an added value to the universal importance in the application of POE in this context. The findings

underscore the role of POE as a critical mechanism for continuous improvement, with respondents emphasizing its function in providing an evidence-based foundation for operational adjustments that enhance building performance. Furthermore, POE was identified as instrumental in informing future design practices by enabling designers to avoid recurring shortcomings, thereby supporting the development of more efficient government office spaces. In addition to these, several practical facilitators were highlighted, including the reduction of long-term operational costs through targeted interventions, improved space utilization by identifying underperforming areas, and the promotion of sustainability through the detection of energy inefficiencies. Notably, benchmarking emerged as a significant yet underrepresented benefit, with POE enabling the establishment and assessment of performance standards across facilities.

Moreover, the interviews revealed the importance of contextual insights, such as the influence of local work habits and social norms on space utilization, further reinforcing the relevance of POE in adapting buildings to the Sri Lankan context. The unanimous agreement on all identified enablers demonstrates POE's comprehensive value proposition for government buildings.

### 4.3 ADOPTION OF ENABLERS OF POE IN GOVERNMENT OFFICE BUILDINGS TO ENHANCE USER SATISFACTION IN SRI LANKA

The synthesis of literature and expert interviews identifies 24 key enablers of that function as both diagnostic and developmental instruments within the built environment as represented in Table 3. Strikingly, all interviewees confirmed the applicability of these benefits to government office buildings in Sri Lanka, particularly considering the tropical climate. In addition, during the interviews, two additional enablers surfaced, namely benchmarking of facilities and adaptation to local work culture and social norms. Primarily, these enablers facilitate innovation by identifying dysfunctional features and establishing a robust feedback loop that aligns design intent with actual performance. By providing empirical data for behavioural adjustments and life-cycle optimisation, POE refines pre-design programming and minimises the recurrence of design errors. In the specific context of Sri Lankan government buildings, these enablers extend to benchmarking facilities and adapting to local work cultures and social norms. Furthermore, by monitoring environmental performance. such as IAQ, visual, and acoustic comfort, POE enablers directly mitigate user dissatisfaction and enhance productivity. Ultimately, this participatory approach fosters a sense of ownership among occupants while providing a data-driven framework for strategic resource allocation and continuous design improvement.

*Table 3: Linkage between factors and benefits*

| Factor | Relevant POE Benefits | Adoption |
|---|---|---|
| Accessibility | Facilitates redesign of dysfunctional features<br>Assists informed pre-design decisions<br>Identifies emerging needs<br>Adapts to local work culture and norms | POE can determine where several users experience a lack of accessibility, which allows designers to alter layouts, advocate for reallocation, or consider accessibility means that are culturally or locally standard, considering inclusivity and comfort for users. |
| Building Aesthetics | Acts as feedback mechanism to design<br>Provides insights for pre-design programming<br>Uses benchmarking and best practices<br>Helps understand budget constraints on design quality | User evaluations will allow designers to reflect on aesthetic aspects with occupant expectations. User feedback can lead to improvements in aesthetic aspects without jeopardizing aesthetic value or satisfaction. |
| Privacy | Assists informed pre-design decisions<br>Predicts effectiveness of new designs<br>Increases occupant participation<br>Adapts to local norms | POE evaluates user feedback on noise handling, spatial division, and visual barriers. These critiques on layouts can be taken into consideration and inform future projects regarding spatial division that improves privacy and sensitive cultural perceptions of personal space. |
| Building Design | Facilitates redesign of rarely used features<br>Acts as feedback mechanism<br>Provides insights for pre-design programming<br>Predicts effectiveness of new designs | POE evaluates user remarks on poorly designed or ineffective spaces. The evaluation data improves spatial configurations, functionality, and efficiencies regarding design that more accurately align with actual user behaviour and user needs. |
| Building Amenities | Facilitates replacement/redesign<br>Identifies emerging needs<br>Identifies developer requirements<br>Guides resource allocation during refurbishments | POE makes the user aware of amenities that may not be designed or performed well, providing focus for refurbishment while ensuring required functions are not eliminated. With respect to diminished functionalities, POE can direct to effectively advocate and restrain future resources and budget allocations. |
| Ergonomic Furniture | Provides insights for pre-design programming<br>Identifies owner/developer requirements<br>Guides resource allocation during refurbishments<br>Helps understand budget constraints | User feedback from POE can indicate discomfort or inefficiencies regarding ergonomic issues. The POE feedback infers how to refine the specifications with the justifiable budget allocation to enhance comfort and productivity issues. |
| Visual Comfort | Provides data for ongoing improvement<br>Assists developing performance measures<br>Encourages accountability to standards<br>Improves environmental sustainability | The monitoring conducted through POE ensures that the levels of lights and the availability of daylight meet the needs of the people using the building. The interventions based on the data keep the visual comfort and the glare under control while practicing the sustainable energy methods. |

| Factor | Relevant POE Benefits | Adoption |
|---|---|---|
| Acoustic Comfort | Provides data for improvement<br>Assists developing performance measures<br>Measures and monitors building quality<br>Encourages accountability to standards | The POE provides qualitative and quantitative data regarding the noise issues. This information supports improvements in acoustic insulation, the maintenance of systems, and the enforcement of design standards to ensure acceptable noise levels. |
| Thermal Comfort | Measures and monitors building quality<br>Encourages accountability to standards<br>Improves environmental sustainability<br>Reduces operating costs | POE enables continuous monitoring of indoor temperature, humidity, and thermal conditions. The collected data supports adjustments to HVAC systems and passive design strategies to maintain optimal thermal comfort. This ensures that indoor environments align with user expectations while also improving energy efficiency and reducing operational costs. |
| Safety | Measures and monitors building quality<br>Encourages accountability to standards<br>Assists informed pre-design decisions<br>Supports policy formation and design standards<br>Aids communication among stakeholders | POE identifies safety concerns such as inadequate emergency access, poor lighting, or unsafe layouts through user feedback and inspections. These insights help enforce safety standards and inform design improvements. Continuous monitoring ensures that buildings maintain safe conditions and comply with regulatory requirements. |
| Spatial Comfort | Acts as feedback mechanism to design<br>Facilitates redesign of dysfunctional features<br>Provides insights for pre-design programming<br>Identifies emerging needs<br>Guides resource allocation | POE evaluates how users interact with spaces in terms of layout, density, and movement. Feedback on overcrowding or underutilized areas allows designers to reconfigure spatial arrangements. This improves usability, circulation, and overall comfort by aligning spatial design with actual user behaviour and requirements. |
| Indoor Hygiene | Provides data for ongoing improvement<br>Measures and monitors building quality<br>Improves environmental sustainability<br>Reduces operating costs | POE assesses cleanliness, sanitation facilities, and maintenance effectiveness through user feedback and performance data. This enables timely interventions in cleaning practices, waste management, and ventilation systems. As a result, indoor hygiene standards are maintained, promoting healthier environments and improving overall user satisfaction. |
| IAQ | Provides data for improvement<br>Assists developing performance measures<br>Measures and monitors building quality<br>Improves environmental sustainability<br>Reduces operating costs | POE allows continuous monitoring of air temperature, humidity, and $CO_2$ levels. This facilitates the HVAC systems to work efficiently while improving the thermal comfort and air quality, thus saving on operational costs. |

## 5. DISCUSSION

The literature review identified 16 factors influencing user satisfaction in government office buildings, with thermal comfort consistently highlighted as the most critical factor at the global level (Bengi & Toprakli, 2020; Frontczak & Wargocki, 2011; Li et al., 2018). Similarly, IAQ and spatial comfort were frequently emphasized as key determinants of occupant satisfaction (Mindeel et al., 2024; Pestana et al., 2021; Preiser, 2002). However, the findings from the expert interviews did not establish a strict prioritization of factors but instead indicated a context-sensitive emphasis. Thermal comfort remained a consistently significant consideration, particularly given Sri Lanka's tropical climate, while factors such as accessibility and building design gained notable importance due to the public nature and functional demands of government office buildings. The global research shows a limited focus on accessibility, yet the interview results exhibited its greater importance for Sri Lanka because it demonstrated actual issues related to insufficient facilities which served different user groups (Pirabath et al., 2019). The interviews revealed that IAQ and spatial comfort hold essential value according to previous research, yet these aspects receive equal treatment with other elements which share equivalent significance. The study results show that user satisfaction at Sri Lankan government buildings develops through environmental factors and functional aspects and contextual elements. The research results show that accessibility and building design function as major elements in this environment. The substantive enablers of undertaking POE, including supporting continuous improvement, informing future design, reducing operational costs, and improving occupant satisfaction (Bengi & Toprakli, 2020; Hadjri & Crozier, 2009; Preiser, 2002) were corroborated through the semi-structured interviews, and the interviews additionally provided context-specific insights that were not addressed firmly in the literature, such as benchmarking and consideration of the local work culture. This research advances beyond the existing knowledge base by empirically connecting distinct factors and POE enablers, while almost all prior research has treated these as separate concepts. The findings illustrated that theoretical enablers are not self-driven but are stimulated through core factors. This establishes an approach progressing from identifying POE enablers to prioritizing the attainment of key factors through the enablers, ultimately enhancing the occupant satisfaction.

## 6. CONCLUSIONS AND RECOMMENDATIONS

This study aims to investigate the potential of POE to address the issues in the government office buildings and to enhance user satisfaction. The study revealed that compared to the office employees at private institutions, the government office employees are not satisfied with the current condition of government office buildings. This user dissatisfaction is attributable to the non-conformance of key factors affecting user satisfaction with the requirements of the occupants, impacting negatively on the occupants' well-being. In this context, POE emerged as an effective approach to address this concern. Building on these enablers, key factors can be achieved to ensure occupant satisfaction. Fundamentally, the factors guide the enablers through operationalizing them for continuous improvement and occupant satisfaction. This study contributes to developing countries by demonstrating the applicability of its findings to similar contexts, while adding to the limited literature on POE, specifically on government office buildings. Furthermore, the outcomes of this research will be beneficial for industry stakeholders to recognise the importance of POE for addressing similar challenges in upcoming construction undertakings. Given the

resource constraints, this study is limited to government office buildings in Sri Lanka. Hence, further studies are encouraged to investigate the potential of POE in other building sectors to obtain a broader understanding of its effectiveness.

# 7. REFERENCES


Albuainain, N., Sweis, G., AlBalkhy, W., Sweis, R., & Lafhaj, Z. (2021). Factors affecting occupants' satisfaction in governmental buildings: The case of the Kingdom of Bahrain. *Buildings*, *11*(6), 231. https://doi.org/10.3390/buildings11060231

Aliyu, A. A., Muhammad, M. S., Bukar, M. G., & Singhry, I. M. (2016, April 28). *A review of post occupancy evaluation as a tool and criteria for assessing building performance*. Proceedings of the Academic Conference on Agenda for Sub-Sahara Africa. Abuja FCT-Nigeria. https://www.researchgate.net/publication/303382704_A_REVIEW_OF_POST-OCCUPANCY_EVALUATION_AS_A_TOOL_AND_CRITERIA_FOR_ASSESSING_BUILDING_PERFORMANCE

Bae, S., & Martin, C. S. (2023). The impact of measurable findings from pre- and post-occupancy evaluations of indoor environmental quality in the primary workspace. *Buildings*, *13*(10), 2486. https://doi.org/10.3390/buildings13102486

Bengi, S. I., & Topraklı, A. Y. (2020). The perspective of Turkey in the post occupancy evaluation studies. *Periodica Polytechnica Architecture*, *51*(1), 83–91. https://doi.org/10.3311/ppar.15318

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., & Walker, K. (2020). Purposive sampling: complex or simple? Research case examples. *Journal of Research in Nursing*, *25*(8), 652–661. https://doi.org/10.1177/1744987120927206

Candido, C., Thomas, L., Haddad, S., Zhang, F., Mackey, M., & Ye, W. (2018). Designing activity-based workspaces: Satisfaction, productivity and physical activity. *Building Research & Information*, *47*(3), 275–289. https://doi.org/10.1080/09613218.2018.1476372

Castro, J. D. A., Landeira, C., Da Silva, J. R., & Ribeiro, C. (2020). Role of content analysis in improving the curation of experimental data. *International Journal of Digital Curation*, *15*(1), 14. https://doi.org/10.2218/ijdc.v15i1.705

Cusumano, L., Farmakis, O., Granath, M., Olsson, N., Jockwer, R., & Rempling, R. (2024). Current benefits and future possibilities with digital field reporting. *International Journal of Construction Management*, *25*(5), 572–583. https://doi.org/10.1080/15623599.2024.2340923

Dahal, R. C., & Dahal, K. R. (2020). A review on problems of the public building maintenance works with special reference to Nepal. *American Journal of Construction and Building Materials*, *4*(2), 39. https://doi.org/10.11648/j.ajcbm.20200402.12

Davoodi, A., Johansson, P., & Aries, M. (2020). The use of lighting simulation in the evidence-based design process: A case study approach using visual comfort analysis in offices. *Building Simulation*, *13*(1), 141–153. https://doi.org/10.1007/s12273-019-0578-5

Fissore, V. I., Fasano, S., Puglisi, G. E., Shtrepi, L., & Astolfi, A. (2023). Indoor environmental quality and Comfort in offices: A review. *Buildings*, *13*(10), 2490. https://doi.org/10.3390/buildings13102490

Ford, G., & Gosling, J. (2024). Professional perceptions of right-first-time and quality management in construction projects through open-ended feedback. *International Journal of Quality & Reliability Management*, *41*(10), 2665–2696. https://doi.org/10.1108/ijqrm-08-2023-0246

Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment*, *46*(4), 922–937. https://doi.org/10.1016/j.buildenv.2010.10.021

González-Lezcano, R. A. (2023). Editorial: Design of efficient and healthy buildings. *Frontiers in Built Environment*, *9*, 1210956. https://doi.org/10.3389/fbuil.2023.1210956

Hadjri, K., & Crozier, C. (2009). Post-occupancy evaluation: Purpose, benefits and barriers. *Facilities*, *27*(1-2), 21–33. https://doi.org/10.1108/02632770910923063

Halicioglu, F. H., Demirkapi, H. B., Gurel, K., & Kasul, N. (2023). Exploring Key Quality Indicators (KQIS) in green office buildings through pareto analysis. *Architecture, Civil Engineering, Environment*, *16*(2), 15–27. https://doi.org/10.2478/acee-2023-0012

Hamida, M. B., & Hassanain, M. A. (2020). Post occupancy evaluation of adaptively reused buildings: Case study of an office building in Saudi Arabia. *Architecture Civil Engineering Environment*, *13*(1), 29–40. https://doi.org/10.21307/acee-2020-003

Kadhim, E. M., & Altaie, M. R. (2023). Factors affecting building maintenance practices: Review. *Journal of Engineering*, *29*(12), 153–172. https://doi.org/10.31026/j.eng.2023.12.10

Kallio, H., Pietilä, A., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kasi, J., & Kaliluthin, A. K. (2024). A comprehensive approach to assess occupant's satisfaction and performances of residential building. *Civil Engineering Journal*, *10*(2), 444–455. https://doi.org/10.28991/cej-2024-010-02-07

Khalil, N., & Nawawi, A. H. (2009). Performance analysis of government and public buildings via post occupancy evaluation. *Asian Social Science*, *4*(9), 103-112. https://doi.org/10.5539/ass.v4n9p103

Li, G. (2025). Indoor environmental quality in architecture: A Review. *Building Engineering*, *3*(1), 2375. https://doi.org/10.59400/be2375

Li, P., Froese, T. M., & Brager, G. (2018). Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. *Building and Environment*, *133*, 187–202. https://doi.org/10.1016/j.buildenv.2018.02.024

Lin, Y., Chang, J., & Su, Y. (2016). Developing construction defect management system using BIM technology in quality inspection. *Journal of Civil Engineering and Management*, *22*(7), 903–914. https://doi.org/10.3846/13923730.2014.928362

Lolli, F., Marinello, S., Coruzzolo, A., & Butturi, M. (2022). Post-Occupancy Evaluation's (POE) applications for improving indoor environment quality (IEQ). *Toxics*, *10*(10), 626. https://doi.org/10.3390/toxics10100626

Mannan, M., & Al-Ghamdi, S. G. (2021). Indoor air quality in buildings: A comprehensive review on the factors influencing air pollution in residential and commercial structure. *International Journal of Environmental Research and Public Health*, *18*(6), 3276. https://doi.org/10.3390/ijerph18063276

Mindeel, T. A., Spentzou, E., & Eftekhari, M. (2024). Energy, thermal comfort, and indoor air quality: Multi-objective optimization review. *Renewable and Sustainable Energy Reviews*, *202*, 114682. https://doi.org/10.1016/j.rser.2024.114682

Norazman, N., Mohd Nashruddin, S. N. A., & Che-Ani, A. I. (2023). Exploring the factors influencing building sustainability of low-cost low-rise residential towards user satisfaction. *Journal of Facilities Management*, *22*(5), 949–974. https://doi.org/10.1108/JFM-08-2022-0089

Pestana, T., Flores-Colen, I., Pinheiro, M. D., & Sajjadian, S. M. (2021). User perception on key performance indicators in an in-service office building. *Infrastructures*, *6*(3), 45. https://doi.org/10.3390/infrastructures6030045

Pirabath, M. D. C., Rajini, D., Mahendrarajah, G., & Premanathan, T. (2019, December 12-14). *Space planning and management practices in government office buildings: Case studies in Sri Lanka*. 10th International Conference on Sustainable Built Environment (ICSBE). Kandy, Sri Lanka. https://www.researchgate.net/publication/349304384_Space_Planning_and_Management_Practices_in_Government_Office_Buildings_Case_Studies_in_Sri_Lanka

Preiser, W. F. (1995). Post-occupancy evaluation: How to make buildings work better. *Facilities*, *13*(11), 19–28. https://doi.org/10.1108/02632779510097787

Preiser, W. (2002). The evolution of post occupancy evaluation: Toward building performance and universal design evaluation. *Learning from our buildings: A State-of-the-Practice* (pp. 9–22). National Academy Press. https://nap.nationalacademies.org/read/10288/chapter/3

Quevedo, M. V. D., Luna-Navarro, A., Pottgiesser, U., & Blum, U. (2025). Methods and approaches for evaluating occupant satisfaction with office space design: A systematic review. *Ergonomics*, *69*(4), 724–748. https://doi.org/10.1080/00140139.2025.2480271

Rane, N. L., Choudhary, S. P., & Rane, J. (2023). Leading-edge technologies for architectural design: A comprehensive review. *International Journal of Architecture and Planning*, *3*(2), 12–48. https://www.researchgate.net/publication/378119365_Leading-Edge_Technologies_for_Architectural_Design_A_Comprehensive_Review

Roberts, C. J., & Edwards, D. J. (2022). Post-occupancy evaluation: Identifying and mitigating implementation barriers to reduce environmental impact. *Journal of Cleaner Production*, *374*, 133957. https://doi.org/10.1016/j.jclepro.2022.133957

Ruth, O., Kuga, K., & Ito, K. (2025). Subjective and objective measurement of indoor environmental quality and occupant comfort in a multinational graduate student office. *Environments*, *12*(4), 117. https://doi.org/10.3390/environments12040117

Subhasingha, H., Disaratna, P., & Perera, B. (2026). User satisfaction in government office buildings: An empirical analysis of influencing factors in Sri Lanka. *International Journal of Construction Management*, *Ahead-of-Print*. https://doi.org/10.1080/15623599.2026.2643739

Subhasingha, H., Disaratna, P., & Wijerathna, M. (2025). Post Occupancy Evaluation (POE) in government office buildings: A literature review. In K.G.A.S. Waidyasekara, H.S. Jayasena, P.L.I. Wimalaratne, & G.A. Tennakoon (Eds.), *Proceedings of the 13th world construction symposium*, (pp. 1083-1097). CIOB. https://doi.org/10.31705/WCS.2025.81

Uşma, G., & Ölçer, D. E. (2024). Development and assessment of a Post-Occupancy Evaluation Scale for sustainable office environments; Insights from the FNN Sustainability Centre. *Prostor*, *32*(1(67)), 26–37. https://doi.org/10.31522/p.32.1(67).3

Venturini, W. T., & Benito, Ó. G. (2015). CRM software success: A proposed performance measurement scale. *Journal of Knowledge Management*, *19*(4), 856–875. https://doi.org/10.1108/jkm-10-2014-0401

Wargocki, P., Frontczak, M., Schiavon, S., Goins, J., Arens, E., & Zhang, H. (2012, January). *Satisfaction and self-estimated performance in relation to indoor environmental parameters and building features*. 10th International Conference on Healthy Buildings, Brisbane, Queensland. https://escholarship.org/uc/item/451326fk

Wijaya, L., Latief, Y., & Machfudiyanto, R. A. (2020). Development of preventive maintenance guidelines for architectural components on government building based on work breakdown structure. *Civil Engineering and Architecture*, *8*(3), 312–319. https://doi.org/10.13189/cea.2020.080315

Yin, R. K. (2018). *Case study research and applications design and methods* (6th ed.). SAGE Publications. https://opac.atmaluhur.ac.id/uploaded_files/temporary/DigitalCollection/YTE3NDlmYTY0ZjE2MDA5ODE4NGI1Y2FhMjdkMjRmYWNkMDA2MTVhOQ==.pdf

Zhang, F., Liu, S., Hu, W., & Yadav, M. (2022). Editorial: Effects of indoor environmental quality on human performance and productivity. *Frontiers in Built Environment*, *8*, 1095443. https://doi.org/10.3389/fbuil.2022.1095443

Zhao, J., Aziz, F. A., Deng, Y., Ujang, N., & Xiao, Y. (2024). A review of comprehensive post-occupancy evaluation feedback on occupant-centric thermal comfort and building energy efficiency. *Buildings*, *14*(9), 2892. https://doi.org/10.3390/buildings14092892

Oo, B.L., Li, R. and Lim, B.T.H., 2026. International students' decision-making and learning experience in construction management coursework master's degree. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1008-1021. DOI: https://doi.org/10.31705/WCS.2026.74. Available from: https://ciobwcs.com/papers/

# INTERNATIONAL STUDENTS' DECISION-MAKING AND LEARNING EXPERIENCE IN CONSTRUCTION MANAGEMENT COURSEWORK MASTER'S DEGREE

**Bee Lan Oo[1], Ruining Li[2] and Benson Teck Heng Lim[3]**

## *ABSTRACT*

*Coursework master's degree programs are rapidly growing and there are growing cohorts of international students in these programs globally. This study focuses on international students enrolled in three construction management related coursework master's degree programs in an Australian university. The research aims: (i) to examine factors influencing the students' decision in pursuing their coursework master's degree; and (ii) to explore the challenges they have encountered while abroad. Data was collected using an anonymous online structured survey questionnaire. The results show that the detected heterogeneity in the respondents' responses is dependent on the respondents' country-of-origin to a greater extent than their gender. The key factors affecting their decision-making are global reputation and university ranking, and career advancement opportunities; and the key challenges are lack of access to student housing or accommodation and limited job opportunities for international students. The findings reinforce the importance of providing employability and career advancement support and academic and social support services in tertiary institutes' strategic international student marketing, recruitment and retention agendas.*

***Keywords:*** *Construction Management; Decision Making; International Students; Master's Degree; Student Experience.*

## 1. INTRODUCTION

In general, there are two main types of master's degrees, namely course-based (taught) and research-based (Haidar 2024). Course-based master's degrees are based on structured courses taught through teaching and learning activities such as lectures, seminars and laboratory work. Research-based master's degrees, on the other hand, require students to carry their own research project in a specialized field of study. The former, course-based master's degrees or commonly known as coursework master's degrees are rapidly growing around the globe and are attracting students from increasingly diverse backgrounds (Jung, 2021). Glazer-Raymo (2005) asserted that coursework master's degree education embraces the capacity to continually evolve as a highly adaptable and affordable credential globally, which is fuelled by globalisation, privatisation,

[1] Associate Professor, School of Built Environment, UNSW Sydney, Australia, bee.oo@unsw.edu.au
[2] PhD Candidate, School of Built Environment, UNSW Sydney, Australia, ruining.li1@student.unsw.edu.au
[3] Associate Professor, School of Built Environment, UNSW Sydney, Australia, b.lim@unsw.edu.au

accountability, and changes in the demographic composition of graduate students. Accordingly, there are growing cohorts of international students in coursework master's degree programs in universities worldwide because of the internationalisation of higher education that promotes cross-border mobility of students (Jung & Li, 2020; Li & Jung, 2023). For example, coursework master's degree programs have witnessed a significant growth over the past few decades and are of immense importance to the Australian higher education (Edwards, 2011). International students in coursework master's degree programs make up around 50% of total enrolments in the Australian higher education sector between 2019 and 2024 (Department of Education, 2025). Authors have urged the need to treat master's degree students as a specialised group, which is characterised by more diverse and internationally mobile student body, to better support them in their learning journey (Calikoglu, 2018; Li & Jung, 2023; Valls-Figuera et al., 2023; Walsh & Tucker, 2011).

This study focuses on international student body enrolled in three construction management related coursework master's degree programs in an Australian university, where these programs are experiencing a surge in enrolments post the COVID-19 pandemic. It aims to explore international students' decision making in pursuing a coursework master's degree and their learning experiences. Using anonymous online questionnaire for data collection, the specific objectives are: (i) to examine factors influencing the students' decision in pursuing a coursework master's degree; and (ii) to explore the challenges they have encountered while abroad. The quantitative statistical analysis in the present study has considered the students' gender and country-of-origin in identifying critical factors and challenges across the respective groupings. These are two demographic variables play an important role in students' decision making to study abroad and their learning experiences in host country (e.g., Jung & Lee, 2019; Valls-Figuera et al., 2023; Van Mol, 2021). With the global trend of international students studying a coursework master's degree in Australia and in many other countries, the findings shed light on our understanding of students' decision-making processes and their concerns while studying abroad, which have implications for tertiary institutes' international student marketing, recruitment and retention strategies.

## 2. LITERATURE REVIEW

International student experiences have been widely examined in the literature. The previous studies can be broadly classified into two main groups. In the first group, a considerable number of studies have examined the motivations of international students to study abroad and their choice of destination. The second group of studies explored on international students' learning experiences abroad, especially on the challenges they faced in their new academic and social environment. Correspondingly, there are systematic review studies based on these collections of studies. For example, Ha et al.'s (2023) review is based on a collection of 46 empirical studies on factors driving international students' choice of Australia as their host country for high education. The top five most frequently reported factors in their collection were career opportunities and life experiences, quality education and qualification, cost of study and living, migration prospect and policy, and reputation of tertiary education institutions and academic staff. Oduwaye et al. (2023), on the other hand, performed a trend analysis of challenges faced by international students based on 175 articles published over 21 years. They grouped the reported challenges into four categories, these are sociocultural, academic, economic and

psychological challenges, of which sociocultural and academic challenges have been well-covered in the literature. Another recent systematic review of 43 publications between 2010 and 2022 revealed that the five key themes and trends in international student mobility research are: (i) betterment of life; (ii) policy of the host country; (iii) role of institutions; (iv) return to home country; and (v) social, economic, environmental, individual and cultural factors (Gutema et al., 2024). Most of the scholarly work, however, has concentrated mainly on higher education in general with key focus on undergraduate education. Additionally, for postgraduate education, authors have mainly explored the learning experiences of doctoral students and there are few studies focused on master's education (Jung, 2021). Authors claimed that coursework master's degree is one of the least understood or researched academic levels in higher education, despite it is becoming the key credential continuing education to the professions (Drennan & Clarke, 2009; Edwards, 2011). Table 1 summarizes the factors influencing students' decision to pursue postgraduate education in the literature, noting that most of the respondents in these studies were international students and some studies have set the focus on coursework master's degree. Also, it is noted that some of the studies on coursework master's degree adopted a qualitative approach using interview data (e.g., Jung & Li, 2020; Wang & Shan, 2007), and there is a mixture of studies from English and non-English countries. It is worth noting that the top ranked factors from this collection of studies on postgraduate education are dissimilar to the studies of overseas higher education that did not specifically focus on postgraduate education. For example, the latter studies have reported career opportunities and cultural experiences as top factors (e.g., Ha et al., 2023; Hung & Yen, 2020), however, career advancement, personal development and self-improvement topped the list in Table 1 with high number of occurrences in the literature.

*Table 1: Factors influencing students' decision to pursue postgraduate education*

| Factors | References | Country/Region |
|---|---|---|
| Career advancement opportunities | Espinoza et al. (2025); Li and Jung (2023)*; Valls-Figuera et al. (2023); Gazo et al. (2022); Jung and Li (2020)*; Wu (2020); Jung and Lee (2019)*; Calikoglu (2018); Wiers-Jenssen (2018); Moogan (2018); Wu (2014); Walsh and Tucker (2011); Wang and Shan (2007)* | Chile, Hong Kong, Spain, UK, South Korea, Finland, Australia |
| Enhancement of future academic prospects | Valls-Figuera et al. (2023); Li and Jung (2023)*; Gazo et al. (2022); Jung and Li (2020)*; Lin et al. (2022); Wu (2020); Jung and Lee (2019)*; Calikoglu (2018); Wiers-Jenssen (2018); Moogan (2018); Wu (2014); Walsh and Tucker (2011) | Spain, Hong Kong, Taiwan, UK, South Korea, Finland, Norway, Australia |
| Personal development and self-improvement | Valls-Figuera et al. (2023); Li and Jung (2023)*; Gazo et al. (2022); Lin et al. (2022); Jung and Li (2020)*; Wu (2020); Jung and Lee (2019); Moogan (2018); Wu (2014); Wang and Shan (2007)* | Spain, Hong Kong, Taiwan, UK, South Korea, Australia |
| Quality of higher education | Valls-Figuera et al. (2023); Lin et al. (2022); Jung and Li (2020)*; Wiers-Jenssen (2020); Calikoglu (2018); Moogan (2018); Wu (2014); Wang and Shan (2007)* | Spain, Taiwan, Hong Kong, Norway, Finland, UK, Australia |
| Home country education experience | Espinoza et al. (2025); Valls-Figuera et al. (2023); Lin et al. (2022); Wu (2020); Jung and Lee (2019)*; Wu (2014) | Chile, Spain, Taiwan, UK, South Korea |

| Factors | References | Country/Region |
|---|---|---|
| Location | Valls-Figuera et al. (2023); Lin et al. (2022); Jung and Li (2020)*; Calikoglu (2018); Moogan (2018); Wu (2014) | Spain, Taiwan, Hong Kong, Finland, UK |
| Cost | Jung and Li (2020)*; Wiers-Jenssen (2020); Wu (2020); Calikoglu (2018); Moogan (2018); Wang and Shan (2007)* | Hong Kong, Norway, Finland, UK, Australia |
| Family influence | Espinoza et al. (2025); Wu (2020); Jung and Lee (2019)*; Moogan (2018); Wang and Shan (2007)* | Chile, UK, South Korea, Australia |
| Friend influence | Lin et al. (2022) | Taiwan |
| Migration opportunities after graduation | Wiers-Jenssen (2020); Calikoglu (2018); Wang and Shan (2007)* | Norway, Finland, Australia |
| Personal interest | Jung and Li (2020)*; Wu (2020) | Hong Kong, UK |
| Safety of host country | Wiers-Jenssen (2020); Wang and Shan (2007)* | Norway, Australia |
| Exposure to different cultures | Wu (2014); Wang and Shan (2007)* | UK, Australia |
| Education policy of host country | Wiers-Jenssen (2020); Wang and Shan (2007)* | Norway, Australia |
| Past working experience | Espinoza et al. (2025); Valls-Figuera et al. (2023) | Chile, Spain |
| Gender | Gazo et al. (2022); Lin et al. (2022), Jung and Lee (2019)* | Spain, Taiwan, South Korea |
| Age | Jung and Lee (2019)* | South Korea |

NB: *study that specifically focussed on coursework master's degrees

## 2.1 CHALLENGES FACED BY INTERNATIONAL POSTGRADUATE STUDENTS

Next, Table 2 summarizes the challenges faced by postgraduate students. Some of these studies have been considered in Table 1 since such studies examined both factors and challenges in the subject area, similar to the present study. While the list of challenges seems short in comparison to those discovered in the systematic review by Oduwaye et al. (2023), it is rather consistent with their findings that academic and sociocultural challenges were most reported in the literature. Of these, the top cited challenges are academic and study pressure, sense of social isolation and cultural shock as evidenced in the literature listed in Table 2.

*Table 2: Challenges faced by international postgraduate students*

| Challenges | References | Country/Region |
|---|---|---|
| Academic and study pressure | Pappa et al. (2020); Calikoglu (2018); Moogan (2018); Wu (2014); Wang and Shan (2007)* | Finland, Finland, UK, Australia |
| Sense of social isolation | Pappa et al. (2020); Yu and Moskal (2019); Calikoglu (2018); Wang and Shan (2007)* | Finland, UK, Australia |
| Cultural shock | Wu (2020); Yu and Moskal (2019); Calikoglu (2018); Wang and Shan (2007)* | UK, Finland, Australia |
| Financial hardship | Lin et al. (2022); Pappa et al. (2020); Jung and Li (2020); Calikoglu (2018) | Taiwan, Finland, Hong Kong |
| Language barrier | Yu and Moskal (2019); Moogan (2018); Wang and Shan (2007) | UK, Australia |

| Challenges | References | Country/Region |
|---|---|---|
| Racial discrimination | Yu and Moskal (2019); Calikoglu (2018) | UK, Finland |
| Mental health issues | Pappa et al. (2020); Moogan (2018) | Finland, UK |
| Physical health issues | Pappa et al. (2020); Moogan (2018) | Finland, UK |
| Access to student housing or accommodation | Calikoglu (2018) | Finland |
| Homesickness | Wang and Shan (2007)* | Australia |
| Limited job opportunities for international students | Calikoglu (2018) | Finland |

NB: *study that specifically focussed on coursework master's degrees

### 2.2 CONSTRUCTION MANAGEMENT EDUCATION

There is a wealth of literature on construction management (CM) education in various aspects. Aliu and Aigbavboa (2021) opined that CM education had attracted a great interest from different stakeholders because of its role in nurturing the future generation of construction professionals and project managers. However, an area of concern is gender disparity in CM education (Burgoon et al., 2025). Despite the calls in the past decades for more diversity in the male-dominated construction industry in which women are seen as untapped resource in addressing workforce shortages and improving diversity in the industry (Hickey & Cui, 2020), university CM degree programs struggle to attract and retain female students to fuel the demand of construction professions (Choi et al., 2022). Correspondingly, there are studies on students' choice of CM degrees, especially from female students' perspective (Oo et al., 2018), which focused on undergraduate CM degree programs. However, little is known about students' choice of CM-related coursework master's degrees, and this study aims to address this research gap in a case study setting that specifically considers the students' gender along with their country-of-origin in the analysis.

## 3. RESEARCH METHOD

This study adopted a single case study research design in achieving the research objectives. Data was collected using an anonymous online structured survey questionnaire. This facilitated the data collection process in an efficient and timely manner from the targeted population (Oo et al., 2018). A purposive sampling method was adopted to reach the targeted population, i.e., the current students in construction management-related coursework master's degrees. A case university in Australia was chosen because it offers as many as three construction management-related coursework master's degrees, of which one is a double coursework master's degree program. The case university is one of the renowned Australia's global universities with large population of international students, which was about 40% of its total enrolments in 2023 (Department of Education, 2023). Additionally, these three programs are experiencing a surge in international student enrolments post the COVID-19 pandemic. The number of current international students in these degree programs was as high as 324 across different study years when the survey questionnaire was distributed. While international students are required to enrol on a full-time study mode due to their student visa requirements, the recorded number of international students may include students who were on program leave and thus unreachable in the recruitment process.

Various recruitment strategies were adopted to maximize the survey response rate including: (i) the survey invitation link was distributed via the university current students' website and student weekly newsletter along with a reminder in subsequent week's newsletter; (ii) the survey was distributed in the middle of the teaching term when students were generally less busy to encourage participation; and (iii) a sufficient time frame of 4-week was allocated for data collection. Additionally, the survey questionnaire was kept short and simple to maximize the survey response rate. There were only two sections in the questionnaire with the main section on the list of influencing factors and challenges adapted from the literature along with a background section on demographic questions. Some other influencing factors and challenges from the relevant literature in the higher education context (e.g., Ha et al., 2023; Oduwaye et al., 2023) were also adapted in the questionnaire. A pilot study was performed to ensure clarity of the questionnaire, and the required changes (i.e., rewording, adding or deleting items) were addressed prior to data collection. The respondents were asked to indicate their perceptions on the subject matter based on a seven-point Likert scale. In total, there were 47 complete responses usable for the data analysis, representing a response rate of 14.5%. While the response rate was low, it was considered satisfactory and adequate when taking into consideration some students might not willingly share their learning experience, regardless of the setting being used to conduct this study. Indeed, it should be noted that similar studies that specifically focussed on coursework master's degrees have adopted interviewing approach with a rather small cohort of 10 (Wang & Shan, 2007) and 70 (Jung & Li, 2020) respondents, which seemingly indicated the challenges in recruitment of study participants and data collection.

## 4. RESULTS

Table 3 shows the demographic profile of the respondents with a rather even number of male (55 %) and female (45%) respondents. About 80% of them are from China (42%) and India (40%). Majority of them (77%) completed their undergraduate degree in their home country, and the current master's degree was the first postgraduate degree pursuit for almost all respondents (96%). About two-thirds of respondents were working on full-time, part-time or casual basis.

*Table 3: The demographic characteristics of the respondents*

| **Demographic characteristics** | | **Respondents** | |
|---|---|---|---|
| | | Freq. | % |
| Gender | Female | 21 | 44.7% |
| | Male | 26 | 55.3% |
| Home country | China | 18 | 41.9% |
| | India | 17 | 39.5% |
| | Others | 8 | 18.6% |
| Country completed undergraduate degree | Australia | 10 | 21.3% |
| | Home country | 36 | 76.6% |
| | Others | 1 | 2.1% |
| Is current master's degree your first postgraduate degree pursuit? | Yes | 45 | 95.7% |
| | No | 2 | 4.3% |

| Demographic characteristics | | Respondents | |
|---|---|---|---|
| | | Freq. | % |
| Current employment status | Employed full-time | 7 | 14.9% |
| | Employed part-time | 11 | 23.4% |
| | Casual worker | 16 | 34.0% |
| | Do not have a paid job | 13 | 27.7% |

On the gender grouping, Table 4 shows the mean and ranking of the respondents' perceived importance of 17 factors affecting their decision to pursue a master's degree. Some factors were not appliable to all respondents, and they were given an "N/A" option in the questionnaire. Nonetheless, the recorded frequencies for all factors are 41 and above (out of 47), signifying that these factors were relevant to most respondents. There is little variation in mean scores between the male and female groups, ranging between 4 and 7 for all factors. The Mann–Whitney U test results show that there is no statistically significant difference in distribution between male and female groups for all the 17 factors at $p < 0.05$ significance level, i.e., gender difference is statistically insignificant. It also noted that the recommendation from agency and influence of family and friend were of least importance for both gender groups (i.e. ranked bottom on the list).

*Table 4: The mean and ranking of the respondents' perceived importance of factors affecting their decision to pursue a coursework master's degree according to gender*

| Factors | | Male | | Female | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| F1 | Quality of higher education in Australia | 5.653 | 7 | 6.050 | 1 | 0.401 |
| F2 | Global reputation and ranking of university | 6.077 | 2 | 6.000 | 2 | 0.873 |
| F3 | Recommendation from student recruitment agency | 4.423 | 16 | 4.833 | 14 | 0.552 |
| F4 | Family influence | 4.826 | 14 | 4.550 | 16 | 0.664 |
| F5 | Friend influence | 4.400 | 17 | 4.263 | 17 | 0.838 |
| F6 | The major of the postgraduate or master's degree program (CPM, PD or both) | 5.923 | 3 | 5.667 | 7 | 0.401 |
| F7 | The flexibility of the course design of the postgraduate or master's degree program | 5.040 | 11 | 5.300 | 9 | 0.666 |
| F8 | Current job experience or employment | 5.250 | 9 | 5.294 | 10 | 0.827 |
| F9 | Career advancement opportunities | 6.115 | 1 | 5.810 | 4 | 0.335 |
| F10 | Specialized job opportunities based on postgraduate or master's degree major | 5.760 | 4 | 5.810 | 5 | 0.982 |
| F11 | Your undergraduate or bachelor's degree major | 4.731 | 15 | 4.950 | 13 | 0.644 |
| F12 | Post-undergraduate working experience | 5.583 | 8 | 4.778 | 15 | 0.146 |
| F13 | Personal development and self-improvement | 5.692 | 5 | 5.905 | 3 | 0.662 |

| Factors | | Male | | Female | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| F14 | Prospect of obtaining professional body certification | 4.840 | 13 | 5.350 | 8 | 0.418 |
| F15 | Enhancement of future academic prospects | 4.880 | 12 | 5.200 | 12 | 0.875 |
| F16 | Exposure to different cultures | 5.680 | 6 | 5.250 | 11 | 0.286 |
| F17 | Migration opportunities after graduation | 5.160 | 10 | 5.714 | 6 | 0.319 |

[a] Scale: not at all important (1), low importance (2), slightly important (3), neutral (4), moderately important (5), very important (6), extremely important (7)
[b] Mann–Whitney test of difference between male and female

Table 5 shows the statistics of male and female groups' perceived level of difficulties in dealing with potential challenges. Similarly, the respondents were given an "N/A" option, and it is evident that some potential challenges were not applicable to all respondents, and the recorded highest and lowest frequencies are 32 and 42, respectively. The challenge that recorded the lowest frequency is family pressure (C10), indicating that the respondents' family were generally supportive of their study even if this challenge was applicable. In terms of mean scores, male group recorded lower mean generally that range between 2.762 and 5.455, with the corresponding female group's mean scores of 3.278 and 5.889. While the female group's mean scores are leaning towards the higher score, the range of the mean scores from both groups is very similar, i.e., around 2.6, signifying comparable variability in their responses. Indeed, it is noted that the mean scores of most factors for both gender groups are on the 'easy' side of the scale (i.e., below 4), suggesting that the respondents were settling in well as international students despite the challenges faced, and had access to university student support services if required (i.e., this challenge ranked bottom of the list for both gender groups). In consistent with preceding results in Table 4, the Mann–Whitney U test results show that there is no statistically significant difference in distribution between two gender groups for all the 16 challenges at $p < 0.05$ significance level. This further affirms that gender difference is statistically insignificant.

*Table 5: The mean and ranking of the respondents' perceived level of difficulties in dealing with potential challenges faced by international students according to gender*

| Challenges | | Male | | Female | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| C1 | Cultural shock | 3.409 | 11 | 3.667 | 11 | 0.619 |
| C2 | Racial discrimination | 3.294 | 14 | 3.889 | 7 | 0.405 |
| C3 | Unfamiliar food options or diet | 2.762 | 16 | 3.278 | 16 | 0.335 |
| C4 | Language barriers | 3.400 | 12 | 3.824 | 9 | 0.497 |
| C5 | Sense of social isolation (loneliness) | 4.381 | 5 | 3.667 | 12 | 0.269 |
| C6 | Homesickness | 3.857 | 9 | 3.765 | 10 | 0.954 |
| C7 | Physical health issues (e.g., insomnia) | 3.316 | 13 | 3.857 | 8 | 0.439 |
| C8 | Mental health issues (e.g., depression) | 3.600 | 10 | 3.375 | 15 | 0.545 |
| C9 | Academic and study pressure | 4.609 | 4 | 4.526 | 5 | 0.888 |
| C10 | Family pressure | 4.000 | 7 | 3.467 | 13 | 0.350 |

| | Challenges | Male | | Female | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| C11 | Financial hardship | 4.381 | 6 | 4.167 | 6 | 0.811 |
| C12 | Access to university student support services | 2.952 | 15 | 3.438 | 14 | 0.185 |
| C13 | Access to student housing or accommodation | 5.000 | 3 | 4.765 | 2 | 0.624 |
| C14 | Limitation on permitted number of working hours on student visa | 5.300 | 2 | 4.647 | 4 | 0.326 |
| C15 | Limited job opportunities for international students | 5.455 | 1 | 5.889 | 1 | 0.946 |
| C16 | A balance between academic and personal life activities | 3.870 | 8 | 4.722 | 3 | 0.312 |

[a] Scale: extremely easy (1), moderately easy (2), slightly easy (3), neither easy nor difficult (4), slightly difficult (5), moderately difficult (6), extremely difficult (7)
[b] Mann–Whitney test of difference between male and female

In repeating the analysis with the respondents' country-of-origin, Table 6 shows the respective results on the respondents' perceived importance of factors affecting their decision to pursue a master's degree. The mean scores of the India group are generally higher and varying between 4.500 and 6.588 with a range of 2.088, compared to the corresponding China group's mean scores of 4.235 and 5.941 and a range of 1.704. The Mann–Whitney U test results show that there are statistically significant differences in distributions between China and India groups on six factors at $p < 0.05$ significance level. These factors are F1, F6, F7, F10, F11 and F12, which are mainly related to the master's degree program quality, program major, course design and specialized job opportunities.

*Table 6: The mean and ranking of the respondents' perceived importance of factors affecting their decision to pursue a coursework master's degree according to their country-of-origin*

| | Factors | China | | India | | Sig. (*p*-value) [b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| F1 | Quality of higher education in Australia | 5.118 | 5 | 6.353 | 3 | *0.010* |
| F2 | Global reputation and ranking of university | 5.941 | 1 | 6.353 | 4 | 0.195 |
| F3 | Recommendation from student recruitment agency | 4.471 | 12 | 4.625 | 16 | 0.825 |
| F4 | Family influence | 4.313 | 15 | 4.733 | 15 | 0.655 |
| F5 | Friend influence | 4.235 | 16 | 4.500 | 17 | 0.772 |
| F6 | The major of the postgraduate or master's degree program (CPM, PD or both) | 5.059 | 8 | 6.588 | 1 | *0.002* |
| F7 | The flexibility of the course design of the postgraduate or master's degree program | 4.235 | 17 | 5.938 | 8 | *0.008* |
| F8 | Current job experience or employment | 5.071 | 6 | 5.125 | 14 | 0.922 |
| F9 | Career advancement opportunities | 5.529 | 2 | 6.412 | 2 | 0.062 |
| F10 | Specialized job opportunities based on postgraduate or master's degree major | 5.000 | 9 | 6.353 | 5 | *0.012* |
| F11 | Your undergraduate or bachelor's degree major | 4.471 | 13 | 5.647 | 10 | *0.027* |

| Factors | | China | | India | | Sig. (*p*-value) [b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| F12 | Post-undergraduate working experience | 4.429 | 14 | 5.750 | 9 | *0.037* |
| F13 | Personal development and self-improvement | 5.235 | 3 | 6.118 | 6 | 0.110 |
| F14 | Prospect of obtaining professional body certification | 4.500 | 11 | 5.471 | 13 | 0.170 |
| F15 | Enhancement of future academic prospects | 4.533 | 10 | 5.588 | 12 | 0.168 |
| F16 | Exposure to different cultures | 5.125 | 4 | 6.118 | 7 | 0.140 |
| F17 | Migration opportunities after graduation | 5.063 | 7 | 5.647 | 11 | 0.322 |

[a] Scale: not at all important (1), low importance (2), slightly important (3), neutral (4), moderately important (5), very important (6), extremely important (7)
[b] Mann–Whitney test of difference between China and India

Next, Table 7 shows the results for the identification of critical challenges according to the respondents' country-of-origin. In terms of mean scores, China group recorded a rather narrow spread of scores between 3.000 and 5.000, compared to the corresponding India group's scores of 1.222 and 6.417 (i.e., range = 5.194). In contrast to mean scores reported in Table 5 (according to gender), the recorded mean scores clearly show a greater variability in the responses when the respondents' country-of-origin was taken into consideration. The Mann–Whitney *U* test results also show that there are statistically significant differences in distributions between China and India groups on two challenges at $p < 0.05$ significance level. These challenges are language barrier (C4) and limited job opportunities for international students (C15). Along with the detected statistically significant differences in Table 6, the findings credibly show that the respondents' country-of-origin attribute has a role in their perceptions of levels of difficulty in dealing with potential challenges.

*Table 7: The mean and ranking of the respondents' perceived level of difficulties in dealing with potential challenges according to their country-of-origin*

| Challenges | | China | | India | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| C1 | Cultural shock | 3.529 | 12 | 3.083 | 13 | 0.346 |
| C2 | Racial discrimination | 3.706 | 10 | 3.250 | 11 | 0.461 |
| C3 | Unfamiliar food options or diet | 3.000 | 16 | 2.727 | 14 | 0.707 |
| C4 | Language barriers | 4.882 | 2 | 1.222 | 16 | *0.000* |
| C5 | Sense of social isolation (loneliness) | 3.882 | 7 | 4.273 | 5 | 0.642 |
| C6 | Homesickness | 3.813 | 9 | 4.000 | 7 | 0.711 |
| C7 | Physical health issues (e.g., insomnia) | 3.438 | 14 | 2.429 | 15 | 0.308 |
| C8 | Mental health issues (e.g., depression) | 3.500 | 13 | 4.000 | 8 | 0.637 |
| C9 | Academic and study pressure | 4.824 | 3 | 3.692 | 10 | 0.135 |
| C10 | Family pressure | 3.667 | 11 | 4.167 | 6 | 0.407 |
| C11 | Financial hardship | 3.867 | 8 | 4.800 | 4 | 0.216 |
| C12 | Access to university student support services | 3.438 | 15 | 3.167 | 12 | 0.616 |

| | Challenges | China | | India | | Sig. (*p*-value)[b] |
|---|---|---|---|---|---|---|
| | | Mean[a] | Rank | Mean[a] | Rank | |
| C13 | Access to student housing or accommodation | 4.706 | 4 | 5.538 | 2 | 0.170 |
| C14 | Limitation on permitted number of working hours on student visa | 4.000 | 6 | 5.462 | 3 | 0.065 |
| C15 | Limited job opportunities for international students | 5.000 | 1 | 6.417 | 1 | *0.030* |
| C16 | A balance between academic and personal life activities | 4.500 | 5 | 3.692 | 9 | 0.341 |

[a] Scale: extremely easy (1), moderately easy (2), slightly easy (3), neither easy nor difficult (4), slightly difficult (5), moderately difficult (6), extremely difficult (7)
[b] Mann–Whitney test of difference between China and India

# 5. DISCUSSION

Despite the importance of this master's degree type in Australia in many ways, including its national economic benefits (McCowage et al., 2025), little is known about international students' experiences in Australian universities (Edwards, 2011). The key findings are discussed below. Firstly, the results detect heterogeneity in the respondents' responses, echoing the necessity to cater for diversity of coursework master's degree student cohorts as affirmed in the literature (e.g., Li & Jung, 2023; Valls-Figuera et al., 2023). The detected heterogeneity is dependent on the respondents' country-of-origin to a greater extent than their gender. The results show that the differences in responses between the male and female groups for the influencing factors (Table 4) and potential challenges (Table 5) they faced are statistically insignificant. Indeed, it is rather surprising that the respondents' responses are not gendered, which contrasts with some previous findings on the gender role in master's education and study abroad decision making (e.g., Jung & Lee, 2019; Van Mol, 2021). It is also worth noting that the major of master's degree is not on the list of top ranked factors influencing the female respondents' decision making (see Table 4) as expected, even though the major in the degree programs is construction management related. Regrettably, the discipline has been experiencing difficulties in the recruitment for female students in construction management undergraduate degrees in the past decades due to the gender stereotype in the construction industry (Oo et al., 2018), which seems to be of less concern to female master's students.

On the other hand, the results show that there are statistically significant differences in responses between China and India groups for six influencing factors (Table 6) and two potential challenges (Table 7). In consistent with many country-specific studies, international students' country-of-origin attribute has a role to play in their study abroad motivation, decision-making and learning experiences (e.g., Calikoglu, 2018; Jung & Li, 2020). Indeed, the results are representative and credible since students from China and India are the top two nationalities for recorded enrolments in master's degree by coursework in Australia (Department of Education, 2025). A credible example with statistically significant difference between the two nationality groups is that challenge of language barrier is least difficult for Indian students, which ranked last on the list (Table 7). Contrastingly, language barrier is top critical challenge for Chinese students abroad, which has also been shared by Chinese postgraduate students in Australia in an interview study by Wang and Shan (2007). Turning into the two key challenges for both groups, it is not surprising that the respondents found it very challenging in accessing student

accommodations, as inadequate student housing provision has been a rooted problem facing by international students in Australia (Zhu et al., 2024). Challenges associated with international students' common career concerns of limited job opportunities reported in the literature have been captured as well in the present study (see Table 2). Collectively, while it is expected that the detected heterogeneities in responses are underpinned by intricate nature of individual students, the findings clearly suggest that an assumption of homogeneity among international students of different nationalities would be unjustified to accommodate their diverse expectations and demands in master's degree education.

# 6. CONCLUSIONS

This study contributes to the emerging body of knowledge on coursework master's education, which has been experiencing rapid growth globally with an increasingly diverse student body. It focuses on international student cohort in three construction management related master's degree programs offered by a university in Australia. The results show that the detected heterogeneity in the respondents' responses is dependent on the respondents' country-of-origin to a greater extent than their gender, echoing the necessity to cater for diversity of coursework master's degree student cohorts in future studies on this student body. Also, the results suggest that the influencing factors and challenges on career opportunities and advancements are intertwined. Thus, care and support pertaining to this aspect are of critical importance for international students since they tend to seek job opportunities both during and after completing their CM-related degrees.

While the findings can broaden the general understanding of the key issues examined, there are limitations that prompt future on master's education. In accommodating the diverse expectations and demands in master's degree education among international students, future studies should aim to recruit respondents across diverse master's degree programs from different tertiary institutes to enrich the knowledge base on this student body. In addition, future studies could explore the causes of challenges faced by international students in exploring the student support services required to improve their learning experiences abroad. Lastly, future studies should consider the international students' demographic profile in the analysis and associated modelling attempts.

# 7. REFERENCES

Aliu, J., & Aigbavboa, C. O. (2021). Structural determinants of graduate employability: Impact of university and industry collaborations. *Journal of Engineering, Design and Technology*, *19*(5), 1080-1100. https://doi.org/10.1108/JEDT-05-2020-0189

Burgoon, J. M., Roebuck Jr, A., & Elliott, J. W. (2024). Evidence of opportunity gaps in construction education: A longitudinal analysis of student success. *International Journal of Construction Education and Research*, *20*(1), 83-97. https://doi.org/10.1080/15578771.2023.2186980

Choi, J. O., Shane, J. S., & Chih, Y.-Y. (2022). Diversity and inclusion in the engineering-construction industry. *Journal of Management in Engineering*, *38*(2), 02021002. https://doi.org/10.1061/(asce)me.1943-5479.0001005

Hickey, P. J., & Cui, Q. (2020). Gender diversity in US construction industry leaders. *Journal of Management in Engineering*, *36*(5), 04020069. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000838

Calikoglu, A. (2018). International student experiences in non-native-English-speaking countries: Postgraduate motivations and realities from Finland, *Research in Comparative and International Education*, *13*(3), 439–456. https://doi.org/10.1177/1745499918791362

Department of Education (2025), International student monthly summary and data tables, Department of Education, Australian Government, Canberra https://www.education.gov.au/international-education-data-and-research/international-student-monthly-summary-and-data-tables

Department of Education (2023), Selected Higher Education Statistics – 2023 Student data, Department of Education, Australian Government, Canberra https://www.education.gov.au/higher-education-statistics/student-data/selected-higher-education-statistics-2023-student-data

Drennan, J., & Clarke, M. (2009). Coursework master's programmes: The student's experience of research and research supervision. *Studies in Higher Education, 34* (5), 483–500. https://doi.org/10.1080/03075070802597150

Edwards, D. (2011). Monitoring risk and return: Critical insights into graduate coursework engagement and outcomes, AUSSE Research Briefing. 9. https://research.acer.edu.au/ausse/3/

Espinoza, O., González, L., Sandoval, L., Corradi, B., Larrondo, Y., Miranda, C., & McGinn, N. (2025). Factors that influence university graduates' choice of postgraduate study. *Studies in Continuing Education*, *47*(2), 361-378. https://doi.org/10.1080/0158037X.2024.2363301

Gazo, P. F., Llanes Ordóñez, J., Torrado Fonseca, M., Valls Figuera, R.G., & Buxarrais Estrada, MR. (2020). Reasons for course selection and academic satisfaction among master's degree students, *Journal of Hispanic Higher Education*, *21*(3), 153819272095457. https://doi.org/10.1177/1538192720954573

Glazer-Raymo, J. (2005). Professionalizing graduate education: The master's degree in the marketplace. *ASHE Higher Education Report*, *31*(4), 1–137. https://eric.ed.gov/?id=EJ791622

Gutema, D.M., Pant, S.K.C., & Nikou, S. (2023). Exploring key themes and trends in international student mobility research —A systematic literature review. *Journal of Applied Research in Higher Education*, *16*(3). https://doi.org/10.1108/jarhe-05-2023-0195.

Ha, N.T.N., Hoang, C.H., Knight, E., & Hurley, P. (2023). What drives international students to choose Australia as their tertiary education destination? A synthesis of empirical evidence, *Journal of International Students*, *13*(4), 146–168. https://doi.org/10.32674/jis.v14i4.5983

Haidar, H. (2024). Types of master's degrees. *Top Universities*. https://www.topuniversities.com/blog/types-masters-degrees

Hung, N.T., & Yen, K.L. (2020). The role of motivation and career planning in students' decision-making process for studying abroad: A mixed-methods study. *Revista Argentina de Clinica Psicologica*, *29*(4), 252–265. https://doi.org/10.24205/03276716.2020.825.

Jung, J. (2021). Learning experience and academic identity building by master's students in Hong Kong. *Studies in Higher Education*, *46*(4), 782–795. https://doi.org/10.1080/03075079.2019.1652811

Jung, J., & Lee, SJ. (2019) Exploring the factors of pursuing a master's degree in South Korea, *Higher Education*, *78*(5), 855–870. https://doi.org/10.1007/s10734-019-00374-8

Jung, J., & Li, X. (2020). Exploring motivations of a master's degree pursuit in Hong Kong, *Higher Education Quarterly*, *75*(2), 321–332. https://doi.org/10.1111/hequ.12276

Li, X., & Jung, J. (2023). Career concerns and needs of mainland Chinese Master's students in Hong Kong. *Asia Pacific Journal of Education*, *43*(2), 335-349. https://doi.org/10.1080/02188791.2021.1896477

Lin, C.H., Chen, J.H., Lin, E.S., & Lo, C.O. (2022). The effects of college student experience on degree aspirations for graduate education. *SAGE Open*, 12(3), 215824402211177. https://doi.org/10.1177/21582440221117798.

McCowage, M., Stinson, H., & Fink, M. (2025). *International students and the Australian economy*, Reserve Bank of Australia, Canberra, https://www.rba.gov.au/publications/bulletin/2025/jul/pdf/international-students-and-the-australian-economy.pdf, accessed 30 July 2025

Moogan, Y.J. (2018). An investigation into international postgraduate students' decision-making process, *Journal of Further and Higher Education*, *44*(1), 83–89. https://doi.org/10.1080/0309877X.2018.1513127

Oduwaye, O., Kiraz, A., & Sorakin, Y. (2023). A trend analysis of the challenges of international students over 21 years. *Sage Open*, *13*(4), 21582440231210387. https://doi.org/10.1177/21582440231210387

Oo, BL, Li, S., & Zhang, L. (2018). Understanding female students' choice of a construction management undergraduate degree program: Case study at an Australian university, *Journal of Professional Issues*

*in Engineering Education and Practice*, 144(3), 05018004. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000365

Pappa, S, Yada, T., & Perälä-Littunen, S. (2020). International master's degree students' well-being at a Finnish university during COVID-19, *Open Education Studies*, *2*(1), 240–251. https://doi.org/10.1515/edu-2020-0128

Valls-Figuera, RG., Torrado-Fonseca, M., Romero-Rodríguez, S., & Jurado-de-los-Santos, P. (2023). The decision-making process in access paths to master's degree studies: The case of international students in Spain, *Sustainability*, *15*(7), 5621. https://doi.org/10.3390/su15075621

Van Mol, C. (2021). Exploring explanations for the gender gap in study abroad: A case study of the Netherlands, *Higher Education*, *83*(2), 441–459. https://doi.org/10.1007/s10734-020-00671-7

Walsh, S.P., & Tucker, K. (2011). The perspectives of students undertaking masters' degrees by coursework on career development learning. *Australian Journal of Career Development*, *20*(2), 42-47. https://doi.org/10.1177/103841621102000206

Wang, T., & Shan, X. (2007). A qualitative study on Chinese postgraduate students' learning experiences in Australia. *Proceedings AARE 2006*. http://pandora.nla.gov.au/pan/24691/20070301-0000/www.aare.edu.au/06pap/wan06121.pdf

Wiers-Jenssen, J. (2020). What brings international students to Norway?, *Journal of International Students*, *10*(1), ix–xii. https://doi.org/10.32674/jis.v10i1.1888

Wu, Y. (2020). Study abroad experience and career decision-making: A qualitative study of Chinese students, *Frontiers of Education in China*, *15*(2), 313–331. https://doi.org/10.1007/s11516-020-0014-8

Wu, Q. (2014). Motivations and decision-making processes of mainland Chinese students for undertaking master's programs abroad, *Journal of Studies in International Education*, *18*(5), 426–444. https://doi.org/10.1177/1028315313519823

Yu, Y., &Moskal, M. (2019). Missing intercultural engagements in the university experiences of Chinese international students in the UK, *Compare: A Journal of Comparative and International Education*, *49*(4), 1–18. https://doi.org/10.1080/03057925.2018.1448259

Zhu, J., Pawson, H., He, S., & Li, B. (2024). COVID-19 and aggravated housing precarity for international students: an Australian case study. *International Journal of Housing Policy*, *24*(2), 344–371. https://doi.org/10.1080/19491247.2024.2339441

Piyasena, R.K.N.P., Farha, M.F.F., Hewage, I.S., Young, S.M. and Halwatura, R.U., 2026. Iron slag substitution in soil-based geopolymers: A comparative study with coal fly ash for non-load bearing applications. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1022-1036. DOI: https://doi.org/10.31705/WCS.2026.75. Available from: https://ciobwcs.com/papers/

# IRON SLAG SUBSTITUTION IN SOIL-BASED GEOPOLYMERS: A COMPARATIVE STUDY WITH COAL FLY ASH FOR NON-LOAD BEARING APPLICATIONS

**R.K.N.P. Piyasena[1], M.F.F. Farha[2], I.S. Hewage[3], S.M. Young[4] and R.U. Halwatura[5]**

## *ABSTRACT*

*The production of traditional Ordinary Portland Cement (OPC) drives significant greenhouse gas emissions, necessitating a shift toward sustainable, low-carbon building materials. This study investigates the development of geopolymerized mud concrete (GMC) by valorizing two industrial by-products—coal fly ash (CFA) and iron slag (IS)—as primary aluminosilicate precursors. The research aimed to establish baseline parameters for a reference CFA-based GMC, optimize an IS-substituted alternative, and evaluate its comparative feasibility. Microstructural characterization confirmed both materials possess essential glass-forming oxides. While CFA relies on abundant silica and alumina to develop robust aluminosilicate networks, IS drives binder formation through complex Fe-A-S-H and C-A-S-H gels. Utilizing an alkaline activator comprising 10M sodium hydroxide and 2% sodium chloride, the methodology was included in two phases. First, optimal thermal curing conditions were established for the 20% CFA reference. Subsequently, to maximize mechanical performance, IS substitution levels (10% to 40%), curing temperatures (ambient to 100 °C), and durations (6 to 24 hours) were systematically optimized through 7-, 14-, and 28-day compressive strength testing. The benchmark CFA mix (cured at 100 °C for 6 hours) achieved a peak 28-day compressive strength of 3.241 MPa. Conversely, the optimized IS matrix (30% IS, cured at 60 °C for 24 hours) attained 1.601 MPa. Although yielding approximately 49% of the CFA baseline capacity, the 1.601 MPa IS-based geopolymer satisfies requirements for non-load-bearing masonry. Ultimately, this study demonstrates that IS is a resilient, low-cost, and eco-friendly precursor alternative that advances circular economy principles, particularly in regions lacking accessible CFA reserves.*

***Keywords:*** *Alkaline Activation; Coal Fly Ash; Compressive Strength; Geopolymerized Mud Concrete; Iron Slag Valorisation.*

---

[1] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, nethmi97praba@gmail.com
[2] Student, Department of Environmental Technology, University of Colombo, Sri Lanka, farhafareed2000@gmail.com
[3] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, iresharesearch1@gmail.com
[4] Professor, Department of Environmental Technology, University of Colombo, Sri Lanka, sansfica@et.cmb.ac.lk
[5] Senior Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangikauh@gmail.com

# 1. INTRODUCTION

The construction industry is under increasing pressure to reduce its environmental footprint due to intensive energy consumption, heavy reliance on non-renewable raw materials, and substantial greenhouse gas emissions. Ordinary Portland Cement (OPC), the primary binder in conventional concrete, is responsible for approximately 5–7% of global anthropogenic $CO_2$ emissions (Singh & Middendorf, 2020; Mohan et al., 2025). At the same time, the construction sector consumes nearly 40% of global energy resources and contributes to severe land degradation through extensive quarrying of limestone and other minerals (United Nations Environment Programme, 2023). In response to these challenges, geopolymer concrete (GPC) has emerged as a promising, eco-friendly alternative. By utilizing aluminosilicate-rich industrial by-products activated with alkaline solutions, GPC can reduce embodied carbon by up to about 80% compared with OPC-based systems, while achieving comparable mechanical performance (Juenger et al., 2011; Mohan et al., 2025).

Parallel to the development of low-carbon binders, there is renewed interest in sustainable earth-based construction. Mud concrete, a soil-based composite typically comprising soil, cement, and water, is valued for its low cost, local availability, and thermal comfort. However, its dependence on OPC limits its environmental benefits (Arooz, 2019; Arooz & Halwatura, 2018). To overcome this, the concept of geopolymerized mud concrete (GMC) has been introduced by Udawattha & Halwatura (2018), in which the cementitious fraction is replaced by alkali-activated industrial by-products rich in alumina ($Al_2O_3$) and silica ($SiO_2$). GMC integrates the climate-responsive advantages of mud construction with geopolymer technology, enabling significant reductions in clinker use while aligning with circular economy principles through waste valorisation.

Among potential GMC precursors, coal fly ash (CFA) and iron slag (IS) are particularly attractive but form chemically distinct binder systems. CFA-based geopolymers are typically low-calcium, forming N–A–S–H–type aluminosilicate gels and often requiring elevated curing temperatures (60–80°C) to accelerate dissolution and strength gain, especially at high fly-ash contents (Zhao et al., 2021; Wijepala et al., 2022). These systems offer excellent thermal and chemical stability at high temperatures, but strength development and workability are highly sensitive to activator concentration, silicate/NaOH ratio, and curing regime (Shi et al., 2021; Chen et al., 2024). In contrast, Fe-rich alkali-activated, where C-(N)-A-S-H and Fe-A-S-H gels dominate and can achieve high early strength and dense microstructures under more moderate curing conditions (often ambient to 70 °C) (Zhang et al., 2021). While increased slag content generally enhances early compressive strength and interfacial bonding, it may reduce high-temperature residual strength compared with fly-ash-dominant systems, revealing a strength–durability trade-off between CFA and IS based binders (Zhang et al., 2021).

These mechanistic differences have practical implications for low-cost masonry. CFA-based systems tend to be more reliant on controlled, often higher-temperature curing to reach target strength, whereas Fe-rich systems can attain comparable or higher mechanical performance at lower curing temperatures but may be more sensitive to fracture behavior, pore structure, and high-temperature degradation (Zhang et al., 2021). Critically comparing CFA and IS based activation pathways is therefore essential to select curing regimes and precursor blends that are both energy-efficient and mechanically robust for non-load-bearing earth masonry (Nath & Kumar, 2013).

In Sri Lanka, substantial deposits of ancient iron-smelting slag exist in regions such as Yodhawewa, while CFA is widely generated by local thermal power plants. The utilization of these specific industrial residues in construction directly supports the transition toward a circular economy and contributes to the United Nations Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). By reducing demand for virgin raw materials, diverting waste from landfills, and lowering the carbon intensity of masonry units, geo-polymerized mud concrete can play a pivotal role in sustainable development.

Accordingly, this study aims to: (i) establish the optimal thermal curing conditions for a reference CFA-based GMC; (ii) determine the optimum precursor substitution level, curing temperature, and curing duration required to maximize the compressive strength of an IS-based GMC; and (iii) evaluate the comparative feasibility of the resulting IS-based material as a resilient, low-cost building solution for non-load-bearing applications. Ultimately, this research contributes to the development of low-carbon masonry products tailored for regions with abundant industrial by-products, minimizing reliance on OPC and non-renewable earth resources.

## 2. MATERIALS AND METHODS

A previously developed systematic approach for GMC, as outlined by Udawattha and Halwatura (2018) and Gayashani et al. (2025), was followed to prepare and test the proposed IS and CFA-based GMC. The procedures were based on relevant standard guidelines for material characterization, mix design, specimen preparation, and performance evaluation.

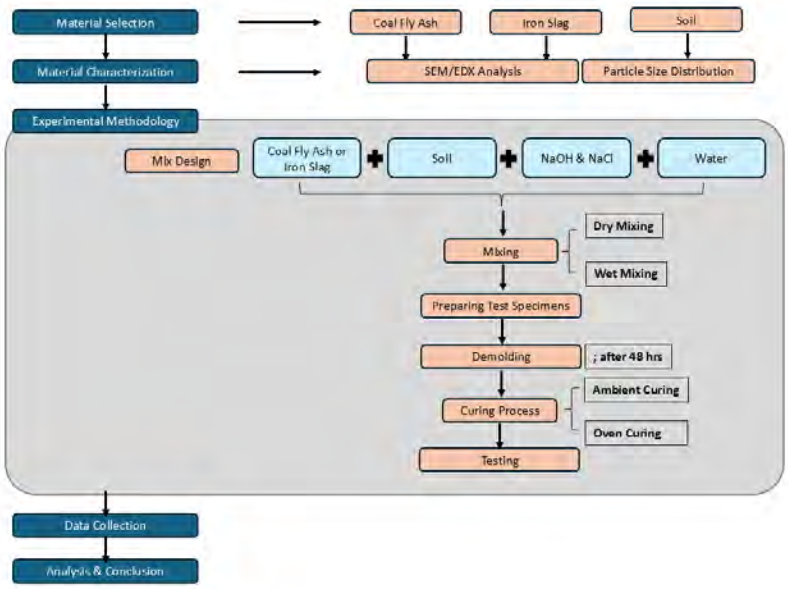



*Figure 1: Developed experimental framework of the study*

### 2.1 MATERIAL SELECTION, COLLECTION, AND PREPARATION

The materials used to produce the novel GMC comprised locally available soil, aluminosilicate precursors iron slag (IS) and coal fly ash (CFA) and an alkaline activator system of sodium hydroxide (NaOH) and sodium chloride (NaCl). Soil was excavated from a homogeneous layer approximately 600 mm below ground level at the University

of Moratuwa premises to minimize organic matter and surface disturbances. Following the removal of visible organic debris, the soil was dried to eliminate free moisture. Sieve analysis (BS 1377-2:1990) was then conducted to verify gradation consistency with prior GMC studies.

IS was sourced from Palugaswewa, Anuradhapura, where it exists abundantly as an underutilized byproduct of iron-smelting activities, while CFA was obtained from the Lakvijaya Coal Power Plant. Both IS and CFA samples were characterized using SEM-EDX to examine their morphology, phase texture, and elemental composition, confirming their suitability as geopolymer precursors. Following characterization, the IS was ground to a fine powder, and particles passing a 75 µm sieve were selected to enhance dissolution and reaction kinetics during alkali activation (Lee et al., 2021). Similarly, the CFA was sieved through a 150 µm sieve to remove coarse particles and improve homogeneity (Haustein & Kuryłowicz-Cudowska, 2020).

The alkaline activator system consisted of analytically pure NaOH and NaCl. Commercial NaOH pellets with a purity of 99 wt% were dissolved in water to prepare the main activating solution, providing hydroxide ions necessary to dissolve silica ($SiO_2$) and alumina ($Al_2O_3$) from the aluminosilicate precursors and soil matrix. NaCl was incorporated as a secondary additive to increase the ionic strength of the pore solution and to introduce chloride ions, which can influence dissolution, early-age reaction rates, and setting behavior in alkali-activated systems.

## 2.2 CHARACTERIZATION OF MATERIALS

### 2.2.1 Characterization of Soil Type

The natural soil serving as the primary matrix in the GMC was characterized through a detailed particle size distribution analysis to assess its engineering suitability. Sieve analysis was conducted in accordance with BS 1377-2:1990, following standard geotechnical practices for grading granular soils. The results confirmed that the soil is a heterogeneous mixture of gravel, sand, and fines, typical of construction soils used in stabilized earth and soil–cement systems (Wang et al., 2025).

Based on the analysis, the soil comprises 39.62% gravel (> 4.75 mm sieve), 55.22% sand (0.075 mm – 4/75 mm), and 5.16% fines (< 0.075 mm sieve). Gradation parameters derived from the particle size distribution curve (Figure 2) show an effective grain size $D_{10}$ of 0.428 mm, alongside $D_{30}$ and $D_{60}$ values of 1.918 mm and 4.704 mm, respectively. From these values, the coefficient of uniformity ($C_u = D_{60}/D_{10}$) was calculated as 10.99, and the coefficient of curvature ($C_c = D_{30}^2/(D_{10} \times D_{60})$) as 1.83, following conventional soil mechanics definitions used to describe particle size distribution.

According to the Unified Soil Classification System (USCS), $C_u > 6$, $1 < C_c < 3$ and a 5–12% fines content, the soil is classified as a well-graded sand with silt (SW–SM). The obtained grading and classification align with soils previously employed in geo-polymerized or stabilized earth systems, where controlled gradation optimizes packing density and mechanical performance (Ferreira et al., 2023; Wang et al., 2025).

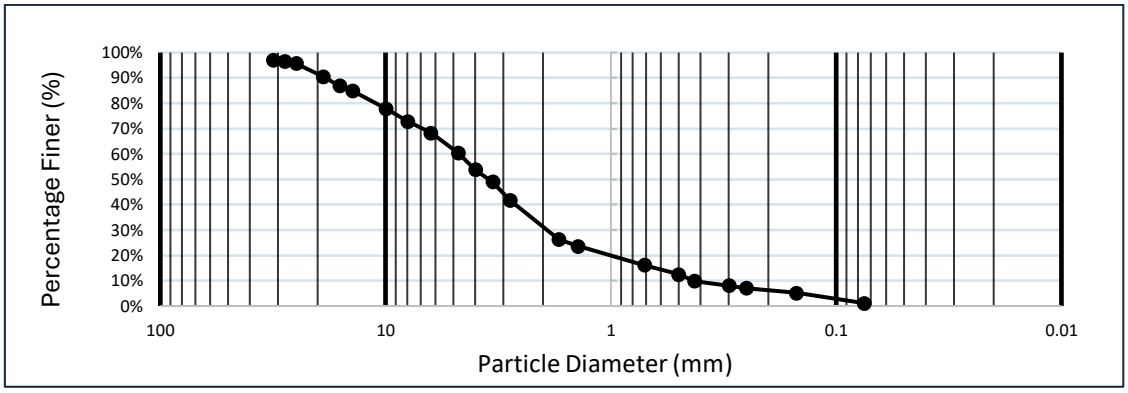



*Figure 2: Particle size distribution curve for soil*

This well-graded nature is highly advantageous for GMC, as a continuous particle size distribution minimizes the void ratio and enhances packing to improve overall strength and durability. Ultimately, the selected gradation provides a robust granular skeleton, facilitating the development of a dense, mechanically efficient geopolymerized matrix (Ferreira et al., 2023).

### 2.2.2 Characterization of Iron Slag

The microstructural and chemical characteristics of the iron slag (IS) were evaluated using SEM-EDX spectroscopy to assess its viability as a reactive geopolymer precursor, following standard methodologies for Fe-rich alkali-activated systems (Nikolov, 2020).

SEM imaging across 1.00K× to 15.00K× magnifications (Figure 2) revealed a heterogeneous assemblage of subrounded to subangular particles. At higher magnifications, the slag exhibits rough, porous, and irregular surface textures. This angularity is highly advantageous for mechanical interlocking within the concrete matrix. Furthermore, the intrinsic porosity significantly increases the specific surface area available for alkaline dissolution, facilitating the development of a dense geopolymeric network (Wang et al., 2024).

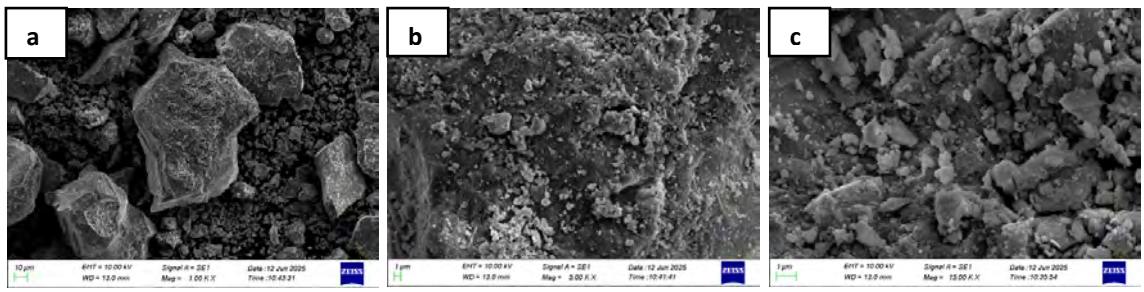



*Figure 3: Surface morphology of iron slag - (a) 10 µm size, 1.00 K × magnification, (b) 1µm size, 5.00 K × magnification, (c) 1 µm size, 15.00 K× magnification*

The elemental composition of the slag was quantified by EDX, with the spectrum and quantitative results presented in Table 1 and Figure 4. The slag is identified as a high-iron precursor, containing approximately 41.18 wt% Fe, accompanied by reactive oxides such as Si (8.76 wt%), Ca (2.56 wt%), and Al (4.21 wt%), along with minor Mg, Mn, and K. Typical Fe-rich metallurgical slags used in alkali-activated materials exhibit comparable Fe–Si–Ca–Al chemistries, often described within a $CaO–FeO_x–SiO_2–Al_2O_3$ system (Nikolov, 2020).

*Table 1: Elemental composition of iron slag*

| Element | Fe | Al | Si | Ca | C | O | Mg | P | K | Ti | Mn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| wt% | 41.18 | 4.21 | 8.76 | 2.56 | 8.60 | 29.28 | 0.86 | 0.00 | 0.39 | 0.20 | 3.96 |
| Atom% | 18.73 | 3.96 | 7.92 | 1.62 | 18.19 | 46.48 | 0.90 | 0.00 | 0.25 | 0.10 | 1.83 |

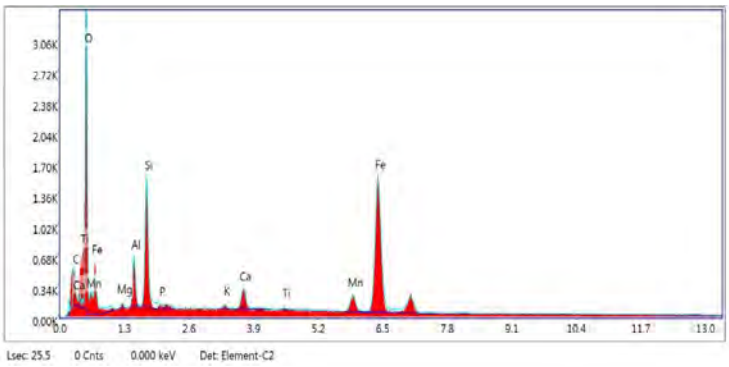



*Figure 4: Elemental composition spectrum of iron slag*

The high Fe content of the slag, together with appreciable amounts of silica and alumina, promotes the formation of complex Fe–A–S–H and C–A–S–H gels (often alongside C–(N)–A–S–H in mixed systems) under alkali activation, which act as the main binding phases responsible for strength gain and microstructural densification in Fe-rich and slag-rich alkali-activated materials (Lee & Lee, 2015; Wang et al., 2024). These reaction products enhance early-age strength, reduce pore connectivity, and improve durability, including resistance to chemical attack and elevated temperatures in Fe-rich systems.

### 2.2.3 Characterization of Coal Fly Ash

The microstructural and chemical properties of the CFA were characterized via SEM-EDX spectroscopy to evaluate its viability as an aluminosilicate precursor for geopolymerization.

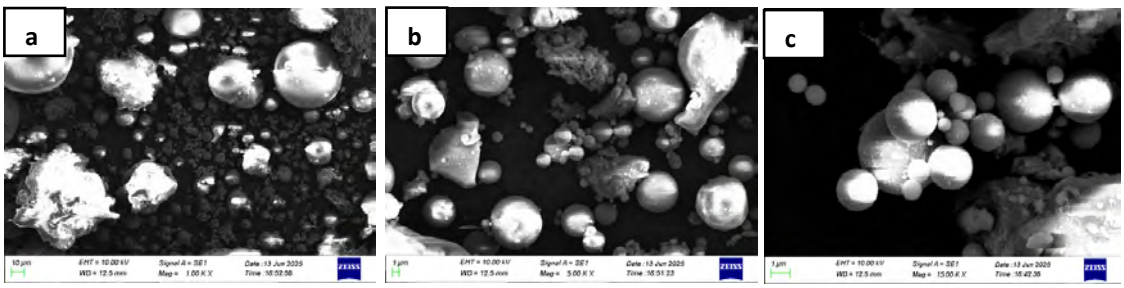



*Figure 5: Surface morphology of coal fly ash - (a) 10 µm size, 1.00 K × magnification, (b) 1µm size, 5.00 K × magnification, (c) 1 µm size, 15.00 K× magnification*

SEM observations at magnifications from 1.00K× to 15.00K× (Figure 4) show that the CFA is a heterogeneous material comprising spherical, irregular, and fine-detritic particles, consistent with the typical morphology of bituminous coal fly ash morphology (Strzałkowska, 2020). The sample is dominated by smooth-surfaced spherical particles, including a substantial proportion of hollow cenospheres, which are characteristically enriched in silica and alumina. These spherical forms enhance pozzolanic reactivity and improve mix workability via a “ball-bearing” effect, which reduces viscosity and

facilitates optimal particle packing, thereby supporting the suitability of the CFA as a precursor for geopolymer binder synthesis (Ma et al., 2021).

EDX analysis (Table 2 and Figure 6), confirms a high concentration of glass-forming oxides essential for geopolymerization. The primary reactive constituents are silica (21.61 wt%) and alumina (12.13 wt%), complemented by notable concentrations of iron (6.48 wt%) and calcium (3.77 wt%). These compositional attributes are consistent with the requirements for Class F fly ash under ASTM C618, a category widely recognized for its efficacy in sustainable geopolymer applications due to its low CaO content and high amorphous phase fraction (Strzałkowska, 2020).

*Table 2: Elemental composition of coal fly ash*

| Element | Si | Al | Ca | Fe | C | O | Na | Mg | K | Ti |
|---|---|---|---|---|---|---|---|---|---|---|
| wt% | 21.61 | 12.13 | 3.77 | 6.48 | 9.99 | 43.06 | 0.17 | 0.60 | 1.29 | 0.90 |
| Atom% | 15.28 | 8.93 | 1.87 | 2.30 | 16.51 | 53.44 | 0.15 | 0.49 | 0.66 | 0.37 |

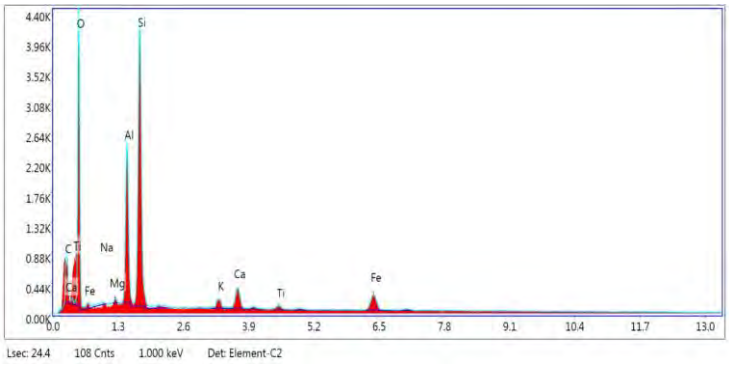



*Figure 6: Elemental composition spectrum of coal fly ash*

The significant combined concentrations of Silica and Alumina are instrumental in facilitating rapid dissolution under alkaline activation. This chemical process leads to the subsequent formation of complex aluminosilicate gels, which serve as the primary binding phases responsible for strength development and microstructural densification within the geopolymer matrix (Pławecka et al., 2022).

## 2.3 MIX DESIGN AND OPTIMIZATION PROCEDURE

### 2.3.1 Initial Reference Mix

Traditional geopolymer concrete mix designs frequently rely on strict stoichiometric molar ratios (such as precise Si/Al or Na/Al elemental targets) or empirical trial-and-error approaches centred purely on workability. However, these conventional alternative methods are often inadequate for soil-based geopolymer systems due to the high physical and chemical heterogeneity inherent in natural soils. Due to the wide variability in precursor materials and the absence of universally accepted guidelines for geopolymer concrete mix design, proportions are typically established through empirical optimization and existing literature.

Accordingly, the initial mix design for this study was adopted from the CFA-based GMC framework proposed by Udawattha and Halwatura (2018). This specific empirical framework was selected over alternative stoichiometric methods because it explicitly accounts for the variable particle size distribution of earth-based matrices. By specifically

integrating the fine, sand, and gravel fractions of the soil, this method successfully optimizes the granular skeleton to minimize voids and ensure structural integrity in mud concrete systems. The reference mix was proportioned by total dry weight, comprising 78% soil, 20% CFA as the primary aluminosilicate precursor, and 2% sodium chloride (NaCl) to increase the ionic strength of the pore solution. To ensure an optimal granular skeleton, the soil fraction was graded to include 5% fines (< 0.425 mm), 55% sand (0.425–4.75 mm), and 40% gravel (4.75–20 mm). For alkaline activation, a 10 M sodium hydroxide (NaOH) solution was prepared using pellets of 99% purity. Finally, the water content was maintained at 15–20% of the total dry mass to ensure adequate workability without compromising the material structural integrity.

### 2.3.2 Optimization Strategy

The optimization of the proposed GMC was conducted in two sequential phases to enhance its overall mechanical performance.

Phase I investigated the influence of curing temperature on the compressive strength of the CFA-based reference mix. To identify the thermal conditions requisite for maximum geopolymeric reactivity and strength development, specimens were subjected to a 6-hour curing period under four specific regimes: ambient temperature, 60°C, 80°C, and 100°C.

Following the thermal optimization of the reference mix, Phase II investigated the functional substitution of CFA with iron slag. The objective was to determine to what extent an iron slag-based GMC could achieve or replicate the maximum compressive strength of the established CFA reference mix. To achieve this, the mix design was systematically refined by evaluating three critical variables concurrently: IS substitution levels (10%, 20%, 30%, and 40% of total dry weight), curing temperatures (ambient, 60 °C, 80 °C, and 100 °C), and curing durations (6, 8, 16, and 24 hours).

## 2.4 MIXING, CASTING, CURING, AND TESTING PROCEDURE

The experimental programme utilized a systematic procedure to ensure the homogeneity of the GMC and the reliability of the mechanical performance. All concrete mixes were prepared using a mechanical mixer under controlled laboratory conditions, employing a two-stage process to promote uniform constituent dispersion and minimize segregation. In the initial dry-mixing stage, the sieved soil, selected precursor (iron slag or coal fly ash), and NaCl were blended for approximately 10 minutes to establish a consistent, homogeneously distributed solid phase prior to alkaline activation.

During the subsequent wet-mixing stage, the 10 M alkaline solution was gradually incorporated to prevent sudden workability loss and maintain appropriate rheological properties. The total mixing duration was strictly maintained at 20 minutes while visually monitoring consistency. After that, a flow table test (BS EN 12350-5:2009) was conducted to assess workability. The fresh GMC was then cast into 100 mm × 100 mm × 100 mm steel cube molds (BS EN 12390-2:2019) and compacted to eliminate entrapped air, ensuring uniform density. Specimens were retained in the molds for 48 hours under ambient laboratory conditions before demolding to facilitate adequate initial setting and preserve early-age structural integrity.

Following demoulding, specimens were subjected to specific curing temperatures (ambient, 60°C, 80°C, or 100°C) for designated durations (6, 8, 16, or 24 hours), depending on the optimization requirements. Upon completing the thermal cycle, these

specimens were transferred to ambient laboratory conditions until testing, allowing further maturation of the geopolymeric binder.

Finally, mechanical performance was evaluated via uniaxial compressive strength testing in accordance with BS EN 12390-3:2002. For each mix proportion, three cube specimens were tested at curing ages of 7, 14, and 28 days. The averaged compressive strength values were used to assess strength evolution and determine the influence of mix composition and thermal curing on the final mechanical behaviour of the GMC.

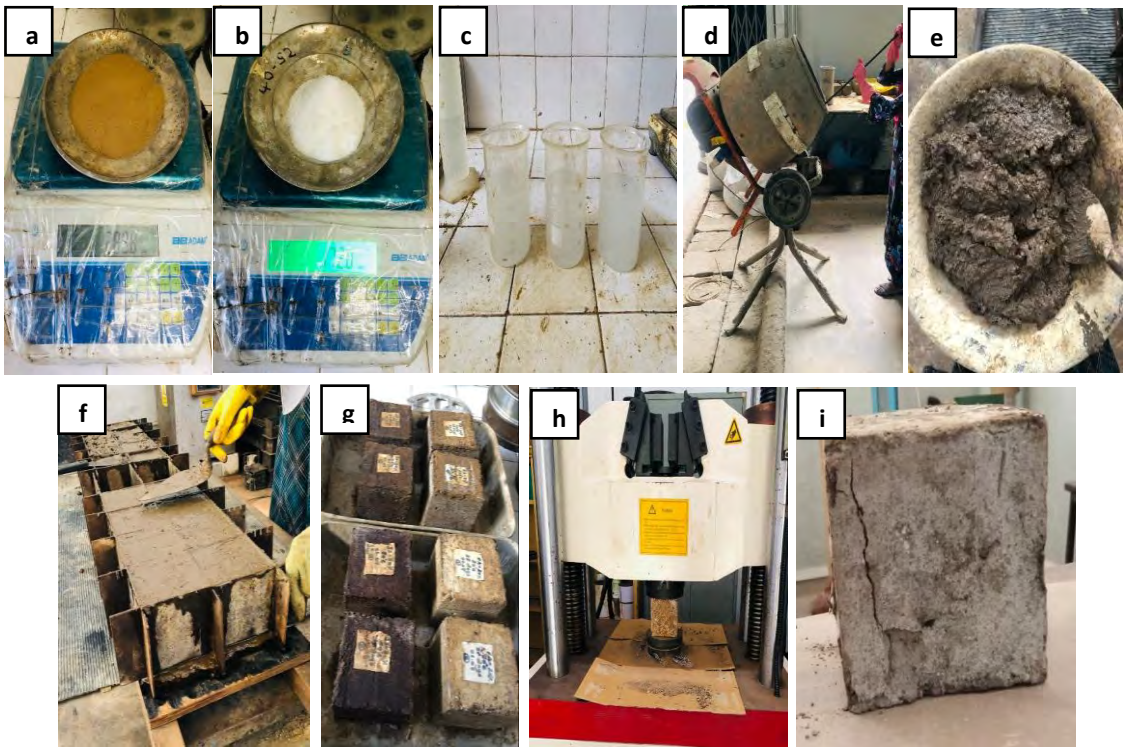



*Figure 7: Experimental work (a), (b) measuring materials, (c) preparing NaOH solution, (d), (e) preparing concrete mix, (f) casting test specimens, (g) curing process, (h) testing specimens using UTM, (i) tested specimen*

# 3. RESULTS AND DISCUSSION

To rigorously assess the statistical significance of the experimental variables, all compressive strength data presented in this study were evaluated using a one-way analysis of variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test using the MINITAB software.

## 3.1 PHASE I: OPTIMIZATION OF CURING TEMPERATURE FOR CFA-BASED GMC

As summarized in Table 3, the thermal regime profoundly influences the rate and extent of geo-polymerization, yielding statistically significant differences in both 14-day ($F(3,8) = 7.16$, $p = 0.0118$) and 28-day ($F(3,8) = 31.82$, $p < 0.001$) compressive strengths.

*Table 3: Compressive strength (Mean ± SD) under various curing temperatures*

| Sample Code | 14-Day Comp. Strength (MPa) | 28-Day Comp. Strength (MPa) |
|---|---|---|
| CFA-RT | 0.95 ± 0.44[b] | 2.37 ± 0.28[b] |
| CFA-60 °C | 0.86 ± 0.35[b] | 1.69 ± 0.27[c] |
| CFA-80 °C | 2.75 ± 0.12[a] | 3.14 ± 0.20[a] |
| CFA-100 °C | 1.84 ± 0.99[ab] | 3.24 ± 0.06[a] |

**Note:** Values within the same column sharing the same superscript letter are not significantly different from each other ($p > 0.05$) based on Tukey's HSD test.

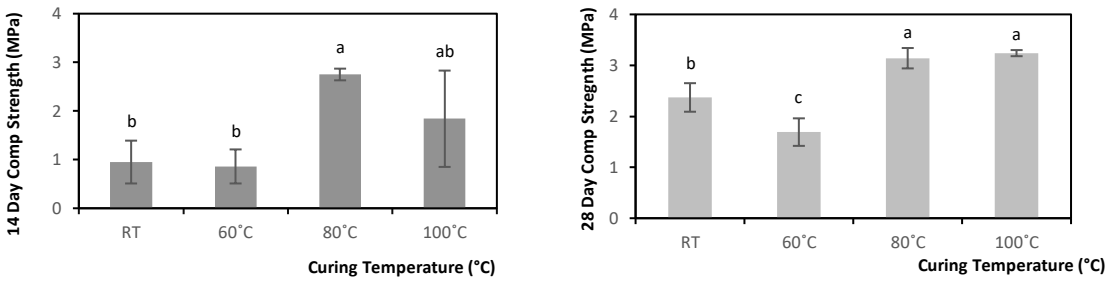



*Figure 8: Effect of curing temperature on 14 and 28-Day compressive strength of CFA- based GMC*

Although the 100 °C curing regime achieved the highest numerical strength at 28 days (3.24 MPa), the 80 °C regime demonstrated superior early-stage performance (2.75 MPa) and avoided the high statistical variability caused by rapid moisture loss. Consequently, while both elevated temperatures reached statistical equivalence in long-term strength development, 80 °C provides a more stable and reliable thermal environment for optimizing structural growth in coal fly ash-based systems.

## 3.2 PHASE II: PRECURSOR SUBSTITUTION AND PARAMETER REFINEMENT

### 3.2.1 Optimization of Iron Slag Content

Following the baseline characterization, Phase II evaluated the substitution of coal fly ash with iron slag at four levels: 10%, 20%, 30%, 40% of the total dry weight. The statistical summary is presented in Table 4.

*Table 4: Compressive strength (Mean ± SD) of GMC at varying iron slag contents*

| Sample Code | 7-Day Comp. Strength (MPa) | 14-Day Comp. Strength (MPa) | 28-Day Comp. Strength (MPa) |
|---|---|---|---|
| IS-10% | 0.11 ± 0.03[c] | 0.12 ± 0.00[d] | 0.21 ± 0.08[c] |
| IS-20% | 0.14 ± 0.02[c] | 0.22 ± 0.03[c] | 0.31 ± 0.04[bc] |
| IS-30% | 0.54 ± 0.06[a] | 0.66 ± 0.02[a] | 0.70 ± 0.02[a] |
| IS-40% | 0.26 ± 0.02[b] | 0.34 ± 0.07[b] | 0.41 ± 0.03[b] |

**Note:** Values within the same column sharing the same superscript letter are not significantly different from each other ($p > 0.05$) based on Tukey's HSD test.

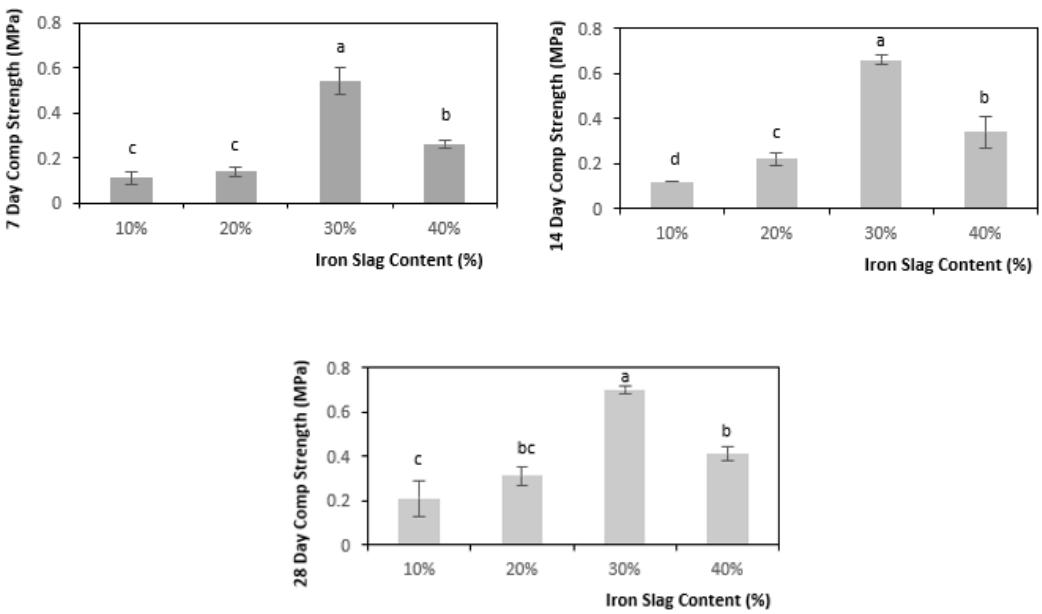



*Figure 9: Effect of IS replacement content on the compressive strength of GMC at 7, 14, & 28 Days*

As illustrated in Table 3 and Figure 9, compressive strength exhibited a distinct parabolic trend, peaking significantly at 30% substitution. This optimal formulation delivered rapid early-age strength (0.535 MPa at 7 days) and a maximum 28-day capacity of 0.698 MPa. Conversely, increasing the slag content to 40% sharply reduced the 28-day strength to 0.410 MPa. This degradation likely stems from precursor agglomeration and an imbalanced Si/Al ratio, which hinders uniform particle dissolution and disrupts matrix integrity, firmly establishing 30% as the optimal replacement ratio.

### 3.2.2 Optimization of Curing Temperature

Following the selection of the 30% iron slag formulation, the thermal curing regime was optimized across four environments: ambient, 60°C, 80°C, and 100°C.

As detailed in Table 5 and Figure 10, curing temperature significantly dictates mechanical performance. Compressive strength peaked significantly at 60 °C, yielding 0.76 MPa at 14 days and 1.49 MPa at 28 days, proving statistically superior to all other thermal regimes.

*Table 5: Compressive strength (Mean ± SD) of 30% iron slag-based GMC at varying curing temperatures*

| Sample Code | 14-Day Comp. Strength (MPa) | 28-Day Comp. Strength (MPa) |
|---|---|---|
| IS-RT | $0.18 \pm 0.02^{d}$ | $0.56 \pm 0.09^{b}$ |
| IS-60 °C | $0.76 \pm 0.05^{a}$ | $1.49 \pm 0.24^{a}$ |
| IS-80 °C | $0.43 \pm 0.03^{c}$ | $0.61 \pm 0.05^{b}$ |
| IS-100 °C | $0.56 \pm 0.07^{b}$ | $0.66 \pm 0.08^{b}$ |

**Note:** Values within the same column sharing the same superscript letter are not significantly different from each other ($p > 0.05$) based on Tukey's HSD test.

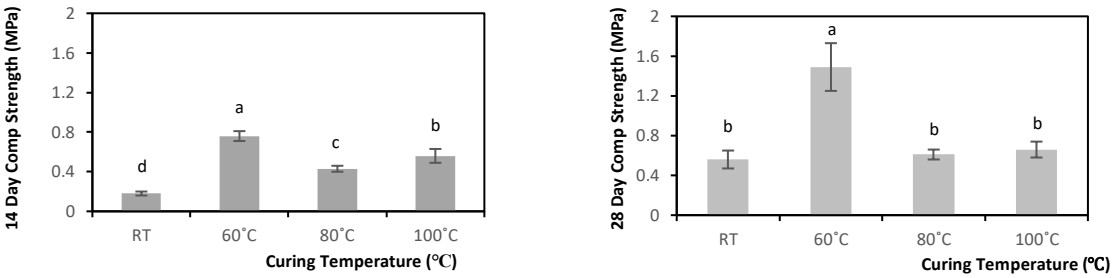



*Figure 10: Effect of curing temperature on the compressive strength of 30% iron slag-based GMC at 14 & 28 days*

These findings align with existing literature Hao et al., (2025) on slag-based geopolymers which demonstrates that higher temperatures cause strength degradation due to rapid moisture loss and shrinkage cracking. Consequently, 60°C is established as the optimal curing temperature for structural development within this matrix.

### 3.2.3 Optimization of Curing Duration

Following the determination of optimal precursor substitution (30% iron slag) and temperature (60 °C), the final phase evaluated curing durations of 6, 8, 16, and 24 hours. The statistical summary is presented in Table 6.

*Table 6: Compressive strength (Mean ± SD) of optimized IS-based GMC at varying curing durations*

| Sample Code | 7-Day Comp. (MPa) | 14-Day Comp. (MPa) | 28-Day Comp. (MPa) |
|---|---|---|---|
| IS-6hrs | $0.26 \pm 0.04^{c}$ | $0.52 \pm 0.06^{c}$ | $0.82 \pm 0.04^{c}$ |
| IS-8hrs | $0.32 \pm 0.04^{bc}$ | $0.66 \pm 0.06^{bc}$ | $1.06 \pm 0.11^{bc}$ |
| IS-16hrs | $0.47 \pm 0.08^{ab}$ | $0.75 \pm 0.05^{b}$ | $1.25 \pm 0.12^{b}$ |
| IS-24hrs | $0.58 \pm 0.08^{a}$ | $0.98 \pm 0.06^{a}$ | $1.60 \pm 0.11^{a}$ |

**Note:** Values within the same column sharing the same superscript letter are not significantly different from each other ($p > 0.05$) based on Tukey's HSD test.

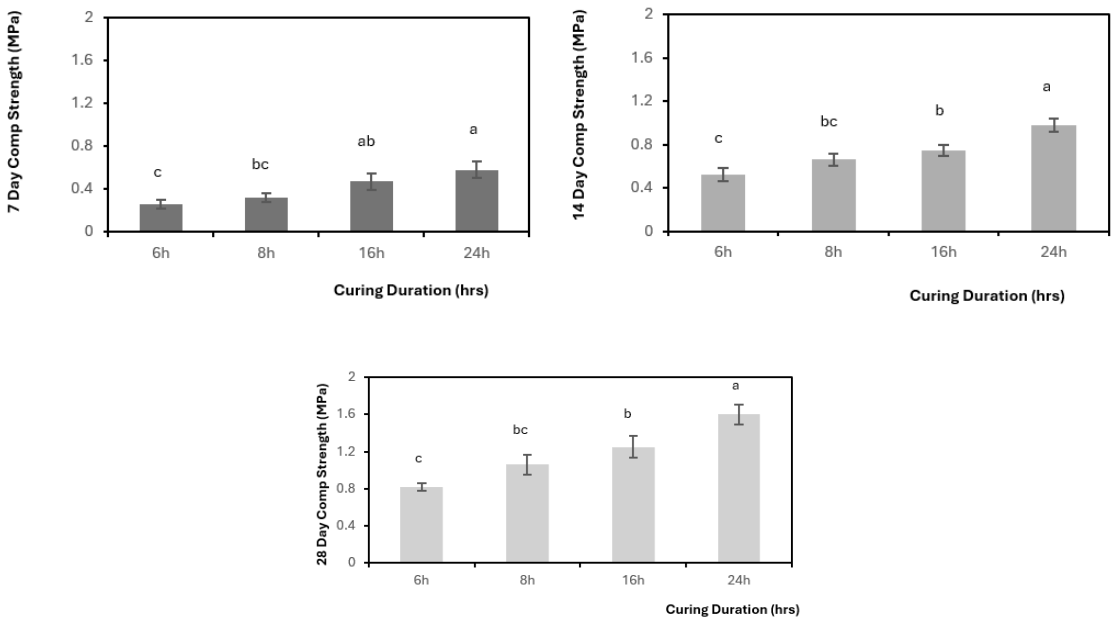



*Figure 11: Effect of curing duration on the compressive strength of optimized IS-based GMC at 7,14, & 28 days*

As illustrated in Table 6 and Figure 11, extending the curing period to 24 hours produced a progressive, statistically significant increase in compressive strength across all testing ages. This 24-hour regime yielded peak capacities of 0.58 MPa at 7 days, 0.98 MPa at 14 days, and 1.60 MPa at 28 days, significantly outperforming the shorter duration.

These results align with Verma and Nigam (2023), which demonstrating that prolonged thermal exposure drives polycondensation kinetics, facilitating thorough aluminosilicate dissolution and the precipitation of denser gel networks. Furthermore, a 24-hour curing period provides an optimal kinetic window that maximizes structural development without inducing the thermal shrinkage risks associated with over-curing. Consequently, 24 hours at 60 °C is definitively confirmed as the optimal curing regime for this iron slag-substituted matrix.

## 4. CONCLUSIONS

This study successfully established the feasibility of substituting CFA with IS in GMC, addressing critical sustainability and resource availability challenges, particularly in regions lacking CFA reserves. Microstructural analyses confirmed that both precursors provide the essential glass-forming oxides requisite for geopolymerization, albeit through distinct gel formation mechanisms dictated by their compositional variations. While the benchmark CFA mix (yielding 3.241 MPa) relies on abundant silica and alumina to develop robust aluminosilicate networks, the optimized IS-substituted matrix incorporating 30% IS and cured at 60 °C for 24 hours drives binder formation through complex Fe-A-S-H and C-A-S-H gels to achieve a maximum 28-day compressive strength of 1.601 MPa.

This mechanical performance demonstrates clear practical feasibility, as compressive strengths in the 1–2 MPa range align with or exceed the minimum requirements of several international standards for non-load-bearing masonry units, such as partition walls (Raja et al., 2023). Furthermore, literature highlights that IS-based geopolymer concretes often exhibit continued strength gain well beyond 28 days under favorable curing regimes, adding to their long-term structural value. However, it is important to note that while a 1.6 MPa capacity is highly suitable for non-structural applications, it may not suffice for environments requiring higher load resistance or severe exposure conditions without further optimization. Ultimately, IS-based GMC serves as an eco-friendly, locally accessible alternative that effectively advances industrial waste valorization and sustainable construction practices.

## 5. RECOMMENDATIONS FOR FUTURE WORK

Future research should prioritize the blending of multi-precursors to address the current load-bearing limitations and further advance the deployment of IS-based geopolymers. Additionally, exploring alternative chemical activation parameters, such as adjusting sodium hydroxide molarity or modifying the silicate-to-hydroxide ratio, may unlock further reactivity within the IS matrix. Finally, to fully validate the real-world applicability of these eco-friendly masonry units, comprehensive Life-Cycle Assessments (LCA) and long-term durability evaluations must be conducted.

# 6. REFERENCES

Arooz, F. R. (2019). *In-situ Mud-Concrete as a material for load-bearing walls and sustainable building practices* [Doctoral dissertation, University of Moratuwa]. University of Moratuwa Institutional Repository. http://dl.lib.uom.lk/handle/123/16439

Arooz, F. R., & Halwatura, R. U. (2018). Case Studies in Construction Materials Mud-concrete block ( MCB ): mix design & durability characteristics. *Case Studies in Construction Materials*, 8(June 2017), 39–50. https://doi.org/10.1016/j.cscm.2017.12.004

Chen, Y., Fan, Y., Huang, Y., Liao, X., Xu, W., & Zhang, T. (2024). A comprehensive review of toxicity of coal fly ash and its leachate in the ecosystem. *Ecotoxicology and Environmental Safety*, 269, 115905. https://doi.org/10.1016/j.ecoenv.2023.115905

Ferreira, R. L. S., Medeiros, M., Pereira, J. E. S., Henriques, G. F., Tavares, J. C., Marvila, M. T., & de Azevedo, A. R. G. (2023). Effects of Particle Size Distribution of Standard Sands on the Physical-Mechanical Properties of Mortars. *Materials*, 16(2), 844. https://doi.org/10.3390/ma16020844

Gayashani, K. G. C., Piyasena, R. K. N. P., Oshadhi, D. A., Young, S. M., & Halwatura, R. U. (2025). Utilization of textile industry by-products to develop and optimize geopolymerized mud concrete for sustainable construction.In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium*. University of Moratuwa. https://doi.org/10.31705/WCS.2025.108

Hao, J., Zhou, Z., Chen, Z., Zhao, Z., & Shen, Y. (2025). Mechanical performance and damage mechanisms of steel slag-cement pasted backfill under high-temperature cured and cyclic static loading for deep-mining applications. *Journal of Materials Research and Technology*, 35, 5698–5716. https://doi.org/10.1016/j.jmrt.2025.02.150

Haustein, E. and Kuryłowicz-Cudowska, A. (2020), "The effect of fly ash microspheres on the pore structure of concrete", *Minerals*, Vol. 10 No. 1, p. 58, doi: 10.3390/min10010058.

Juenger, M. C. G., Winnefeld, F., Provis, J. L., & Ideker, J. H. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research*, 41(12), 1232–1243. https://doi.org/10.1016/j.cemconres.2010.11.012

Pławecka, K., Bazan, P., Lin, W.-T., Korniejenko, K., Sitarz, M., & Nykiel, M. (2022). Development of geopolymers based on fly ashes from different combustion processes. *Polymers*, 14(10), 1954. https://doi.org/10.3390/polym14101954

Lee, N. K., & Lee, H. K. (2015). Reactivity and reaction products of alkali-activated, fly ash/slag paste. *Construction and Building Materials*, 81, 303–312. https://doi.org/10.1016/j.conbuildmat.2015.02.022

Lee, Y. H., Eom, H., Lee, S. M., & Kim, S. S. (2021). Effects of pH and metal composition on selective extraction of calcium from steel slag for Ca(OH)2 production. *RSC Advances*, 11(14), 8306–8313. https://doi.org/10.1039/d0ra08497b

Ma, J., Wang, D., Zhao, S., Duan, P., & Yang, S. (2021). Influence of particle morphology of ground fly ash on the fluidity and strength of cement paste. *Materials*, 14(2), 283. https://doi.org/10.3390/ma14020283

Mohan K, S. M., Kinuthia, J. M., Oti, J., & Adeleke, B. (2025). Geopolymer chemistry and composition: A comprehensive review of synthesis, reaction mechanisms, and material properties—Oriented with sustainable construction. *Materials*, *18*(15), 5432.

Nath, S. K., & Kumar, S. (2013). Influence of iron making slags on strength and microstructure of fly ash geopolymer. *Construction and Building Materials*, 38, 924–930. https://doi.org/10.1016/j.conbuildmat.2012.09.070

Nikolov, A. (2020). Alkali-activated geopolymers based on iron-rich slag from copper industry. *IOP Conference Series: Materials Science and Engineering*, 951, 012006. https://doi.org/10.1088/1757-899x/951/1/012006

Raja, V. K. B., Selvarani, V., Kannan, S., Sujan, S., Sahas, S., Padmapriya, R., Kumar, V. G., & Baalamurugan, J. (2023). Geopolymer based foams from steel slag – A green technology. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.07.156

Shi, X., Zhang, C., Liang, Y., Luo, J., Wang, X., Feng, Y., Li, Y., Wang, Q., & Abomohra, A. (2021). Life cycle assessment and impact correlation analysis of fly ash geopolymer concrete. *Materials*, *14*(23), 7222

Singh, N. B., & Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials*, 237, 117455. https://doi.org/10.1016/j.conbuildmat.2019.117455

Strzałkowska, E. (2020). Morphology and chemical composition of mineral matter present in fly ashes of bituminous coal and lignite. *International Journal of Environmental Science and Technology*, 18(9), 2533–2544. https://doi.org/10.1007/s13762-020-03016-0

Udawattha, C., & Halwatura, R. (2018). Case Studies in Construction Materials Geopolymerized self-compacting mud concrete masonry units. *Case Studies in Construction Materials*, 9, e00177. https://doi.org/10.1016/j.cscm.2018.e00177

United Nations Environment Programme. (2023). *Building materials and the climate: Constructing a new future*. https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future

Verma, M., & Nigam, M. (2023). Investigation on the effect of curing time on the mechanical properties of geopolymer concrete. *AIP Conference Proceedings*. https://doi.org/10.1063/5.0154116

Wang, C., Wu, Y., Xie, L., Yang, Z., Tian, J., Yu, F., Ren, J., & Li, S. (2025). Estimating soil-water characteristic curve from the particle size distribution with a novel granular packing model. *Water Resources Research*, 61(2). https://doi.org/10.1029/2024wr037262

Wang, M., Xu, J., Zhang, X., Tan, L., & Mei, Y. (2024). Mechanical performance optimization and microstructural mechanism study of alkali-activated steel slag–slag cementitious materials. *Buildings*, 14(5), 1204. https://doi.org/10.3390/buildings14051204

Wijepala, W. M. T. B., Young, S. M., & Ishiga, H. (2022). Ancient metalworking at Yodhawewa site, Sri Lanka: Tracing the archaeological and geochemical relationship by analyzing soil and slags. *Archaeological and Anthropological Sciences*, 15(1). https://doi.org/10.1007/s12520-022-01704-1

Zhang, S., Li, Z., Ghiassi, B., Yin, S., & Ye, G. (2021). Fracture properties and microstructure formation of hardened alkali-activated slag/fly ash pastes. Cement and Concrete Research, 144, 106447. https://doi.org/10.1016/j.cemconres.2021.106447

Hansen, S., Shaqman, N. and Darmiyanti, L., 2026. Key issues and root causes in pre-project property selling: A comparative analysis between Indonesia and Malaysia. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1037-1049. DOI: https://doi.org/10.31705/WCS.2026.76. Available from: https://ciobwcs.com/papers/

# KEY ISSUES AND ROOT CAUSES IN PRE-PROJECT PROPERTY SELLING: A COMPARATIVE ANALYSIS BETWEEN INDONESIA AND MALAYSIA

**Seng Hansen[1], Nadrul Shaqman[2] and Lydia Darmiyanti[3]**

## *ABSTRACT*

*Owning a home, whether a landed house or an apartment, is a dream for many people. Property sales continue to increase every year in line with community needs. One strategy used by property developers is pre-project marketing, in which properties are sold before completion or even before construction begins. Although it offers more competitive property prices, this practice poses various risks and challenges, making it an interesting topic to study. This study aims to investigate the key issues and root causes of recurring pre-project property-selling disputes in Indonesia and Malaysia. Using a comparative case study approach, this study identified seven key issues: abandoned/delayed projects, failed/late unit handovers, consumer financial losses, legal/licensing issues, developer bankruptcy/crisis, weak consumer protection, and government intervention. In addition, this study identified seven root causes: weak project governance, fragile financing structure, risky pre-project sales scheme, weak regulation and oversight, conflicts of interest/ethics, lack of an early warning system, and dependence on the government. The results of this study highlight the social dimension of sustainable housing, focusing on strengthening the property sector and regulatory reforms that protect consumers in both countries.*

***Keywords:*** *Marketing strategy; Pre-project selling; Property sector; Risk; Sustainable housing.*

## 1. INTRODUCTION

Owning a home, whether landed or built, has become a dream for many. This is evident in the increase in property sales over the past two decades (except during the global financial crisis and COVID-19) in various countries, including Indonesia and Malaysia. Property developers have been astutely seizing this opportunity to sell their properties. One frequently employed marketing strategy is pre-project selling. Pre-project selling involves marketing and selling properties to consumers before construction is complete

[1] Associate Professor, Civil Engineering Department, President University, Indonesia, seng.hansen@president.ac.id
[2] Senior Lecturer, Faculty of Business, UNITAR International University, Malaysia, nadrul.shaqman@unitar.my
[3] Senior Lecturer, Civil Engineering Department, President University, Indonesia, lydia.darmiyanti@president.ac.id

or begins. Thus, property developers sell residential units solely on the basis of the design and building plans (Rosalind & Sari, 2022).

This pre-project selling mechanism offers several advantages for both developers and consumers. For developers, it allows them to obtain fresh funding to operate their businesses. For consumers, it offers more affordable prices than finished properties. Despite these advantages, this mechanism poses several risks, especially for consumers who purchase property through this pre-project sales mechanism (Elysia et al., 2020; Rosalind & Sari, 2022).

Ideally, the pre-project selling mechanism comprises four main stages: pre-sale, construction fundraising, project execution, and unit handover. The first stage is pre-sale, where property developers market their units through various promotions and advertisements that showcase the building's design and specifications. The second stage is fundraising, in which property developers raise funds from consumers to finance construction. These funds are collected in the form of advance payments or instalment payments made by consumers who have signed the Sales and Purchase Agreement. The third stage is project execution, in which the property developer carries out the work in accordance with the marketed concept and design. The final stage is the handover of the completed unit to the consumer, marking the end of the pre-project selling practice (Therik & Gultom, 2024).

This pre-project selling mechanism is widely used in developing economies where there is a need for affordable housing for the community. However, consumers must be aware of risks, such as delayed unit handover, halted construction, and weak consumer legal protection in the event of problems. In Indonesia, this pre-project selling mechanism has become popular since the 2000s (Therik & Gultom, 2024), especially in urban areas such as Greater Jakarta (now the world's most populous city), Surabaya, and Medan. Similarly, Malaysia was the first to adopt this mechanism (often referred to as the sale of property under construction) (Basir, 2025), particularly in major cities like Kuala Lumpur, Klang Valley, Johor Bahru, and Penang. However, a number of problems and disputes frequently arise in both countries.

For example, in Indonesia, property disputes frequently involve consumers and developers, as seen in the legal cases involving the Jakarta Tower and the Aspen Peak Residence in Jakarta, the Malioboro Park View apartment in Yogyakarta, and the Meikarta apartment in Cikarang (Hansen, 2025). Similarly, in Malaysia, several cases have occurred, including the Residensi Hektar Gombak in Kuala Lumpur, the Peak Project in Tebrau, the Jade Palace in Banga Bay, and the Sovereign Bay Condominium in Johor Bahru (Ariffin et al., 2019). These cases represent just a few examples of property disputes arising from the sale of property before completion, resulting in losses for consumers who have already paid down payments and instalments or even fully paid off their residential units (Tan et al., 2024; Hansen, 2026).

Previous studies on property-selling disputes have primarily focused on legal compliance (Elysia et al., 2020; Rosalind & Sari, 2022), buyer protection (Therik & Gultom, 2024; Tan et al., 2024; Hansen, 2026), and contractual enforcement (Rahmayanti & Setiawati, 2021; Hansen, 2025), with limited attention to the underlying causes of recurring disputes in pre-project selling practices. Considering the complexity and social impact of this pre-project selling mechanism, it is important to conduct a study that investigates the main issues and root causes arising from this practice.

Moreover, comparative analyses across countries with similar socio-legal contexts are still scarce. Indonesia and Malaysia are selected for their comparable legal systems, rapid growth in property markets, and the prevalence of pre-project selling schemes, making them relevant for cross-country analysis. Therefore, this study aims to fill this gap by identifying the key issues contributing to recurring pre-project selling disputes in Indonesia and Malaysia and analysing the root causes underlying these disputes from legal, contractual, and managerial perspective. Thus, this research is expected to provide theoretical and practical contributions to the social and property markets in both countries and can serve as a reference for similar practices worldwide.

## 2. METHOD

To achieve these objectives, this research employed a narrative review and comparative case study approach. A narrative review is a descriptive literature review approach that provides an initial understanding of a research topic by synthesising existing literature. Narrative reviews emphasise the ability to integrate diverse literature to obtain findings and perspectives relevant to the research objectives (Snyder, 2019). This approach is reinforced by comparative case studies, which provide a deeper understanding of the research topic through real-world examples.

In this study, a protocol comprising six steps is implemented (Figure 1). The first step is identifying the topic/problem formulation and research objectives. In this research, the topic is the issues and root causes of pre-project property selling in Indonesia and Malaysia. The second step is case selection, which involves identifying and selecting several problematic actual cases relevant to the research topic. Next is data collection, which is conducted extensively by gathering data from various sources. The research sources in this study include scientific articles, government reports, national media news, and court decisions/legal documents. The fourth step is to assess the reliability and relevance of each collected source to ensure the information is accurate and relevant to the research topic. The fifth step is thematic analysis, where the collected information is grouped by theme and analysed narratively to identify relationships, comparisons, and meanings. The final step is to develop a narrative that reports the findings and answers the research questions.

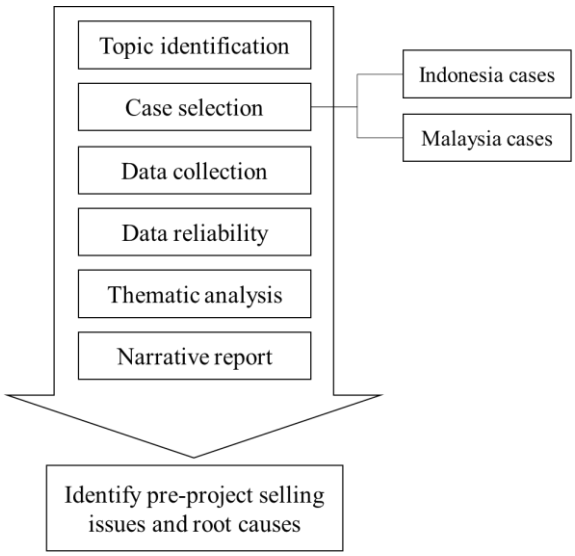



*Figure 1: Research protocol*

Table 1 displays the case studies used in this research. These four case studies were selected based on several considerations, including project scale (medium to large), geographic location (across different cities and countries), and legal system (civil-law and common-law countries). Case 1 is the Meikarta Area development project in Indonesia, a mega-project located in the Greater Jakarta area and managed by a private developer. Case 2, also representative of the Indonesian context, is the Malioboro Park View apartment project, a mid-scale project by a private developer in Yogyakarta. Case 3 represents the Malaysian context: the Sovereign Bay project in Johor Bahru, managed by a private developer in collaboration with foreign partners. Case 4 is the Residensi Hektar Gombak project in Kuala Lumpur, initiated by the Malaysian government. The diversity of the selected cases allows for comparative analysis across countries and project types so the research findings are not limited to a single or local case. This also provides broader global insights.

Furthermore, the selection of these four cases was based on sufficient public documentation, including government reports, court decisions and media coverage. Comprehensive documentation makes the findings more objective and verifiable, and allows for chronological arrangement. Some cases have even been used as study material in various scientific articles, for instance, the Residensi Hektar Gombak Project by Ariffin et al. (2019), the Meikarta Project by Therik and Gultom (2024), and the Malioboro Park View Project by Hansen (2025).

Data collection was conducted using a targeted literature review approach that focused on selected case studies. The literature was collected selectively based on its relevance to each pre-project property sale dispute case analysed. Inclusion criteria included literature discussing similar dispute contexts, legal frameworks, and property sale practices during the pre-project stage related to the cases studied. Literature irrelevant to the case context was excluded from the analysis. The selection process was carried out systematically by examining publication sources and supporting documents to ensure the information was appropriate and credible. This approach was chosen as it allows for a more in-depth and contextual analysis of each case studied.

*Table 1: Case study profile*

| Code | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Country | Indonesia | Indonesia | Malaysia | Malaysia |
| Project name | Meikarta Project | Malioboro Park View Project | Sovereign Bay Project | Residensi Hektar Gombak Project |
| Location | Cikarang | Yogyakarta | Johor Bahru | Kuala Lumpur |
| Start | 2017 | 2016 | 2015 | 2018 |
| Planned completion | 2019-2020 | 2018 | 2019 | 2022 |
| Status | It was stalled, now it's been continued again | Stalled | It was stalled, now it's been continued again | It was stalled, now it's been continued again |

# 3. RESULTS

## 3.1 CASE 1: THE MEIKARTA PROJECT

The Meikarta Project is a mega-development comprising vertical residential and multipurpose developments. With a total investment of IDR 278 trillion, the project has

been aggressively promoted through pre-project sales since 2017, attracting thousands of buyers. The project, initiated by PT Lippo Cikarang Tbk, is located in Cikarang, Bekasi, West Java, with a planned area of 5,000 hectares (Putri & Pratiwi, 2022). However, during its development, the mega-project encountered obstacles that led to its suspension (Asmaaysi, 2025a).

One of the main issues facing the project was the delay in handing over apartment units to buyers who had made instalment payments or paid in full through the pre-project sales system (Juwita, 2025b). Even after the handover deadline passed, the project showed no significant progress, leading to consumer complaints that described it as stalled (Asmaaysi, 2025b). According to the Ministry of Housing and Settlement (PKP), hundreds of consumers filed complaints and requested refunds for their payments (Saputra, 2025).

Another issue facing the project was corruption in the acquisition of land and building permits. This practice was uncovered by the Corruption Eradication Commission (KPK) and led to the arrest of local government officials and company leaders. This contributed to delays and damaged the project's credibility, as it was marketed even though it had not yet obtained all required permits (Lukita & Pusparisa, 2025).

On the other hand, the Meikarta megaproject requires significant investment funds. However, negotiations for foreign investment failed, forcing the developer to restructure its funding (Juwita, 2025a). This is also slowing work progress, leading to delays in project completion. Another frequently raised issue was the lack of transparency in information provided to consumers, particularly regarding project progress, certainty of unit delivery, and the legal status of unit certificates.

Prolonged conflicts and complaints have led many consumers to question the ineffectiveness of regulations and consumer protection (Simamora et al., 2024). In 2025, the government, through the Ministry of Housing and Settlement (PKP) and related agencies, attempted to facilitate mediation between consumers and the company. Some consumers have received early refunds as part of the resolution process.

## 3.2 CASE 2: THE MALIOBORO PARK VIEW PROJECT

The Malioboro Park View project is a mid-scale apartment project in Sleman, Yogyakarta. It was managed by a private property developer and marketed from 2016 to 2018 through a pre-project selling system. This strategy successfully attracted hundreds of consumers who purchased units with either cash or credit. However, several serious problems arose, causing the project to stall (Leon, 2025).

The most significant issue was the failure to hand over apartment units to buyers. Many buyers had already paid in full for their units. Unfortunately, the apartment units were not yet complete, and the building sustained extensive damage due to the developer PT's neglect. Malioboro Ensu Sejahtera. The developer was declared bankrupt by the Semarang Commercial Court in 2021. This further complicated the situation for consumers, as the developer failed to fulfil its obligations (Harminanto, 2025b).

Consumers also demanded accountability from the Bank BTN Yogyakarta Branch for disbursing loans (KPA) and supporting project financing, despite the project being deemed problematic and lacking complete permits. This led consumers to demand

repayment of the loan funds and accountability from the bank for unclear ownership (Sihono, 2024).

Allegations of fraud stem from the fact that the project was marketed through a pre-project selling mechanism despite not yet having a building permit (Palupi, 2025). Unfortunately, several consumers who stopped making instalment payments encountered issues with their Bank Indonesia (BI) credit records, which negatively affected their access to bank loans and credit. Consequently, hundreds of consumers sought assistance from the Yogyakarta Special Region (DIY) Regional People's Representative Council (DPRD) to resolve the disputes (Harminanto, 2025a). They even reported the alleged fraud to the Yogyakarta Regional Police against the developer, the bank, the curator, and the notary involved.

### 3.3 CASE 3: THE SOVEREIGN BAY PROJECT

The Sovereign Bay project is a waterfront condominium project located in Johor Bahru, Malaysia. The project began marketing in mid-2010 and attracted interest from buyers in Malaysia and Singapore. The project was initiated by UE E&C Sanjia (M) Sdn. Bhd., a joint venture between Sichuan Sanjia Real Estate Group of China and UE E&C of Singapore (Yusof, 2025).

The project was originally scheduled for completion in October 2019, but the building remains unfinished. The project was even categorised as abandoned by the Malaysian Ministry of Housing and Local Government due to its failure to complete within the planned timeframe and the absence of significant construction activity for more than six consecutive months (Ali, 2021).

This case highlights structural issues in the Malaysian property sector, particularly in large-scale projects involving foreign investors, joint-venture developers, and cross-border buyers. As in Indonesia, uncertainty regarding project completion and poor communication led to conflicts between developers and buyers, which escalated into disputes. However, the financial losses were borne more heavily by buyers, underscoring the need for stronger consumer protection and stricter government oversight in the Malaysian property sector.

### 3.4 CASE 4: THE RESIDENSI HEKTAR GOMBAK PROJECT

The Gombak Hectares Residency project in Kuala Lumpur is a housing project initiated by the Malaysian government. It consists of five 46-story residential blocks, each with 2,400 units. As part of the government initiative, the project was marketed in 2018 at affordable prices, resulting in immediate sell-out (Basir, 2025).

However, the project encountered various challenges during its execution, resulting in delays in completion (Selvam, 2024). According to the Sale and Purchase Agreement, the completion date was May 2022. However, the project remains unfinished. Consequently, the Malaysian Housing Authority (MPA) has classified the project as a "sick" project (KPKT, 2024).

In 2025, the Ministry of Housing and Local Government (KPKT) injected RM125 million into the project to continue (KPKT, 2025). This case demonstrates that even government-initiated projects are not free of issues, including funding constraints and delays, and that government intervention is required to address them.

# 4. DISCUSSION

Through the analysis, seven key issues were identified in pre-project selling practices in both countries. Table 2 presents a comparison of these seven issues across each case study. The first and most prevalent issue was the abandonment or delay of projects. This issue arose in all cases due to the project's delayed progress. In Malaysia (Cases 3 and 4), the projects were even classified as sick projects. Meanwhile, in Indonesia (Cases 1 and 2), there was no specific government classification, but the public generally considered the projects stalled. By the end of 2025, Cases 1, 3, and 4 had resumed, but Case 2 remained stalled with no clarity for buyers.

The second issue was failed/late unit handovers resulting from delayed/abandoned projects. This issue highlights the failure to deliver the purchased property units, even though they have fulfilled or fully paid their obligations. This also relates to the third issue, consumer financial losses. Buyers are forced to bear economic losses due to ongoing bank instalments, loan interest, and other unnecessary costs, such as temporary rental fees and dispute-resolution fees. In Case 3, which involved a foreign buyer, the losses were felt across borders.

Further legal and licensing issues tended to emerge more frequently in cases in Indonesia than in Malaysia. In Case 1, a criminal case arose due to bribery in obtaining permits, while in Case 2, there were also problems with permits that had not yet been processed, but the project had already been marketed through pre-project selling mechanisms. Issues of developer bankruptcy/crisis also emerged, particularly in Case 2, where the developer was declared bankrupt by the court. In Cases 1, 3, and 4, developers faced funding difficulties that hampered project progress.

The final two issues, weak consumer protection and government intervention, also emerged in all cases, but with varying intensity. In Cases 1 and 2, buyers sought legal assistance from the Consumer Protection Agency, ministries, and even the House of Representatives (DPR) to resolve delayed project completion. This was also the case in Case 3, which involved a cross-border buyer, and Case 4, which involved a government project.

*Table 2: Comparative analysis of pre-project selling issues*

| Key Issues | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Abandoned/Delayed Projects | Dominant | Dominant | Dominant | Dominant |
| Failed/Late Unit Handovers | Dominant | Dominant | Dominant | Dominant |
| Consumer Financial Losses | Dominant | Dominant | Dominant | Dominant |
| Legal/Licensing Issues | Dominant | Dominant | Not Dominant | Not Dominant |
| Developer Bankruptcy/Crisis | Not Dominant | Dominant | Dominant | Dominant |
| Weak Consumer Protection | Dominant | Dominant | Dominant | Dominant |
| Government Intervention | Dominant | Not Dominant | Dominant | Dominant |

Next, this study investigates the root causes of issues in pre-project selling practices. In general, case analysis in both countries reveals similar root causes, stemming not only from legal violations but also from weak governance structures and business models.

There are at least seven root causes of various pre-project selling issues, as presented in Table 3.

Poor project governance is the primary root cause, as many property projects are implemented without a robust project governance system. This is indicated by unrealistic planning, inefficient time and cost control, weak internal oversight, and the absence of early risk management. Property developers often focus on aggressive marketing without adequate financial preparedness. Case 1 illustrates how a megaproject can be marketed without complete permits and stable governance. Case 2 also demonstrates licensing and project control issues that lead to project stagnation and developer bankruptcy. Case 3 involves the management of a cross-border project (Singapore, China, and Malaysia) without effective coordination. Meanwhile, Case 4, a government-initiated project, continues to experience weak oversight of project implementation.

The second root cause is a fragile financial structure, with projects relying on pre-project sales as a primary source of cash flow, long-term bank loans, and foreign investment, all of which are unstable. When obstacles (whether related to permits, capital, or legal issues) arise, project funding is disrupted, and the project is halted, resulting in losses for consumers. Case 3, for example, is a project heavily reliant on foreign capital. Case 2, on the other hand, shows how debt far exceeded the asset value, leading to the developer's bankruptcy. Case 1, a mega-project with enormous financing needs, failed to secure foreign investors, while Case 4 required a government bailout. This demonstrates that pre-project financing for sales is risky and financially unsustainable.

Undeniably, the practice of pre-project sales carries high risks, as units are sold before construction is completed, and the legal system offers no robust guarantees in the event of developer default. Thus, the project risk is transferred to consumers. This is evident in all cases where large sales were made despite incomplete permits (Cases 1 and 2) and without precautions (Cases 3 and 4).

Although Indonesia and Malaysia both have regulations regarding property marketing through pre-project sales mechanisms, oversight remains weak, and sanctions are not stringent. This creates a moral hazard for developers. This is evident in all cases. The permit violation in Case 1 was only addressed after it reached the legal realm. In Cases 2 and 3, no quick solutions were implemented to address the existing problems, leading to customer complaints and even legal disputes. Meanwhile, in Case 4, government intervention only occurred after the crisis.

In several cases, unhealthy relationships were discovered between developers and officials to expedite permit issuance (Case 1), and business decisions were found to be unfounded or based on technical feasibility or professional negligence (Case 2). This suggests conflicts of interest and unethical practices in Indonesia. On the other hand, the Malaysian cases reflect systemic weaknesses rather than explicit criminal violations.

Another key factor is the lack of an early warning system to detect project delays, halt sales early, and protect new buyers from the risk of project failure, which contributed to these pre-project sales problems. For example, in Cases 1 and 2, sales proceeded despite emerging problems. Similarly, in all cases, buyers remained bound by their obligations even if project progress stalled.

When projects failed or encountered obstacles, the solution almost always involved government mediation, bailouts, or state rescue. This demonstrates the failure of market

mechanisms and private contracts to function effectively. This reliance on government intervention is evident in Case 1, where the government facilitated refund negotiations with the developer; Case 2, where buyers requested the Regional People's Representative Council (DPRD) and authorities to intervene to complete the stalled project; Case 3, where the Ministry requested intervention; and Case 4, where the government intervened directly.

*Table 3: Comparative analysis of root causes*

| Root Causes | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Weak project governance | Dominant | Dominant | Dominant | Dominant |
| Fragile financing structure | Dominant | Dominant | Dominant | Dominant |
| Risky pre-project selling | Dominant | Dominant | Dominant | Dominant |
| Weak regulation and oversight | Dominant | Dominant | Dominant | Dominant |
| Conflicts of interest/ethics | Dominant | Dominant | Not Dominant | Not Dominant |
| No early warning system | Dominant | Dominant | Not Dominant | Not Dominant |
| Dependence on the government | Dominant | Dominant | Dominant | Dominant |

The findings show both alignment and divergence with existing literature. Consistent with prior studies, issues such as project delays, failed unit handovers, and consumer financial losses confirm that pre-project property selling inherently carries significant risks, particularly due to uncertainties in construction progress and financing structures (Elysia et al., 2020; Rahmayanti & Setiawati, 2021; Adagba et al., 2023; Hansen, 2026). These similarities reinforce the argument that such disputes are not isolated cases but represent recurring patterns identified in previous research.

However, this study also reveals several important differences. While existing literature tends to emphasise legal and contractual dimensions (Rosalind & Sari, 2022; Hansen, 2025), the findings highlight deeper structural root causes, including weak project governance, fragile financing models, and the absence of early warning systems. These factors demonstrate that the problem extends beyond legal non-compliance, pointing instead to systemic weaknesses in how property projects are planned, financed, and monitored (Chawla & Kumar, 2022; Wang, 2024).

In addition, this study offers unique comparative insights between Indonesia and Malaysia. In the Indonesian context, disputes are more strongly associated with regulatory enforcement gaps, explicit legal violations, and ethical issues such as conflicts of interest (Elysia et al., 2020; Simamora et al., 2024; Therik & Gultom, 2024). In contrast, the Malaysian cases reflect more systemic and institutional weaknesses, supported by relatively more structured regulatory mechanisms, such as formal project classification, although implementation challenges remain (Ariffin et al., 2019; Mohamad & Hassan, 2020). These differences can be attributed to variations in governance practices, regulatory enforcement, and market structures in both countries, highlighting the importance of context-specific approaches in addressing pre-project property-selling disputes.

The findings of this study suggest that problematic property projects are not accidental but rather represent structural problems in the governance of property development and financing. The theoretical implication is the need to strengthen the analytical framework for property projects, focusing not only on financial and technical feasibility but also on governance (transparency and accountability), risk management and consumer protection as key variables (Chawla & Kumar, 2022; Wang, 2024). Therefore, this study enriches the literature on project management and property economics, particularly in developing countries that still rely on pre-project sales practices.

From a policy and regulatory perspective, the findings of this study imply the need to reform the property consumer protection system by strengthening oversight from the early stages of a project, restricting unit sales before the project is ready, and imposing strict sanctions on developers who fail to fulfil contractual obligations. Furthermore, the government needs to establish an early warning system that tracks the physical progress and financial health of projects and developers, enabling interventions before projects are ultimately halted or abandoned. This will minimise the risk of consumer losses.

This research has important practical implications for property developers, banks, and investors, encouraging them to apply stronger prudential principles in the financing and implementation of property projects. Developers are urged to improve project governance and transparency, while financial institutions need to conduct due diligence that focuses not only on collateral value but also on the project's long-term sustainability. For consumers, these findings underscore the importance of legal and financial literacy in property transactions, ensuring that purchasing decisions are based not only on price and promotions, but also on the developer's legality and credibility.

## 5. CONCLUSIONS

This research highlights real-world problems that frequently occur in the property sector. By examining four problematic property projects in Indonesia and Malaysia, this study offers a comprehensive and practical perspective on the issues and root causes of pre-project selling practices. The analysis shows that project failures are not solely the fault of property developers, but rather reflect systemic problems in project governance, financing structures, and consumer protection mechanisms in the property sector, which relies on pre-project sales. The recurring pattern of stalled projects, delayed deliveries, consumer financial losses, and government intervention underscores the need for comprehensive reforms to property regulations, oversight and business practices. Without these structural improvements, the risk of similar cases recurring remains high, eroding public trust in the property industry.

The practice of pre-project selling, which has become a crucial tool in the development of the property sectors in Indonesia and Malaysia, still faces fundamental problems that require urgent addressing, including weak project governance, fragile financing structures and weak regulation and oversight. Legal differences between Indonesia and Malaysia do not fully address the disputes arising from this practice, as the root causes are not only normative but also structural and managerial. Understanding these root causes is crucial not only for regulators but also for developers and financial institutions to ensure that future pre-sale home marketing practices are more sustainable and ethical. Furthermore, pre-sale policy reforms should highlight public transparency, financial oversight, and effective consumer protection.

Thus, this research has clear significance both academically and practically. Academically, this study contributes to the literature on pre-project property sale disputes by identifying key issues and root causes that have not been widely studied, particularly in a comparative context across developing countries. In practice, the results of this study are expected to inform stakeholders, including developers, consumers, and regulators, in formulating dispute-prevention strategies and improving the effectiveness of existing policies and practices.

On the other hand, it is worth noting that this study has several limitations. First, the number of case studies remains limited, making it less representative of all pre-project property selling practices in Indonesia and Malaysia. Second, the approach used is a targeted, case-based literature review, thus heavily dependent on the availability and quality of data from existing sources. Third, this study did not include direct empirical data such as interviews with all stakeholders, thus the perspectives obtained are still limited. Therefore, future research is recommended to use a larger number of cases and a mixed-methods approach to obtain more comprehensive results.

## 6. ACKNOWLEDGEMENTS

The authors would like to thank the UNITAR International University and President University for providing the research matching grant.

## 7. REFERENCES

Adagba, T., Shamsudeen, H., & Ati, J. O. (2023). An analysis of factors causing failures and abandonment of construction projects in Kaduna state, Nigeria. *Global Journal of Business Economics and Management, 13*(3), 215-230. https://doi.org/10.18844/gjbem.v13i3.8853

Ali, K. (2021, March 20). Pembeli kediaman Sovereign Bay mohon campur tangan kerajaan. Utusan.Com. https://www.utusan.com.my/berita/2021/05/pembeli-kediaman-sovereign-bay-mohon-campur-tangan-kerajaan/

Ariffin, M. N., Razak, D. A., & Imtiyaz, M. N. M. (2019). Perception of stakeholders on abandoned housing projects in Malaysia. *International Journal of Islamic Economics and Finance, 2*(1), 131-148. https://doi.org/10.18196/ijief.2118

Asmaaysi, A. (2025a, April 10). Konsumen Meikarta curhat 10 tahun tak kunjung dapat unit hunian. Bisnis.Com. https://ekonomi.bisnis.com/read/20250410/47/1868176/konsumen-meikarta-curhat-10-tahun-tak-kunjung-dapat-unit-hunian

Asmaaysi, A. (2025b, July 22). James Riady tegaskan Meikarta bukan proyek mangkrak, Jelaskan kronologinya! Bisnis.Com. https://ekonomi.bisnis.com/read/20250722/45/1895497/james-riady-tegaskan-meikarta-bukan-proyek-mangkrak-jelaskan-kronologinya

Basir, E. (2025, August 24). MADANI government offers new hope for sick, abandoned housing projects. Bernama. https://www.bernama.com/en/news.php?id=2459978

Chawla, N., & Kumar, B. (2022). Does Indian real estate regulation protect urban homebuyers? policy implications. *Cogent Business & Management, 9*(1), 2117164. https://doi.org/10.1080/23311975.2022.2117164

Elysia, D., Pradana, Z., Affani, R., & Rahman, A. (2020). Tinjauan yuridis transaksi jual beli properti melalui Pre-Project selling. *Jurnal Education and Development, 8*(3), 14–20. https://media.neliti.com/media/publications/561734-juridical-review-of-selling-property-tra-6724f733.pdf

Hansen, S. (2025). Breach of contract in the pre-project selling of the Malioboro Park View apartment in Sleman, Yogyakarta, Indonesia. *Emerald Emerging Markets Case Studies, 15*(4), 1–7. https://doi.org/10.1108/EEMCS-04-2025-0214

Hansen, S. (2026). Legal case study on indent house purchasing in Indonesia. *Journal of Property, Planning and Environmental Law*, 18(1), 20-40. https://doi.org/10.1108/JPPEL-03-2025-0026

Harminanto, F. (2025a, January 22). Wakil Ketua DPRD DIY terima aspirasi korban Malioboro Park View, putus asa kehilangan hak. Krjogja.Com. https://www.krjogja.com/yogyakarta/1245557017/wakil-ketua-dprd-diy-terima-aspirasi-korban-malioboro-park-view-putus-asa-kehilangan-hak

Harminanto, F. (2025b, July 25). Pertanyakan nasib, korban Malioboro Park View kembali datangi DPRD DIY. Krjogja.Com. https://www.krjogja.com/yogyakarta/1246348224/pertanyakan-nasib-korban-malioboro-park-view-kembali-datangi-dprd-diy

Juwita, R. (2025a, March 28). Lippo Group pledges to "resolve" Meikarta project, ministry says. The Jakarta Post. https://www.thejakartapost.com/business/2025/03/28/lippo-group-pledged-to-resolve-meikarta-project-ministry-says.html#:~:text=Once%20touted%20as%20the%20Riady,the%20country's%20notoriously%20congested%20capital.

Juwita, R. (2025b, April 13). Meikarta consumers can claim full refund on stalled units, govt says. The Jakarta Post. https://www.thejakartapost.com/business/2025/04/13/meikarta-consumers-can-claim-full-refund-on-stalled-units-govt-says.html

KPKT. (2024). Status semasa Projek Residensi Hektar Gombak (Residensi Wilayah) oleh Hektar Aneka Sdn. Bhd. KPKT. https://www.kpkt.gov.my/kpkt/resources/user_1/media_akhbar/2024/SM_STATUS_PROJEK_RESIDENSI_HEKTAR_GOMBAK_(RESIDENSI_WILAYAH).pdf

KPKT. (2025). Hasil usaha gigih KPKT, akhirnya kerja pembinaan 2,400 unit Residensi Hektar Gombak (Residensi Wilayah) dipulihkan setelah 7 Tahun. KPKT. https://www.kpkt.gov.my/index.php/pages/view/3470?mid=764

Leon, Y. (2025, January 22). Tuntut penyelesaian masalah apartemen, korban Malioboro Park View mengadu ke DPRD DIY. Harian Jogja. https://jogjapolitan.harianjogja.com/read/2025/01/22/510/1201741/tuntut-penyelesaian-masalah-apartemen-korban-malioboro-park-view-mengadu-ke-dprd-diy

Lukita G, B., & Pusparisa, Y. (2025, April 23). Lippo Group promises to refund Meikarta Apartment victims' funds. Kompas.Com. https://www.kompas.id/artikel/en-lippo-group-janji-refund-dana-korban-apartemen-meikarta

Mohamad, N. N., & Hassan, R. (2020). Understanding abandoned housing projects in Malaysia and the protection for home buyers. *International Journal of Islamic Economics and Finance Research, 3*(2), 77-90. https://doi.org/10.53840/ijiefer41

Palupi, Y. (2025, January 24). DPRD DIY menerima aduan korban Apartemen Malioboro Park View. Koran Bernas. https://koranbernas.id/dprd-diy-menerima-aduan-korban-apartemen-malioboro-park-view

Putri, D., & Pratiwi, I. (2022, December 12). Lini masa kasus Meikarta, dari "Aku Ingin Pindah ke Meikarta" sampai mangkrak diamuk massa. Kompas.Com. https://www.kompas.com/tren/read/2022/12/12/200000565/lini-masa-kasus-meikarta-dari-aku-ingin-pindah-ke-meikarta-sampai-mangkrak?page=all

Rahmayanti, S. A., & Setiawati, A. (2021). Kajian masalah pre-project selling Apartemen The Aspen Peak Residence (Putusan No. 390/PDT.G/2017/PN.JKT.SEL). *Reformasi Hukum Trisakti, 3*(4), 608-618. https://doi.org/10.25105/refor.v4i2.13608

Rosalind, M., & Sari, R. (2022). Karakteristik sistem pre project selling perumahan ditinjau dari asas keseimbangan. *Jurnal Ilmiah Dunia Hukum, 7*(1), 22–34. http://dx.doi.org/10.56444/jidh.v7i1.3026

Saputra, F. (2025, May 22). 13 Meikarta consumers receive refunds worth IDR 3.5 billion. Kompas.Com. https://www.kompas.id/artikel/en-13-orang-konsumen-meikarta-terima-pengembalian-dana-senilai-rp-35-miliar

Selvam, K. (2024, November 26). Homebuyers left in limbo as Residensi Hektar, Gombak faces ongoing delays. Sinar Daily. https://www.sinardaily.my/article/223493/focus/national/homebuyers-left-in-limbo-as-residensi-hektar-gombak-faces-ongoing-delays

Sihono, S. (2024, November 19). Merasa tertipu pembelian Apartemen Malioboro Park View, belasan konsumen membuat laporan ke Polda DIY. Harian Merapi. https://www.harianmerapi.com/news/4013981086/merasa-tertipu-pembelian-apartemen-malioboro-park-view-belasan-konsumen-membuat-laporan-ke-polda-diy

Simamora, J. C., Adira, P. P., & Putri, Z. A. (2024). Legal analysis on the construction of Meikarta Project from the lens of consumer protection. *Problematika Hukum, 9*(1), 49. https://doi.org/10.33021/ph.v9i1.5203

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Tan, T., Vethasalam, R., & Gimino, G. (2024, July 18). Selangor has highest number of abandoned housingprojects, Dewan Rakyat told. The Star. https://www.thestar.com.my/news/nation/2024/07/18/selangor-has-highest-number-of-abandoned-housing-projects-dewan-rakyat-told

Therik, D. F., & Gultom, E. R. (2024). Perlindungan pembeli apartemen pre project selling: Studi kasus keterlambatan serah terima Proyek Meikarta. *Binamulia Hukum, 12*(2), 403–416. https://doi.org/10.37893/jbh.v12i2.392

Wang, Y. (2024). Analysis of the Causes and Countermeasures of the Phenomenon of "Unfinished Buildings". *Highlights in Business, Economics and Management, 41*, 699-702. https://doi.org/10.54097/x3vy9j69

Yusof, A. (2025, October 2). Uncompleted after years, Johor Bahru's "sick" and "abandoned" property projects leave buyers in limbo. CNA. https://www.channelnewsasia.com/asia/malaysia-johor-bahru-sick-abandoned-stalled-property-buyers-limbo-5379511

Kolamunna, P.T., Weerasinghe, U.G.D. and Hirudini, S.M., 2026. Landscape as a signifier of rural social class inequality in contemporary Sri Lankan cinema: An analytical study of three selected films. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1050-1064. DOI: https://doi.org/10.31705/WCS.2026.77. Available from: https://ciobwcs.com/papers/

# LANDSCAPE AS A SIGNIFIER OF RURAL SOCIAL CLASS INEQUALITY IN CONTEMPORARY SRI LANKAN CINEMA: AN ANALYTICAL STUDY OF THREE SELECTED FILMS

**P.T Kolamunna[1], U.G.D Weerasinghe[2], and S.M Hirudini[3]**

## *ABSTRACT*

*This study examines how surrounding landscape elements of rural settlements function as visual signifiers of social class inequality in contemporary Sri Lankan cinema through an analytical study of three films: Sarigama, Vishama Bhaga, and Paradise. While social class representation has been widely discussed in film studies, limited attention has been given to how environmental contexts of rural settlements visually communicate class divisions. This research, therefore, investigates the role of landscape elements as cinematic signifiers of inequality. A mixed method approach has been followed, and the results obtained from interviews with three film directors and the online survey results of 203 participants, with the primary analysis group being 150 participants belonging to the age group of 19–25 years, were used. Some frames of the film, which highlighted the contrasts of class, were shown to the participants in grayscale to avoid any visual distractions and identify the pictorial landscape elements such as sky-scape, bio-scape, water-scape, vegetation-scape, landform-scape, street-scape, and archi-scape. Audience interpretations were further analyzed using four social class inequality indicators: cultural objects, physical appearance, behavior and speech. The findings reveal a hierarchy in the effectiveness of landscape indicators in communicating class inequality, with landform-scape emerging as the most influential element. Open and elevated terrains were frequently associated with upper-class rural environments, whereas enclosed or fragmented landforms indicated lower-class spaces. Overall, the study demonstrates that rural landscape elements function as significant semiotic tools through which filmmakers construct and audiences interpret social class inequality in contemporary Sri Lankan cinema.*

***Keywords:*** *Contemporary Sri Lankan Cinema; Social Class Inequality; Visual Landscape Elements.*

## 1. INTRODUCTION

Cinema is a complex combination of various parts, which include the audio, the visuals, and the narrative. It is not the narrative is being portrayed; rather, it is the overall effect

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, theekshanakolamunna00@gmail.com
[2] Senior Consultant, Department of Architecture, University of Moratuwa, Sri Lanka, gamiweer@uom.lk
[3] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, mihirih@uom.lk

of the influences of the backgrounds. With the development of the film industry, directors convey complex ideas through cinematic elements such as frame composition, colour, lighting and shadow (Wu, 2024).

According to German philosopher Karl Marx, the way in which a group of people participates in public things and services is considered as a social class. A social class stratification system can be seen in the 21st century Sri Lankan social class system depending on the educational level and economic status. There are four main social class levels i.e. (i) upper class, (ii) upper middle class, (iii) lower middle class, and (iv) low class (Riswan, 2014). This study aims to examine the contribution of the landscape signifiers of rural settlements in depicting the gap between two of any social classes in contemporary Sri Lankan cinema.

For this study, the films "Sarigama (2016)", "Vishama Bhaga (2019)" and "Paradise (2022)" were chosen as the case studies. The study examines to what extent directors use this visual landscape in depicting the social imbalance, and to what extent the audience takes the message that the director gives using the landscape signifiers of the rural environments.

Academic literature around the Sri Lankan cinema has not really looked into how the surroundings in a film, can show the differences between rural settlements. By examining this phenomenon systematically, researchers can contribute to the enhancement of cinematic representations of social class inequality. This study aims to fill the gap regarding how the countryside and villagers are visualised in films to highlight the differences between upper class and lower-class people in Sri Lankan cinema today. It also aims to start a conversation about importance of the landscape in film production.

## 1.1 RESEARCH AIM AND OBJECTIVES

The aim of this research is to examine how surrounding landscape elements of rural settlements function as visual indicators of social class inequality in contemporary Sri Lankan cinema. By analysing selected scenes from Sarigama, Vishama Bhaga, and Paradise, the study seeks to identify how specific landscape indicators contribute to the cinematic representation of class differences. The study will evaluate how these environmental elements interact with social class indicators to shape audience perceptions of social inequality in rural contexts. The objectives for the study are as follows,

1. Identify the visual landscape elements and their parameters that reflect the environmental context of rural settlements in selected Sri Lankan films.
2. Examine the awareness of the selected film directors of these visual landscape elements and how they intentionally or intuitively apply them in their work.
3. Investigate the extent to which film audiences recognise and interpret these landscape elements within the environmental context of rural settlements.
4. Develop a framework illustrating how the environmental context of rural settlements has been used to depict social class identity and inequality in the selected films.

## 1.2 SCOPE LIMITATIONS

This study has some limitations, as the analysis has been carried out only based on the three selected case studies, i.e. (i) Sarigama (2016), (ii) Vishama Bhaga (2019), and (iii)

Paradise (2022). Therefore, the findings of the analysis cannot be generalised to the whole of contemporary Sri Lankan cinema. The interpretation of the environmental contexts as well as the social classes, has been based on the visual frames selected, and the perceptions of the audience sample, which comprised young adults belonging to the age group of 19-25 years. The analysis has been carried out in an in-depth manner, which adds to the value of the study, as the focus has been on the symbolism of class through the landscapes depicted in the cinematic works selected.

# 2. LITERATURE REVIEW

## 2.1 ROLAND BARTHES' SEMIOTIC THEORY

Roland Barthes' semiotic theory provides an effective tool for the analysis of the representation of social class and inequality through visual and material signs (Du et al., 2025) (refer Figure 1). Barthes' semiotic theory distinguished between the denotation and the connotation of the signs. Denotation refers to the explicit meaning of the signs (Du et al., 2025), while connotation refers to the cultural and ideological meaning associated with the signs. Using Barthes' semiotic theory, the role of interior spaces in the representation of social inequality and class distinction can be effectively analysed. Barthes' semiotic theory also helped to explain the role of signs in the representation and naturalisation of social inequality and class distinction. According to Barthes' semiotic theory, signs can become part of the cultural and ideological representation and can be viewed as natural facts. In the context of the representation of social inequality and class distinction in films, the role of interior spaces can be viewed as signs and can be analysed effectively using Barthes' semiotic theory (Du et al., 2025).

*Figure 1 :Roland Barthes' semiotic theory: Barthes (1993) redrawn by author*

## 2.2 SEMIOTICS

Semiotics is the study of the role of signs in communication and the creation of meanings in society (Saussure, 2011). It is the study of how various types of signs, such as images and objects, create social and cultural meanings in society. According to Saussure (2011), the signifier is the form of the sign, and the signified is the concept that the sign represents, and the two have a relationship in the creation of meanings.

This concept of denotation and connotation was further developed by Barthes when he introduced the concept of myth as a system of signs that operates on multiple levels. These signs consist of denotation and connotation as major components (Saussure, 2011). In the context of interior spaces in Sri Lankan cinema on the theme of rural housing, the semiotic approach is a method of interpretation for the signs within the interior spaces that reflect social class and challenge the inequalities of society. The furniture, decor, and arrangement within the interior spaces of the rural housing depicted in the cinema constitute signs that communicate social values, status, and identity. The semiotic approach to signs within the interior spaces is a method of interpretation for the

ideological content of the signs within the cinematic representation of the rural housing. (Saussure, 2011)

## 2.3 FILM AS A MEDIUM FOR COMMUNICATING SOCIAL STRUCTURES

Cinema is not a neutral recording of reality. It is a culturally constructed medium that actively produces social meanings. Hall (1997) argues that visual signs operate within cultural codes that connect images to broader social meanings. In film, this includes every element of the frame such as lighting, composition, setting, and the surrounding environment.

## 2.4 LANDSCAPE AS AN IDEOLOGICAL SIGNIFIER

Landscape is not simply a backdrop. It is an active instrument of cultural force through which social identities are constructed (Mitchell, 1994). Cosgrove (1984) further established that landscape is a profoundly ideological concept. The way classes portray themselves is mediated through their depicted relationship with the physical environment (Cosgrove, 1984). In cinema, these ideological encodings of landscape become a visual language. Through this, filmmakers communicate class hierarchies without explicit narrative statement (Turner, 1993).

## 2.5 SOCIAL CLASS AND VISUAL REPRESENTATION IN CINEMA

Social class is not just about how much money people have it is also about the way they live and the things they value (Bourdieu, 1984). When the audience watches films, there can see class in the places and environments where the characters live. These places can show if the characters are from the upper class or if they are powerful depending on how the film visualises them.

## 2.6 SOCIAL CLASSES IN SRI LANKA IN THE 21ST CENTURY

Sri Lanka's social class structure changed a lot after the country opened up its economy in the 1970s and 1980s (Kelegama, 2006). Class distinctions were not prominently evident in the initial phases. However, they became progressively apparent by the late twentieth century and into the early twenty-first century (Kelegama, 2006). In Sri Lankan society, the main ways to tell the difference between social classes are economic status, political power and social networks (Riswan, 2014). Contemporary Sri Lankan society can be broadly classified into four distinct social class strata (refer Figure 2).

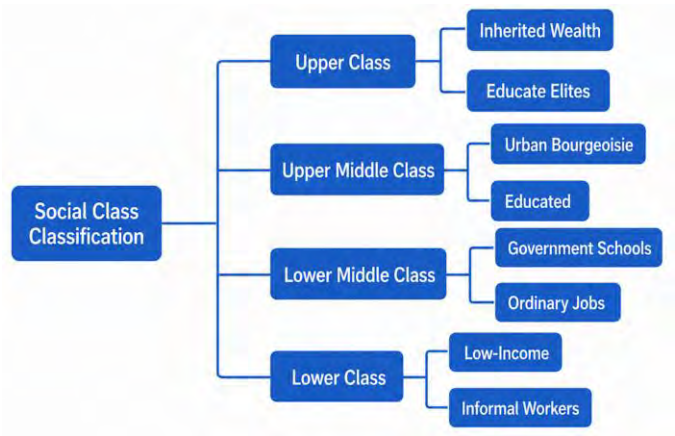



*Figure 2 :Social class classification in Sri Lanka*

## 2.7 SOCIAL CLASS INEQUALITY

Social class inequality is the unequal distribution of privileges, opportunities, and resources among the various social classes in each society (Crossman, 2025). It is reflected the existence of wealth, income, education, healthcare, and social class differences. Social class inequality has a major impact on the lives and mobility of people in the respective societies (Oracle, 2025; Fiveable, 2024). It is built on the economic, historic, and structural pillars and is sustained through inheritance, discriminatory behaviour, and unequal quality of education and work opportunities (Oracle, 2025). It not only causes the misfortune of the individual but also creates societal ills such as poverty, loneliness, stagnation of health levels, and intergenerational patterns of marginalization (StudyRocket, n.d; Huberty, n.d). Therefore, understanding social class inequality means understanding the complex premises and the widespread impact on the lives and societies of people in the respective societies.

### 2.7.1 Indicators of Social Class Inequality

In this study, four key indicators are used to perceive and reinforce social class inequality, based on observable cues that communicate economic and social status (Kraus et al., 2017).

1. Cultural Objects: Clothing and attire, possessions and material items
2. Physical Appearance: Facial features and grooming, photographs and visual cues
3. Behaviour: Gestures and mannerisms, short behavioural snippets
4. Speech: Linguistic patterns and accents, speech style and pronunciation

## 2.8 VISUAL LANDSCAPE ELEMENTS

Visual landscape elements are the special elements that determine the appearance and character of an environmental context. They are mainly divided into two parts as natural landscapes and man-made landscapes. The natural landscape elements include sky, land, and water, and the man-made elements include buildings and roads. The following classification provides a good understanding of the role of environmental context and landscape composition (Ho, 2023).

1. Sky-scape- sky
2. Bio-scape- Animal, Human
3. Water-scape- Vertical-water (fountain, waterfall), Horizon-water (lake, pool, river)
4. Vegetation-scape- Woody-plant (Palm, tree, flora), Herb-plants (grass), Flower
5. Landform-scape- Horizon-land (ground, field, sand), Vertical-land (rock, mountain)
6. Street-scape- Sign (poster, signboards), Vehicles (bike, van, car, bus), Street-furniture (sculpture, chair, pot), Roadways (sidewalks, roads)
7. Archi-scape- Archi-parts (step, wall, window), Architecture (settlements, building, tower)

# 3. RESEARCH METHODOLOGY

This study uses a mixed-methods approach, comprising case study analysis, director interviews, and an audience questionnaire.

## 3.1 CASE STUDY SELECTION

The following framework was used to select suitable films for the study.

1. Released within the contemporary cinema era.
2. Won or been nominated for national or international awards.
3. Represented the social class inequality through a rural settlement environment.
4. Used landscape as a tool to express social class inequality.

Three films were selected to cover the contemporary cinema era in accordance with this framework; “Sarigama” (2016), “Vishama Bhaga” (2019), and “Paradise” (2023). (refer Figure 3).

*Figure 3: Selected films: Internet*

## 3.2 EXPERT INTERVIEWS

Interviews with the directors of the three films provide insight into their use of landscape in their films, the extent to which they use landscape, and their awareness and use of visual landscape elements.

## 3.3 SCENE SELECTION AND AUDIENCE RESPONSES

Based on the available academic literature and insights gathered through expert interviews, several film frames were chosen that most effectively illustrated the depiction of social class inequality through the surrounding landscape context of rural settlements in the selected films. These frames were then organised into two categories representing upper and lower social class environments, according to how the spatial and environmental characteristics supported the portrayal of class differences. To maintain analytical balance, four frames were selected for each class category.

To reduce the potential influence of colour-related distractions and to direct attention toward spatial composition and landscape elements, all selected frames were converted into grayscale. (Clark, 2005).

Following the classification approach proposed by Li et al. (2025), the selected frames were also evaluated based on the proportion of artificial components present within the landscape setting (refer Figure 4). Accordingly, four levels were defined to represent varying degrees of naturalness within the scene:

1. Full naturalness: less than 5% artificial elements.
2. Most naturalness: 5–25% artificial elements.

3. More artificial work: 25–55% artificial elements.
4. Most artificial work: 55–75% artificial elements.

Each frame was overlaid with a 10x10 grid of analysis cells, dividing each frame into 100 equal-sized cells to assess how much of the scene is natural and how much is man-made, enabling a structured visual.

The audience was then shown this graph and asked to identify the social level (high or low) represented by each column. Then, a Likert scale was used to ask how much attention they paid to the visual landscape elements (refer Figure 4).

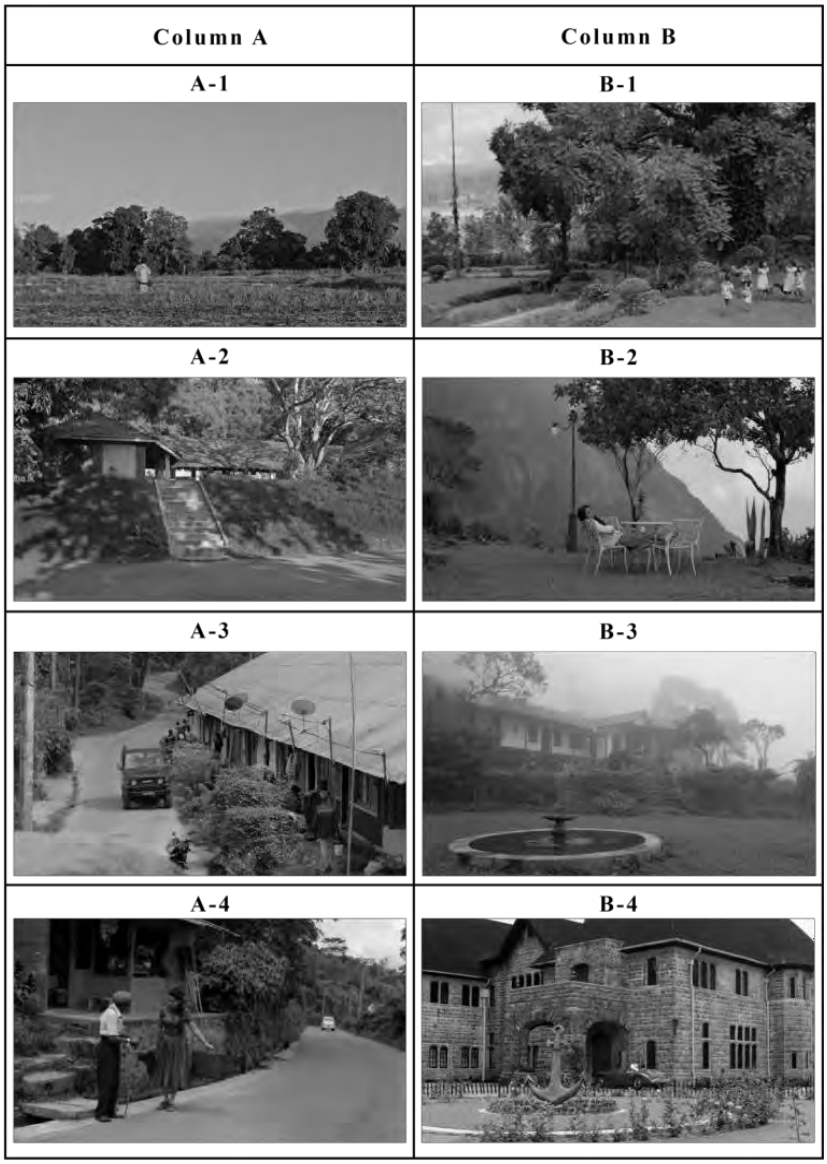



*Figure 4: Selected frames list given in questionnaire (1) Full naturalness, (2) Most naturalness, (3) More artificial works, and (4) Most artificial works. Column A represents the low class and Column B represents the high class: Author*

## 3.4 SCOPE AND LIMITATIONS OF IMAGE SELECTION

Still frames were deliberately selected over moving sequences to isolate landscape elements from narrative and temporal dimensions. Frames were chosen based on

directors' visual intent. A grid-based selection criteria was applied across all three films. Participants were asked whether they had previously watched the selected films; however, prior viewing showed no significant impact on responses. It is acknowledged as a limitation that sequential and transitional dimensions of the moving image were not captured in this phase.

# 4. DATA COLLECTION AND ANALYSIS

## 4.1 DIRECTORIAL PERSPECTIVES ON VISUAL LANDSCAPE CHARACTERISTICS

Insights for this study were gathered from qualitative interviews with three experienced movie directors in Sri Lanka.

### 4.1.1 The Contribution of Landscape to Creating Narratives in Cinema

The three directors share the view that landscape in cinema is far more than a mere backdrop. It is an active storytelling tool. They identified three core roles of landscape:

1. Symbolic expression - Landscape reflects the historical era, political climate, and spiritual values of the society being portrayed.
2. Silent communication - Rather than relying on lengthy dialogue, landscape allows directors to convey meaning and emotion directly to the audience.
3. Class commentary - The background environment subtly signals the characteristics and contrasts of different social classes, making inequality visible without stating it explicitly.

### 4.1.2 The Use of Landscape as a Social Class Identity

According to the directors, they draw a clear distinction between how different environments represent different socioeconomic groups:

Higher social class is linked to places that feel comfortable look good and feel safe. These places are big, clean and high up making people feel special and stable. The directors have shown social class through surroundings that are spacious well-kept and elevated, which reinforce a sense of privilege and stability (refer Figure 5).

*Figure 5: Higher social class representations in selected films*

Lower social class is portrayed through challenging living conditions. It is depicted in areas characterised by small houses and limited resources, highlighting the daily struggles

individuals face in sustaining their livelihoods. The directors portray social class through environments of scarcity and hardship (refer Figure 6).

*Figure 6: Lower social class representation in selected films*

They emphasise that natural and built environments work together as cues allowing audiences to immediately recognise a characters economic and social standing.

### 4.1.3 Practical Contribution of Landscape Features in Cinema

Directors intuitively draw on visual landscape features, such as scale, complexity, naturalness, and stewardship, to communicate social class differences in contemporary Sri Lankan cinema, even without consciously naming these elements. This subtle use of landscape as a marker of inequality was mostly recognized and appreciated by discerning, culturally informed audiences (refer Figure 7).

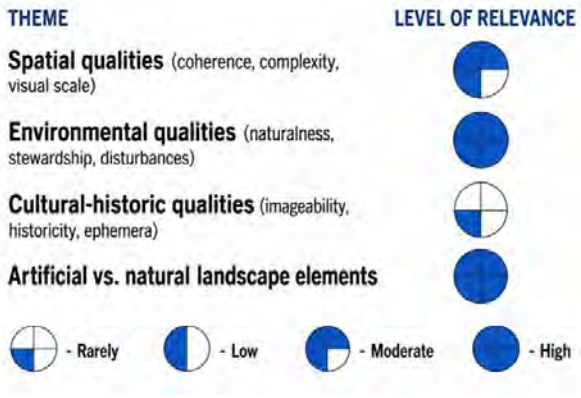



*Figure 7: Thematic relevance for analyzing social class inequality in cinematic landscapes*

### 4.1.4 Application of Directorial Insights for Frame Selection

The interview findings confirmed that the directors intentionally use landscape as a visual device to communicate social class differences. Attention was given to landscape cues such as landform conditions, settlement quality, vegetation management, spatial openness, and the relationship between natural and built elements. These insights guided the selection of still frames for the audience survey. The selected frames represented the landscape characteristics identified during the interviews and provided a consistent basis for evaluating audience interpretations of social class inequality. Section 4.2 examines how audiences responded to these visually selected frames.

## 4.2 AUDIENCE RESPONSES

Both male and female in the age group of 19-25 years pay analytical attention to the content of the films while watching them (Patel et al., 2025). Out of 203 valid audience responses obtained in this study, 150 were students in this age group. Therefore, those 150 responses were considered for the analysis and gender did not affect this study. A classification according to their educational level is shown in Figure 8.

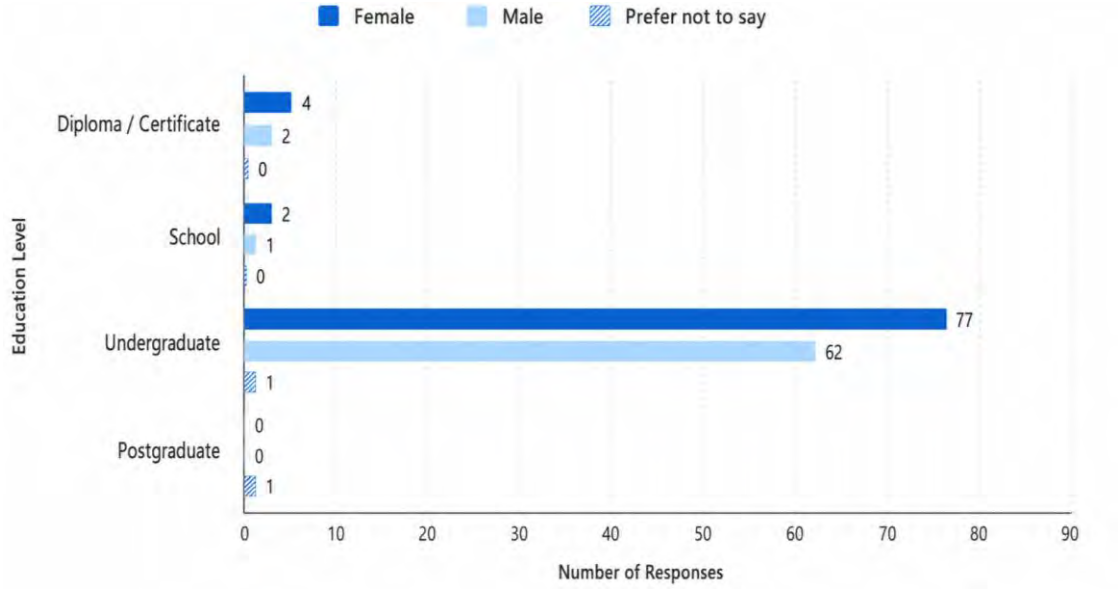



*Figure 8: Gender and education level count of the responses*

From the collected data, the extent to which respondents pay attention to the environmental context while watching films is shown in Figure 9. The majority of the respondents (n=84,56%) stated that they are paying moderate attention to the background environment.

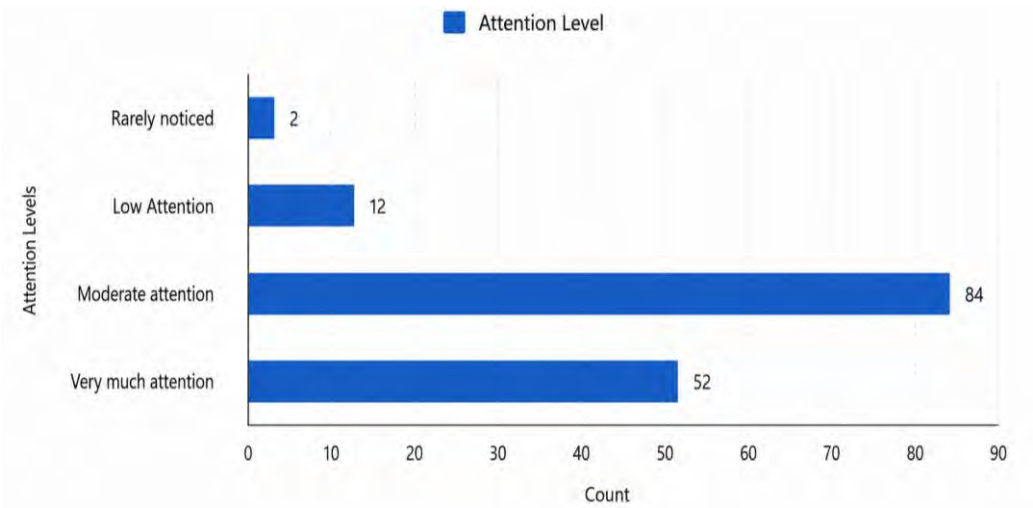



*Figure 9: Audiences' attention to the background landscape when watching a film*

A majority of the respondents agreed that the environmental background of rural settlements can be used to depict social and economic conditions in cinema (refer Figure 10).

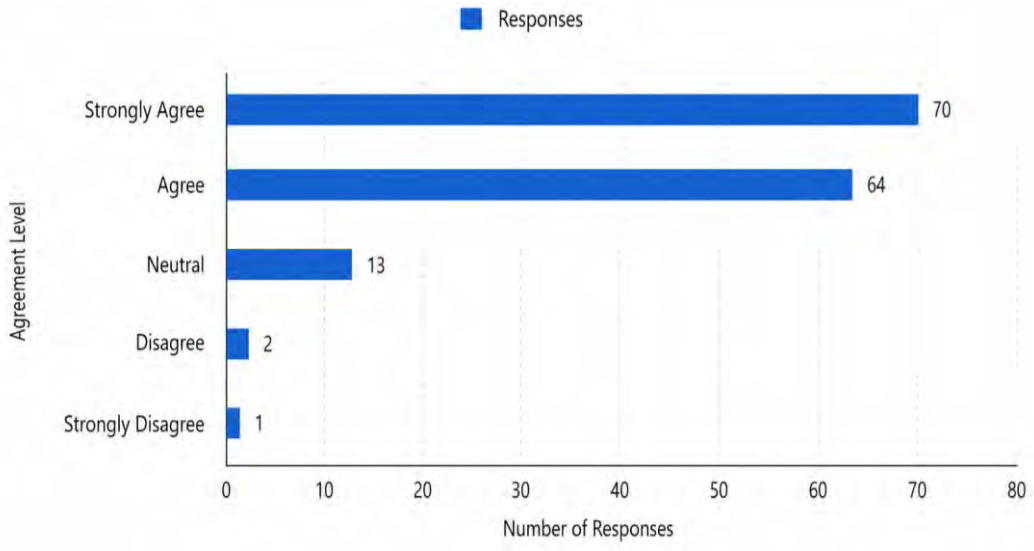



*Figure 10: Respondents' agreement on the role of the environmental context depicting social and economic realities in film*

Considering the total responses, the participant have focused on the landscape elements in rural environments to identify inequality in social class levels (refer Figure 11).

*Figure 11: Respondents' engagement level with visual landscape elements*

Based on the diagram (refer Figure 4) provided in the questionnaire, 139 (93%) respondents selected the column that correctly represented the relevant social class. The way in which it deviated from the overall value, a final hierarchy can be reached regarding the relevance of these visual landscape elements. This is because the accuracy of the responses of the respondents who correctly identified the relevant social class in the diagram increases. The graph obtained in this way is shown in Figure 12.

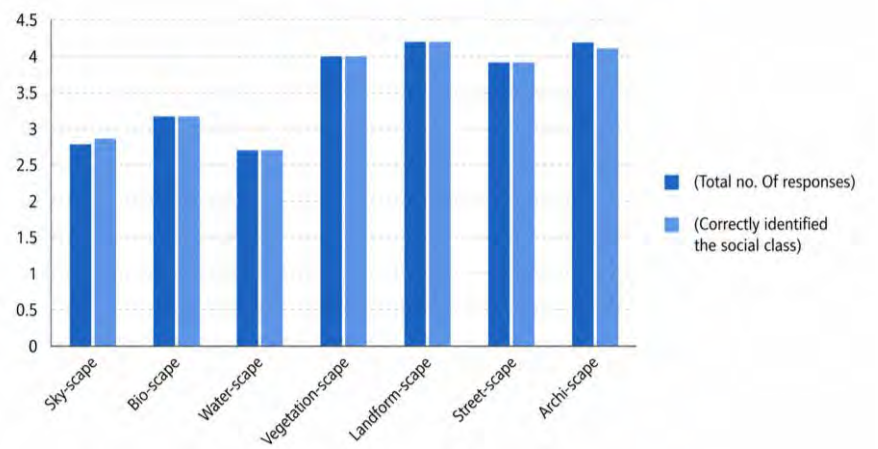



*Figure 12: Deviation between total respondents and those who correctly identified social class*

As the variations among the findings in Figure 12 are minimal, a hierarchical ranking was established (refer Figure 13) to better understand their differences. The results indicate that greater attention is given to the environmental context of rural settlements, including spatial organization, material conditions, and settlement environments, while comparatively less attention is given to aquatic or water-related elements when representing social class differences in films.

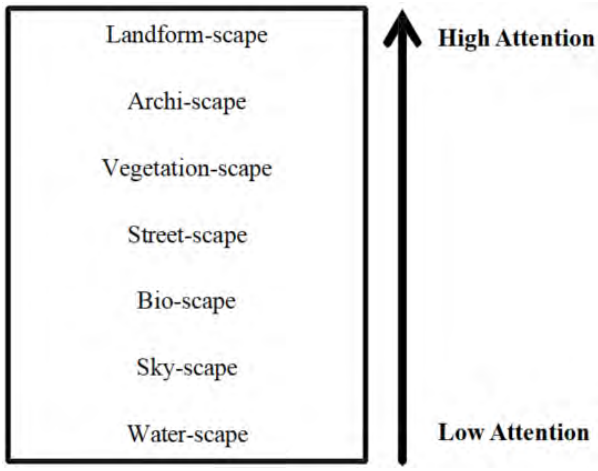



*Figure 13: Hierarchy of audience attention level for the visual landscape elements in cinema*

These findings were based solely on the analysis of three chosen contemporary Sri Lankan films. As may be seen from the findings, it is quite evident that the environmental setting of rural settlements in these chosen contemporary Sri Lankan films plays a significant role in portraying social class inequality in contemporary Sri Lankan cinema.

## 5. DISCUSSION

Based on findings from the literature review, interviews, and audience responses, this study proposes guidelines for using the environmental context of rural settlements to represent social class inequality in contemporary Sri Lankan cinema. The findings show how the class differences are effectively conveyed through visual landscape elements (refer Table 1).

*Table 1: Use of visual landscape elements in rural settlements to depict social class in selected films*

| Visual Landscape Element in Rural Settlements | Subsections | Visual Use for Depicting Social Class Inequality in Selected Films |
|---|---|---|
| Landform-scape | Horizon land (fields, ground, paths, sand)<br>Vertical land (rocks, hills, mountains) | Modified and level land indicates higher class;<br>uneven, eroded, or unmanaged land represents lower class |
| Archi-scape | Architectural parts (steps, doors, windows, walls)<br>Buildings (houses, storage structures) | Permanent and well-maintained settlements suggest higher class;<br>Temporary or deteriorated settlements suggest lower class |
| Vegetation-scape | Woody plants (trees, palms)<br>Herb plants (grass)<br>Flowering plants | Controlled and productive vegetation reflects higher class;<br>Overgrown or neglected vegetation reflects lower class |
| Streetscape | Signs (signboards, markers)<br>Street furniture (lights, poles)<br>Roadways | Paved roads and infrastructure indicate higher class;<br>mud roads and poor access indicate lower class |
| Bio-scape | Humans<br>Animals | Limited physical labour and controlled interaction show higher class;<br>intensive labour and close animal interaction show lower class |
| Skyscape | Sky | Clear and stable skies frame privileged settings;<br>overcast or harsh skies support marginalized conditions |
| Waterscape | Vertical water (wells, small falls)<br>Horizontal water (tanks, ponds, rivers) | Easy access to clean water suggests higher class;<br>distant or scarce water sources suggest lower class |

## 6. CONCLUSIONS

This study shows how the landscape elements of rural communities are used to effectively portray social class inequality in contemporary Sri Lankan cinema. The audience identified environmental visual landscape elements to distinguish social classes, as methodically summarised in Table 1. The Discussion section demonstrates how these components work together rather than separately to create a visual system that conveys rural social hierarchies. These observations are combined into a clear analytical framework in the table, which shows how particular environmental conditions are frequently used to represent privilege and marginalisation based on class in a few chosen films. This study offers an organised method for comprehending how the landscape elements of the rural environment are portrayed in films by presenting them as active visual agents rather than a passive background. The suggested framework highlights the

significance of environmental context in examining social inequality in Sri Lankan cinema and provides a useful instrument for further study.

# 7. REFERENCES


Aitken, S. C., & Zonn, L. E., (1994). *Place, power, situation and spectacle: A geography of film*. Rowman & Littlefield.

Anjani, D., & Junaedi, F. (2022). The social class representation in the Heidi film: Roland Barthes semiotic analysis. In R. R. B. Chasana, D. A. Anggoro, & H. Imaduddin (Eds.), proceedings *of the International Conference on Community Empowerment and Engagement (ICCEE 2021)* (Vol. 661, pp. 215–221). Atlantis Press. https://doi.org/10.2991/assehr.k.220501.024

Ashley, S. (2022). Class inequality. *Society: A global introduction*. BCcampus Pressbooks. https://pressbooks.bccampus.ca/society/chapter/class-inequality/

Barthes, R. (1993). *Mythologies* (A. Lavers, Trans.). Vintage.

Bourdieu, P. (1984). *Distinction: A social critique of the judgement of taste*. Harvard University Press.

Change Oracle. (2025, April 7). Understanding societal inequality: History, types, causes and effects. Change Oracle. Retrieved July 1, 2026 from https://changeoracle.com/2025/04/07/understanding-societal-inequality/

Clark, P. E., & Hardegree, S. P. (2005). Quantifying vegetation change by point sampling landscape photography time series. *Rangeland Ecology & Management*, *58*(6), 588–597. https://doi.org/10.2111/04-111R2.1

Cosgrove, D. E. (1984). *Social formation and symbolic landscape*. University of Wisconsin Press. https://books.google.lk/books?hl=en&lr=&id=NrD2-nJ52aYC&oi=fnd&pg=PR9&dq=Social+formation+and+symbolic+landscape&ots=CuSniJ9WSa&sig=YepKjbmbiHe4j8p63QCCDAMZCho&redir_esc=y#v=onepage&q=Social%20formation%20and%20symbolic%20landscape&f=false

Crossman, A. (2025. May 10). The sociology of social inequality. ThoughtCo. Retrieved July 1, 2026 from https://files.commons.gc.cuny.edu/wp-content/blogs.dir/17873/files/2021/07/Wk-1-Social-Inequality.pdf

Du, P., Li, T., Chen, Y., & Chen, J. (2025). Architectural semiotics unveiled: Parallel investigations into visual processing mechanisms and cognitive discrepancies of She ethnic motifs. *Buildings*, *15*(17), 3123. https://doi.org/10.3390/buildings15173123

Fiveable. (2024). *9.1 social class*. Fiveable. https://fiveable.me/american-society/unit-9/social-class/study-guide/8NvnzOwjIEbSzqqS

Hall, S. (1997). The work of representation. In S. Hall (Ed.), *Representation: Cultural representations and signifying practices* (pp. 13-74). Sage Publications in association with the Open University.

Ho, L.-C. (2023). LaDeco: A tool to analyze visual landscape elements. *Ecological Informatics*, *78*, 102289. https://doi.org/10.1016/j.ecoinf.2023.102289

Human Rights Careers. (2025). 13 ways inequality affects society. https://www.humanrightscareers.com/issues/ways-inequality-affects-society/

Kelegama, S. (2006). *Development under stress: Sri Lankan economy in transition*. Sage Publications.

Kraus, M. W., Park, J. W., & Tan, J. J. X. (2017). Signs of social class: The experience of economic inequality in everyday life. *Perspectives on Psychological Science*, *12*(1), 175–188. https://doi.org/10.1177/1745691616673192

Li, K., Zhai, Y., Dou, L., & Liu, J. (2021). A preliminary exploration of landscape preferences based on naturalness and visual openness for college students with different moods. *Frontiers in Psychology*, *12*(1), 629650. https://doi.org/10.3389/fpsyg.2021.629650

Mitchell, W. J. T. (1994). Imperial landscape. In W. J. T. Mitchell (Ed.), *Landscape and power* (pp. 5-34). University of Chicago Press.

Patel, V., Rajkotiya, A., Mendpara, L., Viramgama, N., Chauhan, R., & Maseleno, A. (2025). The influence of cinema on consumer purchasing behaviour: An analysis of age and gender differences. *Greenation International Journal of Economics and Accounting*, *2*(4), 337–346. https://doi.org/10.38035/gijea.v2i4.306

Riswan, M. (2014). A historical survey of social class and caste system in Sri Lanka. *KALAM: International Journal of Faculty of Arts and Culture, 8*(1), 40-47. https://www.seu.ac.lk/researchandpublications/kalam/vol8/5%20KALAM%20VIII%20%281%29%202014%20%20%28Page%2040-47%29.doc14.11.2014-3.pdf

Saussure, F. de. (2011). *Course in general linguistics* (P. Meisel & H. Saussy, Eds.; W. Baskin, Trans.). Columbia University Press.

Silva, A. P. C. (2021). *The study of post-modern features (if any) in Sri Lankan (Sinhala) cinema with particular reference to the films produced between 2000–2014.* [Master's thesis, University of Kelaniya]. University of Kelaniya Institutional Repository. http://repository.kln.ac.lk/items/0a628b84-65f8-4029-892d-cbf2f32a5c53

Soken-Huberty, E. (n.d.). *13 ways inequality affects society*. Human Rights Careers. Retrieved July 1, 2026 from https://www.humanrightscareers.com/issues/ways-inequality-affects-society/

StudyRocket (n.d). Social inequality in relation to social class: A level sociology OCR revision. StudyRocket, Retrieved July 1, 2026 from https://studyrocket.co.uk/revision/a-level-sociology-ocr/understanding-social-inequalities/social-inequality-in-relation-to-social-class

Turner, G. (1993). *Film as social practice* (2nd ed.). Routledge.

Wu, H. (2024). Metaphors of the lens: Symbolism and visual expression in cinematography. *Region - Educational Research and Reviews, 6*(9), 126-130. https://doi.org/10.32629/rerr.v6i9.2912

Weeranayaka, P.A.D.D.J., Bandara, R.M.H.R. and Thayaparan, M., 2026. Learning from nature: Biomimicry-inspired daylighting design for reducing artificial lighting in urban buildings. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1065-1078. DOI: https://doi.org/10.31705/WCS.2026.78. Available from: https://ciobwcs.com/papers/

# LEARNING FROM NATURE: BIOMIMICRY-INSPIRED DAYLIGHTING DESIGN FOR REDUCING ARTIFICIAL LIGHTING IN URBAN BUILDINGS

**P.A.D.D.J. Weeranayaka[1], R.M.H.R Bandara[2], and M. Thayaparan[3]**

## *ABSTRACT*

*Urban buildings are major contributors to global energy consumption, with artificial lighting representing a significant share of operational electricity demand, particularly in dense urban environments with limited daylight access. Improving natural daylight utilisation has therefore become an important strategy for enhancing building energy efficiency and reducing environmental impacts. Biomimicry, which involves learning from natural forms and processes to solve human design challenges, offers promising opportunities for developing innovative daylighting strategies in architecture. This study evaluates the effectiveness of biomimicry-inspired daylighting strategies in reducing artificial lighting demand in urban buildings. A comparative multiple case study approach was adopted, examining five international buildings incorporating nature-inspired façade systems: Institut du Monde Arabe (France), Sinosteel International Plaza (China), Habitat 2020 (China), Esplanade – Theatres on the Bay (Singapore), and Al Bahar Towers (UAE). Data were collected from architectural documentation, published studies, and reported daylighting performance indicators. The analysis identified key biomimetic daylighting strategies, including adaptive kinetic façades, parametric shading systems, responsive building skins, and geometric façade patterns. Findings indicate that these strategies improve daylight distribution and reduce artificial lighting demand by approximately 20–80%, depending on climatic context and façade configuration. As an exploratory secondary-data-based comparative study, the findings provide an initial foundation for understanding how biomimicry-inspired façade systems contribute to daylight optimisation across different climatic contexts. The study highlights the potential of biomimicry-inspired façade systems to support sustainable and energy-efficient urban building design.*

***Keywords:*** *Artificial Lighting; Biomimicry; Urban Buildings.*

## 1. INTRODUCTION

Urban areas are among the largest consumers of energy and natural resources, and their rapid expansion intensifies environmental and sustainability challenges. The continuous

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, weeranayakapaddj.21@uom.lk
[2] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, bandararmhr.20@uom.lk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk

growth of cities increases the demand for buildings, infrastructure, and services required to support growing populations (Katabaro et al., 2022). This rapid urbanisation has significantly increased the demand for energy intensive buildings and infrastructure, resulting in higher consumption of natural resources and increasing environmental pressures. (Montes-Villalva et al., 2022). Consequently, improving the energy efficiency and environmental performance of buildings has become a critical priority for sustainable urban development.

Among the various operational energy demands in buildings, artificial lighting represents a considerable portion of electricity consumption. Lighting systems are essential for ensuring visual comfort and supporting building functionality; however, they contribute significantly to overall building energy use (Hong & Rahmat, 2022; Villalva et al., 2022). The extensive reliance on artificial lighting is often caused by insufficient access to natural daylight within building interiors, particularly in dense urban environments where surrounding structures limit daylight penetration. As a result, many buildings depend heavily on electric lighting during daytime hours, increasing operational energy consumption, building operating costs, and associated carbon emissions (Papamichael et al., 2018).

In response to growing environmental concerns, a substantial body of research has explored strategies to improve building energy efficiency (Kaitouni et al., 2024). In addition, the development of energy efficient lighting technologies such as LED systems, daylight sensors, and automated lighting controls has contributed to reducing electricity consumption in buildings (Vitalii et al., 2020). While these technological advancements have improved building performance, relatively limited attention has been given to architectural design strategies inspired by natural systems that could enhance daylight distribution within buildings and reduce reliance on artificial lighting.

Biomimicry has emerged as a promising approach for addressing sustainability challenges in the built environment. Biomimicry involves learning from and emulating natural forms, processes, and systems to develop innovative solutions to human design challenges (Hussein & Abbood, 2024). Natural systems demonstrate highly efficient mechanisms for regulating, filtering, and distributing light, offering valuable insights for daylight optimisation in buildings. Despite increasing interest in biomimicry within sustainable design research, its application for improving daylight performance and reducing artificial lighting demand in urban buildings remains relatively underexplored (Verbrugghe et al., 2023). Therefore, further investigation is required to understand how biomimicry-inspired daylighting strategies can be effectively integrated into contemporary building design. Accordingly, this study investigates how biomimicry-inspired daylighting strategies can reduce artificial lighting demand in urban buildings.

This study aims to evaluate biomimicry-inspired daylighting strategies in urban buildings by analysing selected case studies that incorporate nature-inspired façade systems. The research examines how these strategies improve daylight distribution and reduce reliance on artificial lighting.

# 2. LITERATURE REVIEW

## 2.1 DAYLIGHTING IN SUSTAINABLE BUILDINGS

Daylighting refers to the use of natural sunlight to illuminate indoor environments through architectural elements such as windows, skylights, and façade openings. It is widely recognised as a key strategy in sustainable building design because it reduces reliance on artificial lighting and lowers building energy consumption (Reinhart & Wienold, 2011) Lighting accounts for a significant proportion of electricity use in buildings; therefore, maximising daylight utilisation can contribute substantially to energy efficiency and improved environmental performance (Overen et al., 2023).

Beyond energy savings, daylighting enhances indoor environmental quality by improving visual comfort, occupant wellbeing, and productivity. Studies indicate that access to natural daylight can improve occupants' visual performance and psychological comfort compared with artificial lighting environments (Villalva et al., 2022). As urban populations continue to grow and cities become more densely developed, the role of daylighting in reducing energy consumption and improving indoor environmental quality has become increasingly important (Katabaro et al., 2022).

However, conventional daylighting strategies face several limitations, particularly in modern urban buildings. Deep plan building layouts often restrict daylight penetration into interior spaces, resulting in uneven light distribution and increased reliance on artificial lighting. In addition, high rise urban environments frequently experience shading from surrounding buildings, which reduces the effectiveness of traditional daylight design approaches. Excessive sunlight entering through large, glazed façades can cause glare and visual discomfort for occupants while increasing solar heat gain and cooling demand (Overen et al., 2023)

These challenges highlight the importance of façade design in contemporary daylighting strategies. Building façades play a critical role in controlling daylight penetration, reducing glare, and distributing light more evenly within interior spaces. As a result, innovative façade systems are increasingly being explored to improve daylight performance while maintaining thermal comfort and energy efficiency in buildings.

## 2.2 BIOMIMICRY IN ARCHITECTURAL DESIGN

Biomimicry is a design approach that studies nature's strategies and applies biological principles to solve human design challenges. Natural systems have evolved over millions of years to develop efficient, adaptive, and resource efficient solutions, making them valuable models for sustainable design in the built environment (Verbrugghe et al., 2023). In architecture, biomimicry encourages designers to observe natural forms, processes, and ecosystems and translate them into innovative building technologies and systems (Minucciani & Onay, 2018).

Biomimicry can be applied at multiple levels in architectural design. At the organism level, designers imitate the physical form or structure of biological organisms. At the behaviour level, the focus shifts to how organisms interact with their environment, such as plants adjusting their orientation toward sunlight (Pedersen-Zari, 2020). The ecosystem level considers broader environmental relationships and encourages buildings to function as integrated systems that efficiently manage energy, materials, and environmental conditions (Zari, 2020).

Several built environment projects illustrate the application of biomimicry principles in architecture. The Eden Project in the United Kingdom demonstrates organism-level biomimicry, where the structural geometry of the domes was inspired by soap bubbles and pollen grains. This design enables large spaces to be enclosed with minimal material while maximising natural light penetration and structural efficiency (Sydney's one central park, n.d.). Another example is One Central Park in Australia, which represents biomimicry at the ecosystem level. The project integrates vertical gardens and reflective systems inspired by forest ecosystems to improve daylight access, enhance environmental performance, and support urban biodiversity (Sydney's one central park, n.d.)

These examples demonstrate how biomimicry can enhance building performance by integrating natural principles into architectural design, particularly in areas such as ventilation, structural efficiency, and environmental responsiveness.

### 2.3 BIOMIMICRY FOR DAYLIGHTING OPTIMISATION

Nature provides numerous examples of systems that effectively regulate light and environmental conditions. These natural mechanisms have inspired innovative architectural strategies aimed at improving daylight performance in buildings. For example, the human iris controls the amount of light entering the eye through adjustable apertures, which has inspired adaptive façade systems capable of regulating daylight penetration (Verbrugghe et al., 2023). Similarly, honeycomb structures found in beehives provide efficient geometric patterns that distribute light evenly while maintaining structural stability (Sommese et al., 2024; Varshabi et al., 2022).

Plant mechanisms also provide valuable models for architectural design. Plant stomata regulate gas exchange and respond dynamically to environmental conditions, inspiring responsive building skins that adjust openings to control light and airflow (Bijari et al., 2025). In addition, natural structures such as fruit shells provide protective shading from excessive sunlight, influencing the design of architectural shading devices that reduce glare and solar heat gain (Bijari et al., 2025).

These biomimetic strategies offer several advantages for daylighting design. They enable more diffuse daylight distribution within interior spaces, reduce glare, and improve daylight autonomy, thereby decreasing dependence on artificial lighting systems (Minucciani & Onay, 2018) These biomimetic strategies are increasingly reflected in contemporary architecture, particularly in adaptive façade systems designed to regulate daylight penetration and improve visual comfort in buildings.

## 3. METHODOLOGY

This study adopts a comparative multiple case study research design to evaluate the effectiveness of biomimicry-inspired daylighting strategies in reducing artificial lighting demand in urban buildings. The case study approach was selected because it enables an in-depth examination of real-world architectural applications of biomimicry and allows comparison of design strategies implemented in different climatic and urban contexts. Unlike experimental or simulation-based studies, this method focuses on analysing existing buildings where biomimetic principles have already been applied in façade systems or daylighting design, providing practical insights into their performance and applicability.

This research specifically adopts an exploratory secondary-data-based multiple case study approach. Five international case studies were selected based on three main criteria: (1) the integration of biomimicry-inspired façade or daylighting concepts, (2) the availability of documented architectural and daylighting performance information, and (3) representation of diverse climatic and urban conditions. The selected buildings include Institut du Monde Arabe (France), Sinosteel International Plaza (China), Habitat 2020 (China), Esplanade Theatres on the Bay (Singapore), and Al Bahar Towers (UAE). These projects represent a range of biomimetic inspirations, including the human iris, honeycomb structures, plant stomata, and natural shell geometries, which are translated into adaptive or passive façade systems to regulate daylight penetration.

Data were collected entirely from secondary sources including peer-reviewed journal articles, architectural reports, case study publications, and documented performance evaluations of the selected buildings. The collected information included building characteristics, biomimicry inspiration, façade configuration, daylighting mechanisms, and reported performance indicators such as daylight autonomy, useful daylight illuminance ranges, glare control performance, and artificial lighting reduction outcomes.

To ensure consistency in analysis, each case study was examined using a structured comparative framework consisting of five parameters: biomimicry inspiration, architectural translation of the biological principle, daylighting mechanism, performance outcomes related to daylight distribution, and implications for artificial lighting reduction. A cross-case comparative analysis was then conducted to identify recurring biomimicry strategies and evaluate their effectiveness across different climatic conditions and building functions. This analytical approach enabled the identification of key design patterns that contribute to improved daylight penetration and reduced reliance on artificial lighting in urban buildings.

## 4. CASE STUDY ANALYSIS

This section evaluates biomimicry strategies applied in urban building construction to reduce artificial lighting demand. Each case study is structured around: building overview, biomimicry inspiration, daylighting mechanism, performance impact, and design implications.

### 4.1 INSTITUT DU MONDE ARABE - FRANCE

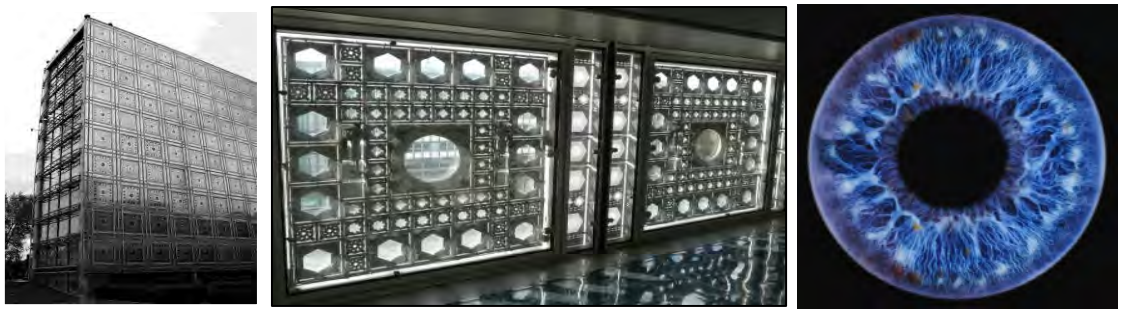


*Figure 1: (a) Institut du Monde Arabe, France (Winstanley, 2011) (b) Façade system (Winstanley, 2011), (c) Human eye's iris (Science Photo Gallery, n.d.)*

#### 4.1.1 Building Overview

The 28,000 m² Institut du Monde Arabe (Paris, France) [refer Figure 1:(a)] by Jean Nouvel functions as a cultural centre housing exhibition space, a library, auditorium, and offices. Its south facing façade [refer Figure 1:(b)] features 240 motorised panels with 30,000 photosensitive apertures (Winstanley, 2011).

#### 4.1.2 Biomimicry Inspiration

Inspired by the human eye's iris [refer Figure 1:(c)] and traditional Arabic Mashrabiya (ornate wooden or metal lattice screens historically used in Islamic architecture), the facade dynamically adapts to varying light levels, combining cultural symbolism with biological responsiveness (Michler, 2010a).

#### 4.1.3 Daylighting Mechanism

The motorised diaphragms respond to external illuminance via photoelectric sensors, adjusting aperture size to allow diffused daylight while blocking direct sun. Wider openings occur on overcast days; tighter closures mitigate glare from low winter or high summer sun (Michler, 2010b; Winstanley, 2011).

#### 4.1.4 Performance Impact

The adaptive façade system significantly improves daylight performance within the building. Studies indicate that the dynamic aperture mechanism enables the building to maintain high levels of daylight autonomy while reducing dependence on artificial lighting. Reported performance evaluations suggest that the system achieves approximately 30–50% reduction in artificial lighting energy, while maintaining useful daylight illuminance levels across interior spaces (Jamilu et al., 2024). The adjustable apertures diffuse incoming sunlight, thereby minimising glare and improving visual comfort for occupants (Attia et al., 2015).

#### 4.1.5 Design Implications

The IMA demonstrates biomimicry's potential for responsive daylight control in temperate climates. Lessons include integrating hybrid sensor driven systems for improved durability and energy efficiency (Attia et al., 2015).

### 4.2 SINOSTEEL INTERNATIONAL PLAZA - CHINA

*Figure 2: (a) Sinosteel International Plaza, China (Bojovic, 2013), (b) Façade system (Bojovic, 2013), (c) Beehive hexagonal cells (Freepik, n.d.)*

#### 4.2.1 Building Overview

Sinosteel International Plaza (Tianjin, China) [refer Figure 2:(a)], designed by MAD Architects, comprises a 358 m office tower and 88 m hotel tower with a total GFA of

350,000 m². The honeycomb inspired facade emphasises structural efficiency and daylight optimisation (Etherington, 2008).

#### 4.2.2 Biomimicry Inspiration

Inspired by beehive hexagonal cells [refer Figure 2:(c)], the façade [refer Figure 2:(b)] uses geometry to maximise daylight diffusion, structural strength, and minimal material usage while integrating traditional Chinese motifs (Bojovic, 2013).

#### 4.2.3 Daylighting Mechanism

Variable hexagonal openings in the honeycomb pattern are sized according to solar exposure, reducing glare and distributing diffuse light throughout interior spaces without kinetic elements (Sino-Steel International Plaza, n.d.).

#### 4.2.4 Performance Impact

The honeycomb-inspired façade contributes to improved daylight distribution through passive geometric modulation. The hexagonal façade pattern allows diffuse daylight to penetrate interior spaces while reducing excessive solar exposure. As a result, the building achieves improved daylight autonomy and reduced reliance on artificial lighting systems. Previous studies estimate that the façade design contributes to 20–30% reductions in lighting and cooling energy demand, particularly in high-density urban environments (Villalva et al., 2022; Etherington, 2008).

#### 4.2.5 Design Implications

The project illustrates how passive biomimetic strategies using parametric geometry can optimise daylight in high density urban environments while maintaining cultural resonance (Etherington, 2008).

### 4.3 HABITAT 2020 - CHINA

*Figure 3: (a) Habitat 2020 conceptual design, (b) Facade system (Yoneda, 2008)*

#### 4.3.1 Building Overview

Habitat 2020 is a conceptual biomimetic housing project [Figure 3: (a)] aiming for off grid, adaptive, eco systemic urban habitats with dynamic “living skin” facades [Figure 3:(b)] (Yoneda, 2008).

#### 4.3.2 Biomimicry Inspiration

Inspired by plant stomata, the facade functions like a living organism, opening and closing in response to environmental stimuli to regulate light, air, and energy flows (Yoneda, 2008).

#### 4.3.3 Daylighting Mechanism

Responsive panels modulate light entry, allowing diffuse daylight while blocking excessive sun. The system channels natural light deep into interiors, reducing shadows and hotspots (Yoneda, 2008).

#### 4.3.4 Performance Impact

The conceptual design of Habitat 2020 demonstrates the potential of organism-level biomimicry for daylight optimisation. The responsive façade system, inspired by plant stomata, dynamically regulates light penetration according to environmental conditions. This adaptive mechanism allows daylight to penetrate deeper into interior spaces while minimising excessive solar radiation. Conceptual performance evaluations indicate that such responsive systems could reduce artificial lighting demand by 50–80%, while maintaining high daylight autonomy and useful daylight illuminance levels (Sommese et al., 2024; Yoneda, 2008).

#### 4.3.5 Design Implications

Habitat 2020 demonstrates the potential of organism-level biomimicry for self-sustaining, daylight optimised urban habitats, though real world implementation challenges remain (Sommese et al., 2024).

### 4.4 ESPLANADE THEATRE - SINGAPORE

*Figure 4: (a) Esplanade Theatre, Singapore, (b) Facade system, (c) Durian fruit*

#### 4.4.1 Building Overview

The 60,000 m² Esplanade Theatre (Marina Bay, Singapore) [refer Figure 4:(a)] by DP Architects and Michael Wilford features concert halls, studios, and public spaces. Its signature façade [refer Figure 4:(b)] is clad with 7,000+ triangular Aluminium sunshades (Architecture, n.d.).

#### 4.4.2 Biomimicry Inspiration

Inspired by the durian fruit shell [refer Figure 4:(c)], the sunshade geometry provides passive shading and light diffusion for equatorial conditions (Esplanade Theatres, 2025).

#### 4.4.3 Daylighting Mechanism

Parametrically varied triangular sunshades block direct sun and create dappled interior illumination, maintaining uniform daylight levels while minimising glare (Chayaamor-Heil, 2023).

#### 4.4.4 Performance Impact

The durian-inspired façade of the Esplanade theatre demonstrates the effectiveness of passive biomimetic shading strategies in tropical climates. The triangular Aluminium sunshades filter incoming sunlight and create diffuse interior illumination, which improves daylight distribution throughout the building. This design significantly reduces glare while maintaining comfortable lighting levels in public interior spaces. Performance studies indicate that the façade system contributes to approximately 55% reduction in artificial lighting demand, while also improving overall building energy efficiency (Chayaamor-Heil, 2023; Esplanade Theatres, 2025).

#### 4.4.5 Design Implications

The Esplanade highlights durable, fixed biomimetic shading as a solution for tropical climates, integrating environmental, aesthetic, and cultural objectives (Biomimicry Architecture #3, 2019).

### 4.5 AL BAHAR TOWERS - UAE

*Figure 5: Al Bahar Towers, UAE, (b) Facade system, (c) Pinecone*

#### 4.5.1 Building Overview

Al Bahar Towers (Abu Dhabi, UAE) [refer Figure 5:(a)], designed by Aedas, are twin 145 m office towers featuring over 2,000 motorised triangular mashrabiya panels (Attia, 2016; Cilento, 2012).

#### 4.5.2 Biomimicry Inspiration

Combining traditional Mashrabiya with pinecone [refer Figure 5:(c)] and flower inspired movements, the kinetic façade [refer Figure 5:(b)] opens/closes according to sun position, offering adaptive shading in a hot desert climate (Attia, 2016; Cilento, 2012).

#### 4.5.3 Daylighting Mechanism

Photoelectric sensors control panel movement to maximise diffuse daylight while minimising glare. Panels adjust for morning, evening, and peak sun exposure, preserving interior comfort and views (Attia, 2016).

#### 4.5.4 Performance Impact

The kinetic Mashrabiya façade of Al Bahar Towers demonstrates the effectiveness of responsive shading systems in hot desert climates. The motorised triangular panels automatically adjust according to solar position, allowing diffuse daylight while limiting

excessive solar radiation. This adaptive mechanism improves daylight penetration and reduces glare within office spaces. Performance assessments indicate that the façade contributes to 30–50% reduction in artificial lighting energy consumption, while improving daylight autonomy across interior floor areas (Attia, 2016; Cilento, 2012).

#### 4.5.5 Design Implications

Al Bahar Towers exemplify kinetic, culturally informed biomimicry for extreme climates (refer Table 1).

*Table 1: Comparative Analysis of Case Studies*

| Building | Biomimicry Inspiration | Daylighting Strategy | Artificial Lighting Reduction |
|---|---|---|---|
| Institut du Monde Arabe, France | Human eye iris | Motorized photo-sensitive apertures adjust to external illuminance levels | 30-50% |
| Sinosteel International Plaza, China | Honeycomb structure | Passive hexagonal window pattern diffuses daylight | 20-30% |
| Habitat 2020, China | Plant stomata | Responsive dynamic facade panels for diffuse light | 50-80% (conceptual) |
| Esplanade Theatre, Singapore | Durian fruit shell | Triangular aluminium sunshades block direct sunlight, diffuse light | 55% |
| Al Bahar Towers, UAE | Flowers / pinecones | Motorized panels open/close with sun position to optimize daylight | 30-50% |

Despite mechanical complexity and maintenance needs, the towers achieve substantial lighting efficiency and occupant comfort (Cilento, 2012).

### 4.6 ANALYTICAL DISCUSSION

Table 1 highlights key patterns in biomimicry inspired daylight strategies. Kinetic versus passive facades show distinct performance trade-offs: motorised facades (Institut du Monde Arabe, Al Bahar Towers) allow precise daylight control but involve higher maintenance and mechanical complexity, whereas passive systems (Sinosteel, Esplanade) offer simpler, lower maintenance solutions through geometry and orientation. Climate influence is evident: hot arid regions e.g. Abu Dhabi favour kinetic shading to mitigate intense solar gain and glare, whereas temperate or tropical regions benefit from diffusive passive shading. The range of artificial lighting reduction varies widely from 20-80%, with dynamic responsive systems achieving the highest potential savings, while passive strategies provide consistent, moderate energy reductions. These patterns demonstrate biomimicry's versatility in enhancing daylight autonomy while balancing operational practicality and cultural design considerations. As an exploratory comparative analysis based on secondary data sources, these findings should be interpreted cautiously and

considered as a conceptual foundation for more detailed future investigations involving simulation modelling, occupant-level measurements, and empirical energy performance analysis.

## 5. DISCUSSION

These findings contribute to the growing discourse on form- and behavior-driven daylight optimisation as a key strategy for decarbonising the built environment. The comparative analysis of the case studies indicates that adaptive and passive biomimicry strategies can reduce artificial lighting demand by 20-80%, depending on climate, façade complexity, and building type. Unlike conventional daylighting studies that primarily attribute energy reductions to technological interventions or glazing modifications, this analysis isolates the role of biomimetic geometry and dynamic façade behavior as the principal variable influencing daylight performance. By maintaining consistent building envelope materials and environmental conditions across projects, the attribution of performance improvements to adaptive forms is reinforced.

Exemplar projects, such as the Institut du Monde Arabe and Al Bahar Towers, demonstrate kinetic strategies where motorised apertures respond to solar intensity and orientation, modulating interior light levels and reducing glare. In contrast, passive systems such as the Sinosteel International Plaza and Esplanade theatre, Singapore rely on geometric or parametric shading patterns to diffuse sunlight and optimise daylight distribution. Analytical comparison shows that kinetic systems offer finer control over illumination and glare but incur higher maintenance complexity and operational costs. Passive geometric systems provide lower maintenance solutions, yet their performance is constrained by the fixed orientation and climatic conditions, highlighting the trade-offs inherent in façade strategy selection.

Climate influence emerges as a critical determinant of system effectiveness. Hot-arid climates, as in Abu Dhabi, benefit from responsive kinetic shading to mitigate extreme solar gains, while tropical contexts, exemplified by Singapore, achieve adequate daylighting through fixed parametric or modular patterns. These results align with prior studies (Etherington, 2008), yet the present analysis emphasises the interaction between climate, form, and dynamic behavior as a measurable factor in operational energy reduction, rather than merely aesthetic or conceptual innovation.

Several limitations must be acknowledged. Quantitative data on occupant-level illumination and energy savings remain limited, particularly for conceptual projects such as Habitat 2020, where performance modeling is theoretical rather than empirically validated. Additionally, the long-term operational impacts, such as façade maintenance requirements, mechanical wear, and lifecycle performance of kinetic systems, are not fully captured within the current evaluation. Since the study relies entirely on documented secondary data sources, the findings should be considered exploratory and suitable as a foundation for more detailed future studies involving simulation modelling and empirical performance validation. Despite these constraints, the findings underscore the potential of early stage morphological and geometric interventions to enhance visual comfort and reduce artificial lighting reliance, independent of changes to building systems or occupancy patterns.

Taken together, these results position biomimicry inspired daylighting not merely as a symbolic or aesthetic exercise, but as a quantifiable, form and behavior driven strategy

with implications for sustainable architecture, lifecycle energy modeling, and adaptive urban design. By integrating multiple passive and kinetic functions such as light modulation, glare reduction, and solar control within a coherent morphologically inspired envelope, these designs mirror ecological principles where structures often perform multiple functions simultaneously, offering a resilient and energy efficient logic for future buildings.

## 6. CONCLUSIONS

This study evaluated the effectiveness of biomimicry-inspired daylighting strategies in reducing artificial lighting demand in urban buildings through the analysis of five international case studies. The findings demonstrate that nature-inspired façade systems, including adaptive apertures, honeycomb geometries, responsive skins, and parametric shading structures, significantly enhance daylight penetration and interior illumination while reducing reliance on artificial lighting. The comparative analysis indicates that both passive and kinetic biomimetic façade strategies can improve daylight distribution and reduce lighting energy consumption, with reductions ranging from approximately 20–80% depending on climatic context and façade configuration.

The results highlight the importance of integrating biological principles into architectural design to improve building environmental performance. Biomimicry-inspired daylighting strategies provide a promising approach for achieving energy-efficient and climate-responsive urban buildings. Future research should further explore parametric modelling, adaptive façade technologies, and advanced materials to develop scalable biomimetic design solutions that optimise daylight utilisation in contemporary urban architecture.

## 7. REFERENCES

*Architecture*. (n.d.). Esplanade – Theatres on the Bay, Retrieved 15 March 2026, from https://www.esplanade.com/architecture

Attia, S. (2016). *Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. QScience Proceedings, 2016*(3), 8. https://doi.org/10.5339/qproc.2016.qgbc.8

Attia, S., Favoino, F., Loonen, R., Petrovski, A., & Monge-Barrio, A. (2015). Adaptive façades system assessment: An initial review. In *10th Conference on Advanced Building Skins* (pp.1275-1283). Economic Forum. https://pure.tue.nl/ws/files/8287219/15_abs_attia.pdf

Bijari, M., Aflaki, A., & Esfandiari, M. (2025). Plants inspired biomimetics architecture in modern buildings: A review of form, function and energy. *Biomimetics, 10*(2), 124. https://doi.org/10.3390/biomimetics10020124

*Biomimicry Architecture #3*. (2019, February 15). Parametric House, Retrieved 15 March 2026, from https://parametrichouse.com/biomimicry-architecture-3/

Bojovic, M. (2013, March 26). Honeycomb facade for softer urban landscape / Sinosteel, Tianjin by MAD architects. *eVolo | Architecture Magazine*. https://www.evolo.us/honeycomb-facade-for-softer-urban-landscape-sinosteel-tianjin-by-mad-architects/

Chayaamor-Heil, N. (2023). From bioinspiration to biomimicry in architecture: opportunities and challenges. *Encyclopedia, 3*(1), 202–223. https://doi.org/10.3390/encyclopedia3010014

Cilento, K. (2012, September 5). *Al Bahar Towers responsive facade / aedas*. ArchDaily. https://www.archdaily.com/270592/al-bahar-towers-responsive-facade-aedas

Kaitouni, S. I., Sangkyu, P., Mghazil, M. O., El-Mansouri, A., Jamil, A., Ahachad, M. & Brigui, J. (2024). Design parameters influencing the energy performance and indoor comfort of net zero energy building "NZEB" designed for semi-arid urban areas: Digital workflow methodology, sensitivity analysis and comparative assessment. *Solar Energy, 268*, 112264. https://www.sciencedirect.com/science/article/abs/pii/S0038092X23008988

Etherington, R. (2008, July 30). *Sinosteel international plaza by MAD*. Dezeen. https://www.dezeen.com/2008/07/30/sinosteel-international-plaza-by-mad/

Hong, W. Y., & Rahmat, B. N. N. N. (2022). Energy consumption, CO2 emissions and electricity costs of lighting for commercial buildings in Southeast Asia. *Scientific Reports*, *12*(1), 13805. https://doi.org/10.1038/s41598-022-18003-3

Hussein, E. A., & Abbood, O. A. (2024). Biomimicry as a sustainable solution in Architecture: Analytical study. *BIO Web of Conferences*, *97*, 00015. https://doi.org/10.1051/bioconf/20249700015

Jamilu, G., Abdou, A., & Asif, M. (2024). Dynamic facades for sustainable buildings: A review of classification, applications, prospects and challenges. *Energy Reports*, *11*, 5999–6014. https://doi.org/10.1016/j.egyr.2024.05.047

Katabaro, J. M., Yan, Y., Hu, T., Yu, Q., & Cheng, X. (2022). A review of the effects of artificial light at night in urban areas on the ecosystem level and the remedial measures. *Frontiers in Public Health*, *10*, 969945. https://doi.org/10.3389/fpubh.2022.969945

*MAD*. (n.d.). MAD. Retrieved 18 February 2026, from https://www.i-mad.com/www.i-mad.com

Michler, A. (2010, September 17). *Jean Nouvel's stunning museum façade dilates to let in daylight*. INHABITAT. https://inhabitat.com/jean-nouvels-stunning-museum-facade-dilates-to-let-in-daylight/

Minucciani, V., & Onay, N. S. (2018). Evaluation of design approaches for wellbeing in interiors. *Journal of Engineering and Architecture*, 6(1), 112-122. https://doi.org/10.15640/jea.v6n1a11

Montes-Villalva, E., Pereira-Ruchansky, L., Piderit-Moreno, B., & Pérez-Fargallo, A. (2022). Impact of urban re-densification on indoor lighting demand and energy poverty on the equator, in the city of Quito. *Sustainability*, *14*(7), 3783. https://doi.org/10.3390/su14073783

*Sydney's one central park by jean nouvel features lush vertical gardens*. (n.d.). Designboom. Retrieved 15 March 2026, from https://www.designboom.com/architecture/jean-nouvel-one-central-park-sydney-10-08-2014/?utm_source=chatgpt.com

Overen, O. K., Meyer, E. L., & Makaka, G. (2023). Daylighting assessment of a heritage place of instruction and office building in Alice, South Africa. *Buildings*, *13*(8), 1932. https://www.mdpi.com/2075-5309/13/8/1932

Papamichael, K., Hathaway, N. G., Ang, A., & Mckenzie, G. (2018). Daylight harvesting for commercial buildings. California Lighting Technology Center. https://cltc.ucdavis.edu/sites/g/files/dgvnsk12206/files/inline-files/Daylighting_181008_Web.pdf

Pedersen-Zari, M. (2020). Biomimetic urban and architectural design: Illustrating and leveraging relationships between ecosystem services. *Biomimetics*, *6*(1), 2. https://doi.org/10.3390/biomimetics6010002

*Esplanade Theatres: Biomimetic Architecture*. (2025, December). SCRIBD. Retrieved 15 March 2026, from https://www.scribd.com/document/960033265/A-3-Esplande-Theatre

Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard – A simulation-based design analysis for daylit spaces. *Building and Environment*, *46*(2), 386–396. https://doi.org/10.1016/j.buildenv.2010.08.001

*Science Photo Gallery*. (n.d.). Science Photo Gallery. Retrieved 15 March 2026, from https://sciencephotogallery.com/featured/human-eye-showing-close-up-of-blue-iris-and-pupil-cristina-pedrazziniscience-photo-library.html

*Sino-steel International Plaza | MAD Architects*. (n.d.). Archello. Retrieved 15 March 2026, from https://archello.com/project/sino-steel-international-plaza

Sommese, F., Hosseini, S. M., Badarnah, L., Capozzi, F., Giordano, S., Ambrogi, V., & Ausiello, G. (2024). Light-responsive kinetic façade system inspired by the Gazania flower: A biomimetic approach in parametric design for daylighting. *Building and Environment*, *247*, 111052. https://doi.org/10.1016/j.buildenv.2023.111052

Varshabi, N., Arslan Selçuk, S., & Mutlu Avinç, G. (2022). Biomimicry for energy-efficient building design: A bibliometric analysis. *Biomimetics*, *7*(1), 21. https://doi.org/10.3390/biomimetics7010021

Verbrugghe, N., Rubinacci, E., & Khan, A. Z. (2023). Biomimicry in architecture: A review of definitions, case studies, and design methods. *Biomimetics*, *8*(1), 107. https://doi.org/10.3390/biomimetics8010107

Vitalii, B., Mykola, K., Khomyshyn, V., & Sabat, N. (2020). Economic and energy efficiency of artificial lighting control systems for stairwells of multistorey residential buildings. *Journal of Daylighting*, *7*(1), 93–106. https://doi.org/10.15627/jd.2020.8

Winstanley, T. (2011, October 2). *AD classics: Institut du monde arabe / enrique jan + jean nouvel + architecture-studio*. ArchDaily. https://www.archdaily.com/162101/ad-classics-institut-du-monde-arabe-jean-nouvel

Yoneda, Y. (2008, July 9). HABITAT 2020: Future smart 'living' architecture. *Inhabitat - Green Design, Innovation, Architecture, Green Building | Green Design & Innovation for a Better World*. https://inhabitat.com/habitat-2020-off-the-grid-future-abode/

Abeynayake, M.D.T.E., Perera, B.A.K.S., Mahanamahewa, P. and Abeysekara, T.B., 2026. Legislative Provisions for Circular Economy Implementation in the Construction Industry within the Sri Lankan Jurisdiction. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1079-1093. DOI: https://doi.org/10.31705/WCS.2026.79. Available from: https://ciobwcs.com/papers/

# LEGISLATIVE PROVISIONS FOR CIRCULAR ECONOMY IMPLEMENTATION IN THE CONSTRUCTION INDUSTRY WITHIN THE SRI LANKAN JURISDICTION

**M.D.T.E. Abeynayake[1], B.A.K.S. Perera[2] , Prathibha Mahanamahewa[3] and T.B. Abeysekara[4]**

## *ABSTRACT*

*The Construction Industry (CI) is a significant contributor to waste generation and environmental degradation. The Circular Economy (CE) concept has emerged as a promising approach to improve resource efficiency and minimising waste within CI. However, the lack of adequate legislative support remains a key barrier to implementation of CE particularly in developing countries including Sri Lanka. Despite growing interest in CE adoption, limited research has examined the extent to which existing legislative provisions facilitate the implementation within the Sri Lankan CI. This research aims to investigate the adaptability of existing legislative provisions relevant to CE implementation in the Sri Lankan CI. The study adopted a qualitative research approach, comprising a document review and semi-structured interviews with experts. A documentary review revealed seven legislative-related CE practices in the Sri Lankan jurisdiction. The findings reveal that while existing legislation provides several indirect enablers for CE implementation, the overall regulatory framework remains fragmented and lacks dedicated provisions to effectively support circular construction practices. This study contributes to the literature by providing one of the first systematic assessments of legislative provisions relevant to CE implementation within the Sri Lankan construction industry. The findings offer valuable insights for policymakers and industry stakeholders seeking to strengthen the regulatory framework for a transition towards a circular built environment.*

***Keywords:*** *Circular economy; CE Laws; Construction industry; Enablers; Sri Lankan Jurisdiction.*

## 1 INTRODUCTION

The CI is a significant economic sector that accounts for over 30% of global natural resource extraction and approximately 25% of global solid waste production (Benachio

[1] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk
[2] Senior Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] Professor, Department of Commercial Law, Faculty of Law, University of Colombo, Sri Lanka, prathiba@law.cmb.ac.lk
[4] Senior Lecturer, Faculty of Management Studies and Commerce, University of Sri Jayewardhenepura, Sri Lanka, thusitha@sjp.ac.lk

et al., 2020). While the industry plays a vital role in supporting economic development, it is associated with considerable environmental burdens arising from intensive resource consumption and waste generation. Victar and Waidyasekara (2023) and Wijewansha et al. (2021) highlighted that construction activities contribute substantially to economic growth while encompassing a significant pressure on the environment. The CI is estimated to consume more than over 50-60% of global raw materials annually, including large quantities of sand, gravel, cement, and steel, resulting in considerable environmental impacts throughout extraction processing and transportation stages (Eštoková et al., 2023; Alhawari et al., 2021). In addition to direct resource consumption, various construction related activities create a ripple effect on the environment. For instance, cement production alone accounts for approximately 8% of global carbon emissions (Jayawardhana et al., 2023) while sand extraction disrupts riverine ecosystems and coastal morphology and steel production requires significant energy inputs and generates air pollutants (Purchase et al., 2022). Construction activities, including over-ordering, inefficient site management and poor coordination between design and construction processes, contribute significantly to waste generation and material efficiencies (Victar & Waidyasekara, 2024). Consequently, the construction industry accounts for approximately 39% of global carbon emissions, including both operational and embodied carbon. In many countries, Construction and Demolition Waste (C&DW) constitutes 30-40% of total waste production, causing to landfill congestion, soil contamination, and Greenhouse gas emissions associated with transportation and waste decomposition (Jayawardhana et al., 2023). These challenges are particularly pronounced in developing countries where waste management systems and regulatory mechanisms are often less developed (Saja et al., 2021).

Given the substantial environmental footprint of CI, the CE has emerged as one of the most promising approaches for improving sustainability and resource efficiency within the sector (Badejo et al., 2024). Unlike the traditional linear economy model based on the "take-make-dispose" approach, CE seeks to minimise resource extraction and waste generation by establishing closed-loop systems that retain materials within productive use for as long as possible (Castro et al., 2022). Accordingly, CE is widely recognised as a sustainable economic model founded on the principles of Reduction, Reuse, and Recycling (3Rs) (Weerakoon et al., 2023). Within the construction context, CE facilitates improved resource efficiency, reduced waste generation, and enhanced resource conservation throughout the project lifecycle (Wanaguru et al., 2022). Gamage et al. (2024) emphasised that successful implementation of CE practices requires consideration from the design stage, as early project decisions significantly influence downstream construction and end-of-life outcomes (Gamage et al., 2024). Similarly, Wijewansha et al. (2021) explored practical application of CE concept across both the planning and post-construction phases of the Sri Lankan construction industry.

The successful implementation of CE within the CI requires not only technical and managerial interventions but also an enabling legislative and regulatory environment. Legislative provisions play a pivotal role in governing environmental protection, waste management, resource conservation, environmental impact assessment, and sustainable construction practices. Consequently, legal frameworks can serve as important enablers for the transition towards a circular construction sector by creating regulatory mechanisms that encourage resource efficiency, waste minimisation, and sustainable material management practices (Hossain et al., 2020).

Several studies have examined CE implementation within the construction industry from different perspectives. For example, Wijewansha et al. (2021) investigated the practical application of CE principles across the lifecycle of building projects in Sri Lanka, while Gamage et al. (2024) highlighted the importance of integrating CE considerations during the design stage to improve resource efficiency and waste reduction. International studies have similarly focused on construction and demolition waste management, resource recovery, stakeholder engagement, business models, and technical strategies for CE implementation within the built environment (Badejo et al., 2024). Furthermore, several researchers have acknowledged policy and regulatory support as a critical enabler for the successful transition towards CE (Bleischwitz et al., 2022; Hossain et al., 2020). However, these studies primarily discuss legislation as a contextual or supporting factor rather than systematically examining specific legislative provisions and their capacity to facilitate CE implementation within the construction sector.

The lack of legislation specifically aligned with CE principles remains a common challenge in many developing countries (Bleischwitz et al., 2022). In the Sri Lankan context, the absence of dedicated CE legislation may hinder the transition towards more sustainable construction practices, resulting in continued resource depletion, environmental degradation, and inadequate waste management. Although previous studies have examined CE concepts, implementation strategies, and sustainability practices within the construction sector, limited attention has been paid to the legislative provisions that may facilitate CE implementation in Sri Lanka. Furthermore, the extent to which existing legislation and regulatory provisions support CE principles within the Sri Lankan construction industry remains largely unexplored.

This represents a significant knowledge gap within both the CE and construction management literature. There is no previous study that systematically examined the existing legislative framework of Sri Lanka from a CE perspective to evaluate the potential contribution towards CE implementation in the construction industry. Therefore, the novelty of this study lies in the comprehensive assessment of existing legislative provisions relevant to CE implementation and the identification of legislative gaps and opportunities for strengthening regulatory support for a circular built environment in Sri Lanka. In this context, this research aims to investigate the adaptability of existing legislative provisions relevant to CE implementation in the CI within the Sri Lankan jurisdiction and address this knowledge gap. The objectives of the study are to identify relevant legislation and its provisions related to CE in the Sri Lankan Jurisdiction, and to investigate how these provisions enable the implementation of CE in CI in the Sri Lankan Jurisdiction.

## 2 METHODOLOGY

Following Crossman (2020), this study uses a qualitative research methodology to collect detailed insights from documents and experts participants regarding the legislative provisions relevant to CE implementation in the Sri Lankan construction industry. A qualitative approach was considered appropriate as the study seeks to explore and interpret the extent to which existing legislative provisions facilitate CE implementation rather than quantify predefined variables. Furthermore, legal and regulatory frameworks are context-dependent and often require interpretive analysis to understand their practical implications within a specific jurisdiction. Choosing a qualitative multi-method approach for this research is justified for several reasons.

- CE implementation is not governed by a single piece of legislation but rather by an interconnected framework of environmental, planning, waste management, and construction-related legislation. Qualitative research enables the systematic examination of these legislative relationships and facilitates an understanding of their collective contribution towards CE implementation.
- Many legislative provisions associated with CE principles, such as resource efficiency, waste minimisation, recycling, and extended producer responsibility, are evolving within the Sri Lankan regulatory landscape. Qualitative methods, including documentary review and expert interviews, provide the flexibility required to identify legislative gaps, overlaps, and implementation challenges.
- Qualitative approaches facilitate the capture of expert interpretations and practical experiences, thereby providing insights into how legislative provisions operate within real-world construction and regulatory environments.

## 2.1 RESEARCH PROCESS

Accordingly, this research followed a systematic three-stage research process, comprising literature review, documentary review, and expert interviews as illustrated in Figure 1.

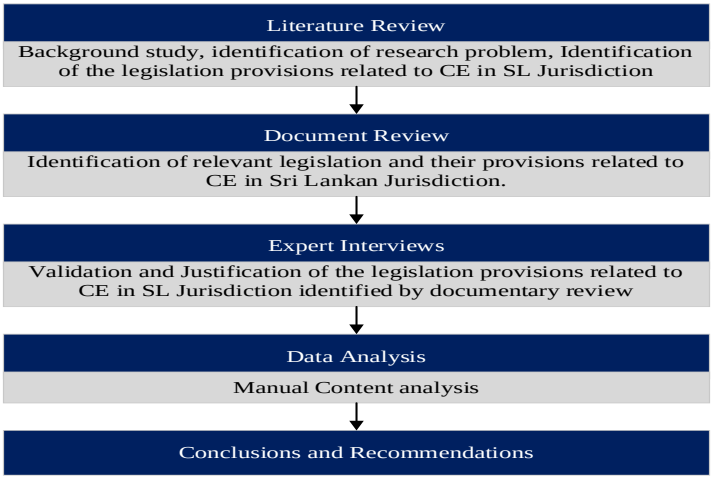



*Figure 1: Research process for the research*

The literature review was conducted to establish the theoretical foundation of the study and identify CE principles, implementation requirements, and legislative dimensions discussed in previous research. The documentary review subsequently examined existing legislative instruments relevant to CE implementation within the Sri Lankan construction industry. Finally, expert interviews were conducted to validate, contextualise, and enrich the findings derived from the documentary review.

## 2.2 LITERATURE REVIEW

A comprehensive literature review was conducted to identify CE practices and the legal provisions used in CI, legislative considerations relevant to CI. The review included peer-reviewed journal articles, conference papers, policy reports, and legislative studies related to Circular Economy implementation within the built environment. The literature review examined the role of legislation in facilitating CE practices in the CI. The findings of the literature review provided the basis for identifying potential legislative dimensions that were subsequently explored through the documentary review and expert interviews.

## 2.3 DOCUMENTARY REVIEW

Documentary reviews are particularly useful for qualitative research as they bridge theoretical perspectives with empirical realities (Swain et al., 2025). Documentary review is the main content of legal research, involving the analysis of various sources of law to establish legal principles (Wills, 2022). Legal research supplements the area of practice by backing up everything with credible sources, and even legislation for documentary review. In this study, the documentary review served as the primary data collection method for identifying legislative provisions relevant to CE implementation within the Sri Lankan construction industry. Legislative documents were accessed through publicly available official sources, including the Sri Lanka Parliament database, the Ministry of Environment, the Central Environmental Authority (CEA), and other relevant government regulatory institutions. The selection of legislative documents was guided by their relevance to construction activities, environmental protection, waste management, resource conservation, sustainable development, and related regulatory functions. Consequently, the review focused on legislation that contained provisions associated with key CE principles. The documentary review followed a structured process comprising three stages: (1) identification of potentially relevant legislation through literature findings and government sources; (2) screening and selection of legislation based on relevance to CE principles and construction activities; and (3) detailed examination of legislative provisions to identify mechanisms that may facilitate or hinder CE implementation. The findings obtained from this stage formed the basis for the development of the expert interview protocol.

## 2.4 EXPERT INTERVIEWS

This study explored the adaptability of laws to support CE in the CI of Sri Lanka. Accordingly, semi-structured expert interviews were conducted to obtain in-depth, insights from professionals possessing specialised knowledge of legislation, environmental governance, and construction industry practices. A purposive sampling strategy was employed to select experts with substantial experience and expertise relevant to the research topic. Purposive sampling was considered appropriate as the study required participants who possessed specialised knowledge regarding legislative frameworks, regulatory implementation, environmental management, and construction industry practices. Semi-structured interviews were conducted with five experts who are having more than 15 years of professional experience. The selection of five experts was considered adequate due to the specialised and exploratory nature of the study. Previous qualitative research (Saunders et al., 2015) has recognised that smaller samples may be appropriate where participants possess extensive domain expertise and where the objective is to obtain detailed, information-rich insights rather than statistical representation. Following Table 1 presents the profile of the experts.

*Table 1: Profile of the experts*

| Code | Professional Designation | Sector | Years of Experience | Relevance to the Study |
|---|---|---|---|---|
| E1 | Director (Legal) | Statutory Regulatory Body | 18 | Extensive experience in interpreting and implementing environmental and planning legislation relevant to CE adoption in construction |

| Code | Professional Designation | Sector | Years of Experience | Relevance to the Study |
|---|---|---|---|---|
| E2 | Professor in Law | Academia | 30 | Expertise in legal frameworks, policy analysis, and legislative development related to sustainability |
| E3 | Senior Lecturer / Attorney-at-Law | Academia / Legal Practice | 21 | Experience in legal interpretation and application of legislation within the built environment |
| E4 | Lawyer / Environmental Specialist | Legal and Environmental Sector | 20 | Practical experience in environmental compliance and implementation of sustainability-related regulations |
| E5 | Lawyer / Researcher | Legal Research and Practice | 32 | Expertise in evaluating legislative frameworks and identifying regulatory gaps relevant to CE implementation |

The interview guide was developed based on the findings of the documentary review. Specifically, legislative provisions identified during the documentary review were presented to the experts to assess their relevance, applicability, strengths, limitations, and potential contribution towards CE implementation within the construction industry. In addition, experts were invited to identify legislative gaps, implementation challenges, and opportunities for strengthening regulatory support for CE adoption in Sri Lanka. These semi-structured interviews allowed experts to elaborate on issues beyond the predefined questions and provided valuable contextual insights regarding the practical implementation of legislative provisions within the Sri Lankan construction industry.

### 2.5 DATA ANALYSIS

The data obtained from the documentary review and expert interviews were analysed using manual content analysis. Manual content analysis was considered appropriate due to the relatively small number of legislative documents and interview transcripts involved in the study, as well as the interpretive nature of legal and regulatory analysis. Unlike automated coding approaches, manual content analysis enabled the researchers to closely engage with the data and capture contextual meanings embedded within legislative provisions and expert opinions (Zai et al., 2025). The analysis process involved several stages: (1) familiarisation with the collected data; (2) identification of legislative provisions relevant to CE principles; (3) coding and categorisation of findings into thematic areas; (4) comparison and validation of themes using expert interview data; and (5) synthesis of findings to identify legislative enablers, limitations, and gaps related to CE implementation within the Sri Lankan construction industry.

## 3 FINDINGS OF THE DOCUMENT REVIEW

### 3.1 LEGISLATION IN SRI LANKA RELEVANT TO CE IN THE CONSTRUCTION INDUSTRY

The selection of legislative Acts for this study followed a structured screening process. Initially, legislation identified through the literature review and documentary review was compiled from official government and regulatory sources. The identified legislation was subsequently screened based on three criteria: (1) relevance to construction industry activities; (2) presence of provisions related CE, and (3) potential influence on decision-making and operational practices within the CI. Based on these criteria, seven Acts were selected for detailed analysis as they contained the most direct and substantive legislative

provisions relevant to facilitating CE implementation within the Sri Lankan CI. While additional legislation, regulations, policies, and guidelines may indirectly contribute to CE, they were beyond the scope of the present analysis due to their limited direct applicability to construction-related CE practices. Following are the selected legislations for the ersearch.

1. National Environmental Act, No. 47 of 1980 and its Amendments
2. Urban Development Authority Law, No. 41 of 1978
3. Coast Conservation Act, No. 57 of 1981
4. Town and Country Planning (Amendment) Act, No. 49 of 2000
5. Municipal Councils Ordinance, Urban Councils Ordinance, and Pradeshiya Sabhas Act (Local Authority legislation)
6. Construction Industry Development Act, No. 33 of 2014
7. Sustainable Development Act, No. 19 of 2017.

The findings are analysed to identify gaps within the existing legislative provisions relevant to CE implementation. The following sections critically examine each selected legislative instrument in relation to the alignment with CE principles and its potential role in facilitating CE implementation.

## 3.2 LEGISLATION, ITS PROVISIONS AND ENABLERS RELATED TO CE IN THE SRI LANKAN JURISDICTION

### 3.2.1 National Environmental Act, No. 47 of 1980 and its Amendments

The NEA No. 47 of 1980, with amendments (No. 56 of 1988, No. 53 of 2000), provides the legal framework for CE in Sri Lanka, focusing on waste management, pollution control, and resource efficiency through tools such as the Environmental Protection License (EPL) and Environmental Impact Assessment (EIA). From a CE analytical perspective, the NEA's EIA regime serves as a regulatory gateway through which significant construction projects must pass before receiving project approval. In principle, that gateway provides an opportunity to assess CE-relevant dimensions of the proposed project, including estimates of material consumption and waste generation. Enablers for CE implementation in the NEA is revealed in Table 2.

*Table 2: Enablers for CE implementation in the National Environmental Act, No. 47 of 1980*

| Section | Legal Provisions related to CE | Enablers for the Implementation of CE Laws |
|---|---|---|
| **Sec. 24** | Introduce discharge standards for pollution, regulates environmental discharges. | • Regulatory Enablers - Essential Environmental Policies and Pollution Control regulations for C&DW: Stringent rules requiring waste management and emission reductions (e.g., in the construction industry and urban development) act as top drivers (C&DW and secondary material-use standards are still not incorporated). |
| **Sec. 17** | Natural resources protection that provides leverage for CE capability requirements. | • Legally holding producers accountable for the entire lifecycle of their products, from design to end-of-life (CE competencies not yet embedded in grading criteria).<br>• Societal Enablers - Awareness and Public Pressure: Public pressure for cleaner environments and corporate social responsibility (CSR) drives firms to adopt the circular model. |

| Section | Legal Provisions related to CE | Enablers for the Implementation of CE Laws |
|---|---|---|
| **Part IV B - Sec. 23** | Waste Management and Pollution Control: focuses on environmental quality. | • Integrating Extended Producer Responsibility (EPR) into the NEA introduces regulations for CW&D (while Part IV A requires EPLs for industries, compelling compliance with standards that encourage cleaner production and waste recycling). |
| **Part IV C - Sec. 23** | Mandatory EIAs for prescribed projects ensure environmental sustainability and resource optimisation in large-scale projects. | • Environmental and Technical Enablers-Reduction of Natural Resource Depletion: Shifting to renewable inputs and materials, reducing raw material dependency, Industrial Symbiosis (IS): Incentivising networks where waste from one organisation becomes the feedstock for another.<br>• Enablers for Advanced Technologies: Adoption of technologies via artificial intelligence (AI), IoT, and advanced, cleaner production methods to enable efficient waste handling. |

Under the NEA, C&DW is not recognised as a scheduled waste category subject to Central Environmental Authority (CEA) licensing requirements. As a result, C&DW is excluded from the more rigorous regulatory controls and monitoring mechanisms governing hazardous and industrial wastes, potentially limiting effective oversight of the management and disposal.

### 3.2.2 Urban Development Authority Law, No. 41 of 1978 and its Amendments

The Urban Development Authority (UDA) Law No. 41 of 1978 establishes the UDA's mandate to regulate urban development activities within designated urban development areas, including the review and approval of development permits for significant construction projects. The UDA's development permit system is one of the regulatory gateways through which significant urban construction occurs. From a CE perspective, the UDA's development permit system offers a parallel mechanism to the EIA for imposing CE conditions on urban construction projects. Table 3 depicts the enablers for CE implementation in Urban Development Authority Law.

*Table 3: Enablers for CE implementation in Urban Development Authority Law, No. 41 of 1978*

| Section | Provisions related to CE | Enablers for CE implementation |
|---|---|---|
| **Sec. 17 and Sec. 21** | Empowers UDA to issue implementing regulations for urban development | • Green Procurement Regulations encourage and require the government and private sectors to procure recycled or sustainable materials.<br>• New regulations require the incorporation of CE permit conditions for development projects (for C&DW and secondary material requirements). |

The current development permit application process and review criteria contain no CE-specific requirements. The applications are assessed against urban planning, land-use compatibility, structural, and safety criteria, without any provisions addressing material specifications, waste management, design for disassembly, or secondary material use.

### 3.2.3 Coast Conservation Act, No. 57 of 1981 and its Amendments

The Coast Conservation Act No. 57 of 1981, administered by the Coast Conservation and Coastal Resource Management Department (CCCRMD), regulates construction activities within the coastal zone. This conservation orientation has produced detailed assessments and permit conditions addressing dredging, sand mining, shoreline modification, and pollution discharge in the coastal zone. However, it has not extended to the CE dimensions of construction projects within the coastal zone. Enablers for CE implementation in the Coast Conservation Act is revealed in table 4.

*Table 4: Enablers for CE implementation in the Coast Conservation Act, No. 57 of 1981, and its Amendments*

| Section | Provisions related to CE | Enablers for CE implementation |
|---|---|---|
| **Sec. 12** | The development scheme preparation and planning framework determines where and what development may occur; it is a potential instrument for area-wide material flow and CE infrastructure planning | • New Regulations for CE Concept. Limited explicit CE provisions in the legislation.<br>• Focused primarily on quality and safety rather than environmental sustainability. |
| **Sec. 16 and Sec. 32** | Development control; Development approvals under the planning framework can be conditioned to require CE assessments | • New Regulations (No specific CE provisions). |

The Coast Conservation Acts permit conditions for projects to address coastal ecological impacts but impose no requirements regarding the management of construction waste, the specification of secondary materials, or the design of structures for future adaptation or disassembly.

### 3.2.4 Town and Country Planning Ordinance and its Amendment Act No. 49 of 2000

The Town and Country Planning Ordinance (Cap. 269) and its Amendment Act 2000 provide the legislative framework for development planning and land-use control, allowing provincial and local authorities to prepare development plans, regulate land use, and control construction development within their jurisdictions depicted in Table 5.

*Table 5: Enablers for CE implementation in the Town and Country Planning Ordinance and its Amendment*

| Sections | Provisions related to CE | Enablers for CE implementation |
|---|---|---|
| **Sec. 10** | Development control. Development approvals under the planning framework can be conditioned to require CE assessments. | Impose New Regulations (No specific CE provisions) (No such CE-related regulations issued to date). |
| **Sec. 14** | Local approval authority covering all residential and smaller commercial projects, numerically the largest approval class. CE content is absent from all local building laws. | Introduce New Regulations (No specific CE provisions) for Building Plan Approval Provisions in the coastal belt. |

From a CE perspective, the planning framework could serve as a potential instrument for area-wide CE policy. In principle, planning authorities could require the preparation of material flow assessments for large development areas, designate zones for secondary material processing facilities, require infrastructure for waste segregation as a planning

condition, and incentivise the reuse of existing building stock over greenfield development through planning policies favouring adaptive reuse.

### 3.2.5 Municipal Councils Ordinance, Urban Councils Ordinance, and Pradeshiya Sabhas Act (Local Government legislation)

Three principal local government authorities establish the legal framework for building regulations, waste management, and development control at the local scale. Local authorities exercise building plan approval authority for construction projects within their jurisdictions, requiring applicants to submit structural plans and specifications for compliance review against applicable building laws before construction commences. The table 6 reveals Enablers for CE implementation in Local Government Law.

*Table 6: Enablers for CE implementation in Local Government Law*

| Section | Provisions related to CE | Enablers for CE implementation |
|---|---|---|
| **Waste Management Provisions** | Mandate for local solid waste management services, C&DW could be incorporated into local waste management frameworks. National standards for local C&DW management are not available. | Impose Financial Incentives: Tax reductions or financial support for projects turning waste into resources (e.g., reuse material, etc.). |
| **Local building bylaws** | Local approval authority covering all residential and smaller commercial projects, numerically the largest approval class. Building Plan Approval Provisions. | Introduce new bylaws for CE implementation (CE content absent from all local building bylaws). |

The absence of CE criteria from local authority building approval processes is analytically significant because local authorities administer approval for the vast majority of construction projects.

### 3.2.6 Construction Industry Development Act No. 33 of 2014

The Construction Industry Development Act No. 33 of 2014 established the Construction Industry Development Authority (CIDA) as the regulatory body for the construction sector. It is directly involved in construction, does not contain CE content, and mentions registration criteria focused on conventional construction standards. Amendments to the contractor registration criteria may be necessary to incorporate CE related competencies and capabilities.

### 3.2.7 Sustainable Development Act No. 19 of 2017

This is the most directly relevant legislation for enforcing sustainable principles in line with Sections 11, 12, and 13. However, the CE concept is not addressed, and it does not include CE principles. Consequently, the above legislation shows that CE legislation in Sri Lanka is fragmented and primarily policy-driven. While waste minimisation and recycling principles are mentioned in the NEA Act and UDA Act, they are less acknowledged and not enforced through binding obligations. Furthermore, recycling and sustainable construction practices, though encouraged by regulatory bodies, are still underdeveloped due to a lack of regulatory mandates. The legal provisions in the CI ensure that construction activities comply with environmental law, building regulations and urban development law.

## 3.3 VALIDATION OF FINDINGS OF DOCUMENT REVIEW BY EXPERTS' INTERVIEWS

As mentioned earlier, five legal experts systematically reviewed and validated seven types of legislation. Drawing on expert perspectives, multiple sections of the NEA were recognised as applicable to CE practices within the construction industry. Based on the insights of the experts, Section 10 of NEA serves as the primary legal bedrock for CE due to following reasons:

- It establishes the legal "powers, functions, and duties," essentially setting the boundaries of what an environmental regulator is permitted to do.
- It provides the mandate to draft the specific regulations that govern how construction projects operate.
- Specifically, Subsection (1) (m) is identified as an important tool as it focuses on waste utilisation, which is the core mechanism for keeping materials in use within a circular system.

The experts (E1, E2 and E4) confirmed the consensus that Section 17 of NEA serves as the primary legal backbone for CE in construction. By focusing on Natural Resources Management, it provides the necessary framework for shifting from traditional waste disposal to resource optimisation. Experts further explained that,

- It directly supports material reuse and the creation of material stock data, turning buildings into "resource banks." (confirmed by E2 and E3),
- It bridges the gap between policy and practice through selective demolition and the evaluation of materials for their next life cycle (confirmed by E1 and E3), and
- It aligns with sustainable material flows, prioritising conservation over extraction (confirmed by E2 and E3).

The experts acknowledged that Section 21 of the NEA on Forestry Management is applicable for implementing CE practices in the CI, as it governs the sustainable sourcing and management of timber, a key construction material. E2 emphasised that this section "impacts timber sourcing for construction", indicating its regulatory influence over the process (how, where) of obtaining timber. Additionally, E5 highlighted that Section 21 relates to sustainable timber use in construction, "relevance to CE goals like using renewable resources, promoting recyclability, and reducing dependency on virgin materials by establishing guidelines for forestry conservation, controlled harvesting, and sustainable supply chains". Section 21 of NEA supports CE practices such as designing material reuse, and E2 highlighted "extending the lifespan of wood-based elements" and "reducing construction waste." E1, E2, and E4 experts emphasised the importance of Section 32 of the NEA on Regulation-Making Powers. E2 emphasised that this section "provides the legal mechanism through which specific CE requirements could be implemented without amending the entire Act", indicating that it offers a flexible and responsive tool for integrating CE principles into CE practices. E4 further noted it "as critical as for it allows adaptability and timely updates, ensuring that emerging CE practices such as material reuse mandates, waste reduction targets, or deconstruction guidelines can be legally supported and enforced".

The experts' focus on Section 32 (Regulation-Making Powers) of the NEA highlights it as the engine of the Act's long-term success. According to the experts, this section provides:

- The ability to implement specific CE requirements, such as material reuse mandates, quickly as technology evolves, and
- A legal path to set and enforce waste reduction targets or deconstruction guidelines.

All experts acknowledged the need for appropriate legislation before commencing any CE practice in the CI. Therefore, the first step is to create a new CE law with the new CE Act. E1 pointed out that each stage of a construction project needs different legal rules. For the design stage, laws are necessary to enable architects to plan buildings that can be altered later and easily dismantled. The law should mention at least "the percentage of building materials that are reusable or recyclable". All experts identified three critical failures preventing the effective implementation of CE Law in the construction sector as follows:

- There is a fundamental disconnect between law and the actual regulatory obligations and enforcement mechanisms on the ground.
- Current CE requirements apply only to large-scale projects meeting a high contract value threshold. This excludes the residential and small commercial sectors, which represent the vast majority of construction activity.
- The existing legislations lacks a credible threat of enforcement, undermining its overall authority and effectiveness.

## 3.4 ENABLERS FOR CE LAWS WITH EXISTING LEGISLATION IN THE SRI LANKAN JURISDICTION

The enablers for existing CE laws in the Sri Lankan jurisdiction were identified based on document reviews and expert interviews. Table 7 presents a detailed discussion of enablers of CE implementation in existing legislation.

*Table 7: Enablers for CE laws with existing legislation in the Sri Lankan jurisdiction*

| Legislation | | Enablers |
|---|---|---|
| **National Environmental Act No. 47 of 1980** | Secs. 17 and 24 | • Introduce Pollution discharge standards for construction activities.<br>• C&DW and secondary material-use standards should be incorporated. |
| | Sec .23 | • CE competencies are not yet embedded in the assessment criteria. |
| **Construction Industry Development Act No. 33 of 2014** | Sec. 57 | • To make Rules. Authority to promulgate technical standards regulations can be exercised to mandate CE practices. Not yet familiar with CE practices. |
| | Secs. 12, 13, and 35 | • Revisit CIDA functions, objectives, and registration of contractors with CE requirements. |
| **Urban Development Authority Law No. 41 of 1978** | Sec. 17 | • Empowers UDA to issue implementing regulations, amendments, or new regulations required to incorporate CE permit conditions. |
| | Sec. 21 | • Amending the Coastal Zone Permit System. The permit system covers all coastal construction, including tourism, residential, and port facilities. Coastal ecology must be addressed (C&DW and secondary material requirements are absent). |
| **Coast Conservation Act No. 57 of 1981** | Sec. 16 | • Permit conditions. Conditions may be imposed on coastal construction permits. The mechanism is available to embed CE requirements, but it has not yet been utilised for this purpose. |

| Legislation | | Enablers |
|---|---|---|
| | Secs. 12, 32 | • Development scheme preparation. The planning framework determines where and what development may occur, serves as a potential instrument for area-wide material flow, and supports CE infrastructure planning. |
| **Town and Country Planning Ordinance & Amendments** | Sec. 10 | • Development control. Development approvals under the planning framework can be conditioned to require CE assessments. No such conditions have been issued to date. |
| | Building Plan Provisions | • Local approval authorities cover all residential and smaller commercial projects, numerically the largest approval class. CE content is absent from all local building laws. |
| **Municipal Councils Act, Urban Councils Act, and Pradeshiya Sabhas Act** | Waste Management Service Provisions | • C&DW could be incorporated into local waste management frameworks. National standards for local C&DW management are absent. |

According to Table 7, implementing enablers for the CE concept within the construction industry of Sri Lanka is driven through a patchwork of existing environmental, urban, and development laws rather than a single, standalone CE Act. To establish effective "enablers" for resource efficiency, waste reduction, and extended product lifecycles, several key legislative provisions are identified for amendment or enhanced enforcement.

# 4 CONCLUSIONS

This study investigated the adaptability of existing legislative provisions to support CE implementation within the Sri Lankan construction industry. The findings revealed that while several legislative instruments contain provisions that indirectly support CE principles, the overall legislative framework remains fragmented and lacks a coordinated regulatory approach specifically aimed at facilitating circular construction practices. Among the legislation reviewed, the National Environmental Act (NEA) emerged as the most significant legislative instrument, containing the majority of provisions relevant to environmental protection, waste management, and resource conservation that align with CE principles. The findings further indicate that although certain legislative provisions and regulatory mechanisms capable of supporting CE implementation are already in place, their effectiveness is constrained by inadequate monitoring, enforcement, and institutional coordination. In particular, the absence of dedicated legislative provisions relating to material recovery, construction and demolition waste segregation, reuse, and recycling limits the widespread adoption of CE strategies within the construction sector. This study contributes to the academic literature by providing one of the first systematic assessments of legislative provisions relevant to CE implementation within the Sri Lankan construction industry, thereby extending current knowledge on the regulatory dimensions of Circular Economy adoption. From a practical perspective, the findings offer valuable insights for policymakers, regulatory authorities, and industry stakeholders seeking to strengthen legislative support for circular construction practices. While the study focused on selected legislative instruments and employed a qualitative approach, future research could evaluate the implementation feasibility of the proposed legislative reforms, examine stakeholder readiness for regulatory changes, and develop governance frameworks to facilitate CE implementation within the construction industry. Accordingly, the study highlights the need for a more integrated and dedicated legislative framework to support the transition towards a Circular Economy within the Sri Lankan construction sector.

### 4.1 RECOMMENDATIONS

Sri Lanka is currently at a relatively early stage of adopting CE principles within the CI. Therefore, there is a need to strengthen the legislative and regulatory framework to establish a coherent vision for circularity and promote the systematic implementation of CE practices across the construction lifecycle. The findings identified significant gaps within the current legislative framework, particularly in relation to provisions that directly support or mandate CE-aligned practices within the construction industry. The recommendations focus on the successful adaptation of law to implement CE practices in the Sri Lankan construction industry as follows:

- Review and amend relevant legislation, particularly the NEA No. 47 in 1980, CIDA No. 14 of 2014 and other related regulations for implementing CE practices for the construction industry.
- Enhance the operational capacity of regulatory authorities by allocating a new division to lead CE implementation, especially considering the construction industry and providing new concepts and legal knowledge for industry practitioners.
- Develop and implement a dedicated a CE Act for Sri Lanka to provide a comprehensive legislative framework for promoting circularity within the construction industry.

## 5 REFERENCES

Alhawari, O., Awan, U., Bhutta, M. K. S., & Ülkü, M. A. (2021). Insights from circular economy Literature: A review of extant definitions and unravelling paths to future research. *Sustainability*, *13*(2), 859. https://doi.org/10.3390/su13020859

Badejo, A. O., Aminu, N. I., Sekar, L. K., & Okoroafor, E. R. (2024). Assessment of the environmental risks and policies associated with carbon capture and storage in the United Kingdom: A case study of the HyNet Northwest project. *Abu Dhabi International Petroleum Exhibition & Conference*. ADIPEC. https://doi.org/10.2118/222780-ms

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, *260*, 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Bleischwitz, R., Yang, M., Huang, B., Xu, X., Zhou, J., McDowall, W., Andrews-Speed, P., Liu, Z., & Yong, G. (2022). The circular economy in China: Achievements, challenges and potential implications for decarbonisation. *Resources Conservation and Recycling*, *183*, 106350. https://doi.org/10.1016/j.resconrec.2022.106350

Castro, C. G., Trevisan, A. H., Pigosso, D. C., & Mascarenhas, J. (2022). The rebound effect of circular economy: Definitions, mechanisms and a research agenda. *Journal of Cleaner Production*, *345*, 131136. https://doi.org/10.1016/j.jclepro.2022.131136

Coast Conservation Act, 57 (1981). https://env.gov.lk/web/images/downloads/acts/coast_conservation_act_no_57_of_1981.pdf

Construction Industry Development Act, 33 (2014). https://www.srilankalaw.lk/YearWisePdf/2014/CONSTRUCTION_INDUSTRY_DEVELOPMENT_ACT,_No._33_OF_2014.pdf

Crossman, A. (2020) An overview of qualitative research methods: Direct observation, interviews, participation, immersion, focus groups. Thought Co. https://www.thoughtco.com/qualitative-research-methods-3026555

Eštoková, A., Picazo, M. Á. P., Luptakova, A., & Václavík, V. (2025). Editorial: Environmental impacts of materials and their life cycle. *Frontiers in Environmental Science*, *13*, 1557206. https://doi.org/10.3389/fenvs.2025.1557206

Gamage, I., Senaratne, S., Perera, S., & Jin, X. (2024). Implementing circular economy throughout the construction project life Cycle: A review on potential practices and relationships. *Buildings*, *14*(3), 653. https://doi.org/10.3390/buildings14030653

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, *130*, 109948. https://doi.org/10.1016/j.rser.2020.109948

Jayawardhana, N., & Withanage, K. (2023). Quantity surveyor's role towards circular economic principles in the pre-contract phase of construction projects in Sri Lanka. In *S. Samarawickrama, (Ed.), FARU 2023 Conference Proceedings: 16th International Research Conference - FARU 2023* (pp. 57–66). Faculty of Architecture, University of Moratuwa. https://doi.org/10.31705/faru.2023.8

National Environmental Act, 47 (1980). https://www.cea.lk/web/images/pdf/acts/act47-80.pdf

Purchase, C. K., Zulayq, D. M. A., O'Brien, B. T., Kowalewski, M. J., Berenjian, A., Tarighaleslami, A. H., & Seifan, M. (2021). Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. *Materials*, *15*(1), 76. https://doi.org/10.3390/ma15010076

Saja, A.M.A., Teo, M., Goonetilleke, A. & Ziyath, A.M. (2021). A critical review of social resilience properties and pathways in disaster management. *International Journal of Disaster Risk Science*, *12*, 790–804. https://doi.org/10.1007/s13753-021-00378-y

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2015). *Research methods for business students* (7th ed.). Pearson Education Limited.

Sustainable Development Act, 19 (2017). https://www.srilankalaw.lk/YearWisePdf/2017/19-2017_E.pdf

Swain, S., Foote, W., Golding, F., & Krogh, C. (2025). Documentary analysis. In *Handbook of Research Methods in Social Work*, (pp. 237–248). *Edward Elgar Publishing*. https://doi.org/10.4337/9781035310173.00029

Town and Country Planning (Amendment) Act, 49 (2000). https://documents.gov.lk/view/act/2000/8/49-2000_E.pdf

Urban Development Authority Law, 41 (1978). https://www.uda.gov.lk/attachments/act/FnBTmBVbLt.pdf

Victar, H. C., & Waidyasekara, A. S. (2024). Optimising construction waste management in Sri Lanka through Circular economy strategies: A focus on construction and renovation and use and operate stages. *Engineering Construction & Architectural Management*, *32*(7), 4275–4309. https://doi.org/10.1108/ecam-06-2023-0608

Victar, H., & Waidyasekara, K. (2023). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management & Research the Journal for a Sustainable Circular Economy*, *42*(11), 953–976. https://doi.org/10.1177/0734242x231206988

Wanaguru, K., Mallawaarachchi, H., & Vijerathne, D. (2022). Circular economy (CE) based material selection: Development of a CE-based '10R' evaluation framework for building construction projects in Sri Lanka. In *Y.G. Sandanayake, S. Gunatilake, & K.A.G.S. Waidyasekara (Eds.). Proceedings of the 10th World Construction Symposium* (pp. 208–219). University of Moratuwa. https://doi.org/10.31705/wcs.2022.18

Weerakoon, T. G., Wimalasena, S., & Zvirgzdins, J. (2023). Assessment of implementation of circular economy framework in the Sri Lankan construction sector. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1), 133–152. https://doi.org/10.2478/bjreecm-2023-0009

Wijewansha, A. S., Tennakoon, G., Waidyasekara, K., & Ekanayake, B. (2021). Implementation of circular economy principles during pre-construction stage: The case of Sri Lanka. *Built Environment Project and Asset Management*, *11*(4), 750–766. https://doi.org/10.1108/bepam-04-2020-0072

Wills, W. M. (2022). Reviews and documentary research methods in a scientific article. *International Journal of Research*, *9*(9), 1-6. https://www.researchgate.net/publication/363346178_Reviews_and_Documentary_Research_Methods_in_a

Zai, F., Rohrbach, T., & Hänggli Fricker, R. (2025). Voices and media frames in the public debate on artificial intelligence: Comparing results from manual and automated content analysis. *Frontiers in Communication 10*, 1599854. doi: 10.3389/fcomm.2025.1599854

Hemantha, H.H.A.P., Uduwage, D.N.L.S., Shiwakoti, R.K. and Waidyasekara, K.A.G.S. 2026. Macroeconomic driven cement price forecasting in Sri Lanka using econometric and deep learning models. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1094-1108. DOI: https://doi.org/10.31705/WCS.2026.80. Available from: https://ciobwcs.com/papers/

# MACROECONOMIC DRIVEN CEMENT PRICE FORECASTING IN SRI LANKA USING ECONOMETRIC AND DEEP LEARNING MODELS

**H.H.A.P. Hemantha[1], D.N.L.S. Uduwage[2], Ranju Kumari Shiwakoti[3] and K.A.G.S. Waidyasekara[4]**

## *ABSTRACT*

*Cement price stability is fundamental to the performance of the construction sector, which significantly contributes to national economic development in Sri Lanka. However, recent macroeconomic instability characterized by exchange rate depreciation, inflationary pressures, and fuel price volatility has intensified cement price fluctuations, particularly during the 2022 economic crisis. Despite the growing need for reliable forecasting tools, limited research has evaluated the combined application of econometric and deep learning models for cement price prediction in highly volatile emerging economies. This study develops and compares forecasting models using a 20-year monthly macroeconomic dataset (2006 to 2025). An Autoregressive Integrated Moving Average with Exogenous Variables (ARIMAX) model was established as a linear baseline, incorporating key predictors including Inflation, Exchange Rate, Diesel Price, and Global Coal Prices identified through Pearson correlation analysis. Advanced deep learning architectures, namely Long Short-Term Memory (LSTM), Gated Recurrent Units (GRU), and Attention-based LSTM (ATT-LSTM), were implemented to capture non-linear temporal dependencies. Model performance was evaluated using Mean Absolute Percentage Error (MAPE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R-squared ($R^2$). Results indicate that while the GRU model achieved the highest accuracy under optimized sequence-length configurations, the LSTM demonstrated greater stability and robustness during crisis-period testing. Overall, deep learning architectures outperformed the ARIMAX baseline in capturing cement price volatility during the Sri Lankan economic crisis. These findings can support contractors, quantity surveyors, and policymakers in improving procurement planning and managing construction cost risks during periods of economic instability.*

***Keywords:*** *Cement; Construction Economics; Deep Learning; Macroeconomic Variables; Price Forecasting.*

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, hemanthaprasad590@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk
[3] Assistant Professor, Department of Electronics and Computer Engineering at Pulchowk Campus, Institute of Engineering (IOE), Tribhuvan University, Nepal, ranju.shiwakoti@ioe.edu.np
[4] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk

# 1. INTRODUCTION

The construction sector plays a vital role in the economic development of Sri Lanka, contributing significantly to Gross Domestic Product (GDP) and generating employment opportunities nationwide (Central Bank of Sri Lanka, 2021). Within this sector, cement serves as a foundational material that supports residential, commercial, and large-scale infrastructure projects (Petrova, 2024). Cement plays a fundamental role in construction activities, and fluctuations in cement prices directly influence investment decisions, project feasibility, and broader urban development strategies. Consequently, cement price stability is closely associated with both construction sector performance and national economic growth (Tokyo Cement Company (Lanka) PLC, 2025).

In recent years, however, Sri Lanka has experienced severe macroeconomic instability characterized by high inflation, currency depreciation, and disruptions in global supply chains (Lanka News Web, 2022). These macroeconomic shocks have intensified volatility in construction material markets, particularly affecting cement prices (Tokyo Cement Company (Lanka) PLC, 2025). Since cement production and distribution are highly sensitive to exchange rate movements, fuel prices, and global coal prices, external shocks quickly translate into domestic price fluctuations (Fortune Business Insights, 2026). As a result, contractors, project managers, and suppliers face increasing uncertainty, which often leads to budget overruns, delayed project completion, and contractual disputes (Abdelalim et al., 2024). Given these challenges, accurate forecasting of cement prices has become essential for effective procurement planning and risk mitigation within the construction industry (Ma et al., 2024).

Although forecasting techniques have evolved significantly, emerging economies such as Sri Lanka present unique modelling challenges because economic instability and crisis periods often cause sudden and unpredictable price fluctuations. Traditional econometric approaches, including regression models and statistical time-series techniques such as Autoregressive Integrated Moving Average (ARIMA), are widely used to analyse relationships between economic variables. These approaches provide interpretable relationships between macroeconomic variables and commodity prices, making them valuable tools for policy analysis (Shiha & El-adaway, 2024). However, such methods may struggle to capture complex non-linear interactions that arise during periods of extreme economic instability. In contrast, deep learning techniques are capable of modelling sequential dependencies and non-linear dynamics that conventional statistical methods may overlook (Osman & Otaibi, 2025). Therefore, integrating econometric and deep learning approaches offers a comprehensive analytical framework capable of capturing both linear macroeconomic effects and complex temporal patterns.

Despite increasing global research on construction material price forecasting, limited attention has been given to forecasting construction material prices within the Sri Lankan context. Previous forecasting studies in Sri Lanka have primarily focused on other economic sectors, including short-term electricity demand forecasting (Shiwakoti et al., 2025), tourism demand prediction (Hewapathirana, 2025), and unemployment rate modelling (Gunawardhana, 2023). These studies demonstrate that statistical and machine learning techniques have been successfully applied to economic forecasting problems in the country. However, similar analytical approaches have not been applied to modelling the price behaviour of construction materials such as cement. As a result, there remains a significant research gap in developing forecasting models for construction material prices

in Sri Lanka, particularly under conditions of prolonged macroeconomic instability and economic disruptions.

To address this research gap, this study utilizes monthly cement price data from January 2006 to December 2025, covering both stable economic periods and the economic crisis of 2022. The study develops and evaluates multiple forecasting models, including an econometric baseline model, Autoregressive Integrated Moving Average with Exogenous Variables (ARIMAX), and several deep learning architectures, namely Long Short-Term Memory (LSTM), Gated Recurrent Units (GRU), and Attention-based LSTM (ATT-LSTM). These models are trained and evaluated independently, and their forecasting performance is compared using multiple error metrics. By analysing model performance across different sequence lengths and assessing predictive robustness during periods of economic instability, the study aims to develop a forecasting framework suitable for Sri Lanka's volatile economic environment.

The objectives of this study are as follows:

1. To analyse historical cement price fluctuations in Sri Lanka (2006–2025) and assess the relationship between cement prices and selected macroeconomic variables through correlation analysis to identify significant predictive variables.
2. To compare the predictive performance of a baseline ARIMAX model against deep learning architectures (LSTM, GRU, and ATT-LSTM) in forecasting volatile cement prices.
3. To investigate the impact of varying historical sequence lengths (3 to 24 months) on deep learning accuracy to determine the optimal look-back period for time-series forecasting.
4. To evaluate model resilience and error metrics during periods of extreme market volatility and structural economic breaks.

## 2. LITERATURE REVIEW

Accurate forecasting of cement prices is critically important for the construction industry because cement represents a fundamental input in infrastructure and building projects (Petrova, 2024). Fluctuations in cement prices directly influence project cost estimation, procurement planning, and financial risk management (Ma et al., 2024). Sudden increases in material prices can lead to budget overruns, contract disputes, and project delays, particularly in economies experiencing macroeconomic instability (Abdelalim et al., 2024).

Research on construction material price forecasting has traditionally relied on statistical modelling techniques, particularly in developed economies with relatively stable markets (Xiong et al., 2025). These approaches typically utilize historical price data together with macroeconomic variables such as inflation, exchange rates, fuel costs, and interest rates (Shiha & El-adaway, 2024). Common statistical techniques include regression-based models and time-series methods such as Autoregressive Integrated Moving Average (ARIMA), Seasonal ARIMA (SARIMA), and Vector Autoregression (VAR) (Alzubi, 2023). These models perform well when market behaviour follows relatively stable linear or seasonal trends. However, their predictive accuracy often declines when markets experience abrupt economic disruptions or non-linear price volatility (Xiong et al., 2025).

To address these limitations, Artificial Intelligence (AI) techniques, particularly Machine Learning (ML) and Deep Learning (DL), have increasingly been applied to price

forecasting problems. Deep neural networks such as Feedforward Neural Networks and Multilayer Perceptrons can capture complex relationships within economic data (Zhang et al., 2022). However, these architectures do not inherently capture temporal dependencies. Recurrent Neural Networks (RNNs) address this limitation by incorporating feedback connections that allow the model to retain sequential information (Mienye et al., 2024). Advanced variants including Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRU) further improve performance by enabling models to learn long-term dependencies within time-series data and mitigate vanishing gradient problems (Mienye et al., 2024). Empirical studies indicate that LSTM-based models frequently outperform traditional neural networks when forecasting complex commodity price dynamics (Xiong et al., 2025).

Recent research has therefore explored hybrid modelling approaches that combine the interpretability of econometric models with the predictive power of deep learning techniques (Osman & Otaibi, 2025). Such approaches have shown promising results in forecasting complex commodity markets. However, limited studies have examined the application of these forecasting techniques to cement price prediction within highly volatile emerging economies such as Sri Lanka. This gap highlights the need for a comprehensive forecasting framework capable of evaluating econometric and deep learning models under conditions of significant economic instability.

## 3. RESEARCH METHODOLOGY

This section describes the macroeconomic dataset, the data pre-processing steps including feature selection via correlation analysis, the architectural details of the econometric and deep learning models, and the proposed forecasting model.

### 3.1 CEMENT PRICE AND MACROECONOMIC DATASET

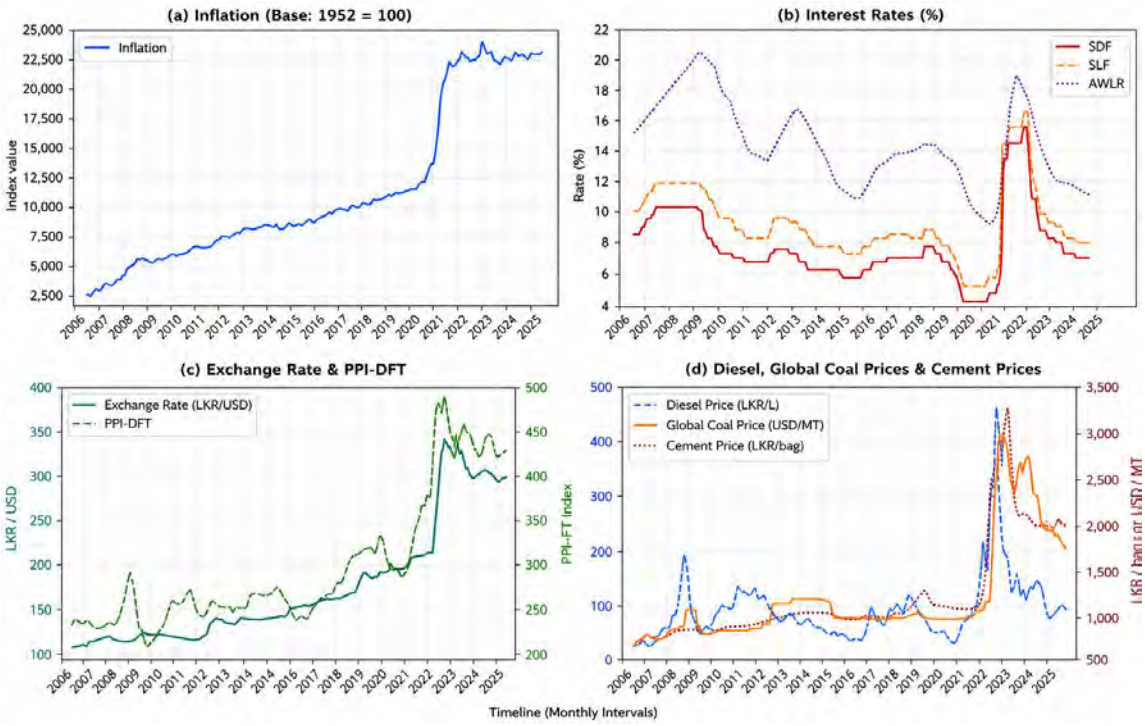



*Figure 1: Historical trajectory of cement price and macroeconomic variables and energy indices*

The dataset comprises monthly observations from January 2006 to December 2025. The dependent variable is the Monthly Cement Price Index. Exogenous macroeconomic variables were obtained from the Central Bank of Sri Lanka (CBSL), the Department of Census and Statistics, and global energy market sources. These variables include Inflation (Base 1952 = 100), Standing Deposit Facility (SDF), Standing Lending Facility (SLF), Exchange Rate (LKR/USD), Average Weighted Lending Rate (AWLR), Producer Price Index for Deep Sea Freight Transportation (PPI-DFT), Diesel Price, and Global Coal Prices (GCP).

Figure 1 illustrates the historical trajectories of cement prices and macroeconomic variables using a dual-axis format to accommodate scale differences. The dataset captures both long-term macroeconomic trends and periods of heightened volatility.

## 3.2 DATA PRE-PROCESSING AND FEATURE SELECTION

Missing values were handled using forward filling to maintain continuity in monthly observations. Due to substantial scale variation across variables, Min-Max normalization was applied to rescale all features into the range [−1, 1] as defined in Equation 1, where each feature value $x$ is rescaled linearly based on its minimum ($x_{min}$) and maximum ($x_{max}$) values to transform it into the desired range[a ,b], in this case [-1, 1] (Han et al., 2011).

$$x_{Scaled} = a + \frac{(x - x_{min})(b - a)}{x_{max} - x_{min}} \qquad (01)$$

To refine the feature set and reduce redundancy, Pearson correlation analysis was conducted as a preliminary feature-screening technique to assess linear relationships between cement prices and candidate predictors. The analysis was intended to support variable selection rather than establish causal relationships. The correlation coefficient was computed using Equation (2), where $X_i$ and $Y_i$ represent the individual data points of the two variables being compared, $\bar{X}$ and $\bar{Y}$ are their respective means (Cohen et al., 2003).

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \qquad (02)$$

Variables exhibiting weak explanatory contribution were excluded to enhance model stability.

## 3.3 MODELS

The methodological framework was selected to capture both linear macroeconomic relationships and complex non-linear price dynamics. Pearson correlation analysis was employed as an initial feature-screening technique to identify variables strongly associated with cement prices and reduce redundant inputs. Min-Max normalization was applied to ensure consistent scaling across variables and improve neural network training stability. ARIMAX was selected as an interpretable econometric benchmark capable of incorporating exogenous macroeconomic variables, while LSTM, GRU, and ATT-LSTM were adopted due to their ability to model temporal dependencies and non-linear relationships commonly observed in volatile economic time series.

### 3.3.1 Auto Regressive Integrated Moving Average with Exogenous Variables (ARIMAX)

The ARIMAX model extends ARIMA by incorporating external predictors. It captures linear relationships between historical cement prices and macroeconomic variables (Zhang et al., 2025). The general model is shown in Equation 3, where $y_t$ denote the dependent variable at time t; $\phi_i$ represent the autoregressive coefficient, $\theta_j$ denote the moving average coefficients; $y_{k,t}$ represents the $k^{th}$ exogenous variable at time t; $\beta_k$ are corresponding coefficients of the exogenous variables, and $\epsilon_t$ is the error term at time t (Hyndman & Athanasopoulos, 2021).

$$y_t = \mu + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{j=1}^{q} \theta_j \epsilon_{t-j} + \sum_{k=1}^{r} \beta_k y_{k,t} + \epsilon_t \qquad (03)$$

### 3.3.2 Gated Recurrent Unit (GRU)

The Gated Recurrent Unit is a variation of recurrent neural networks designed to utilize reset and update gates to regulate information flow with a simplified structure (Mienye et al., 2024). The update gate determines how much of the previous information needs to be passed along to the future, while the reset gate decides how much of the past information to forget.

### 3.3.3 Long Short-Term Memory (LSTM)

The LSTM network, which employs input, forget, and output gates to capture long-term temporal dependencies (Osman & Otaibi, 2025). This architecture allows LSTM networks to map complex input sequences of macroeconomic variables $(x_1, x_2, \ldots, x_n)$ an output sequence of predicted cement prices $(y_1, y_2, \ldots, y_n)$ without losing information from early time steps.

### 3.3.4 Attention-based LSTM(ATT-LSTM)

The ATT-LSTM, which integrates an attention mechanism to weight influential time steps in the input sequence (Liao et al., 2023). The architecture of the ATT-LSTM follows a systematic five-stage experimental process, encompassing data acquisition, comprehensive pre-processing and feature selection, attentional weighting of temporal sequences, LSTM-based predictive modeling, and the final evaluation of denormalized results as illustrated in Figure 2.

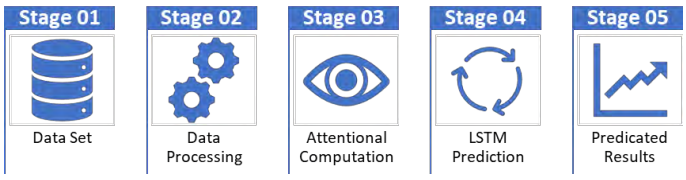



*Figure 2: Five-stage experimental process for the ATT-LSTM architecture*

### 3.3.5 Hyperparameters

This study focuses on selecting the optimal model architecture and corresponding hyperparameters for predicting monthly cement prices in Sri Lanka. A suitable model is one that accurately captures complex macroeconomic data patterns, avoids both overfitting and underfitting, and maintains a structure that is both computationally efficient and industrially applicable. The deep learning models were trained using the Adam optimizer with Mean Squared Error (MSE) as the loss function. All architectures

were trained for 200 epochs with a batch size of 16, and a validation split of 10% was used during training. To reduce overfitting, a dropout rate of 0.2 was applied after each recurrent layer. The input sequence length representing the historical look-back period was varied between 3 and 24 months, while other hyperparameters remained constant across experiments to ensure fair model comparison.

## 3.4 PROPOSED MODEL

The proposed workflow for cement price forecasting includes five key stages: (1) data preprocessing, which encompasses handling missing values, Pearson correlation-based feature selection, and Min-Max normalization; (2) preparation of input sequences using a sliding window approach; (3) model training across econometric and deep learning architectures; (4) denormalization of the predicted price indices; and (5) performance evaluation.

The dataset was divided into a training period (January 2006 to December 2021) and a testing period (January 2022 to December 2025), corresponding to approximately an 80%–20% chronological split. Input sequences were generated using a sliding-window approach, where the preceding 3 to 24 months of observations were used to predict the subsequent month's cement price. The training dataset represents relatively stable economic conditions, whereas the testing dataset includes the 2022 economic crisis and the subsequent market adjustment period. This design enables an out-of-sample crisis evaluation in which the models are trained only on pre-crisis data and tested on their ability to forecast cement price dynamics during and after a major economic disruption. A rolling window approach was intentionally avoided to prevent information from the crisis period entering the training phase. This ensures that the forecasting models are evaluated under realistic conditions where future economic shocks are not observed during model training. The forecasting experiments include an econometric baseline (ARIMAX) and deep learning models (LSTM, GRU, and ATT-LSTM). The ARIMAX model incorporates the filtered exogenous variables (Diesel Price, GCP, Exchange Rate, PPI-DFT, and Inflation) alongside the historical price lag and seasonal orders. The deep learning models utilize specialized architectures to capture non-linear dependencies.

All deep learning models employed two recurrent layers (100 and 50 units), followed by dropout (0.2) and dense output layers. The models were trained using the Adam optimizer with Mean Squared Error (MSE) as the loss function as shown in Equation 4 (Chai & Draxler, 2014). To evaluate the accuracy and reliability of the forecasting models, four statistical metrics were utilized. These metrics compare the actual cement price ($y_i$) against the predicted value ($\hat{y}_i$) over n total observations. Mean Absolute Percentage Error (MAPE), defined in Equation (5), expresses accuracy as a percentage, allowing easier comparison across different datasets and timeframes (Kim & Kim, 2016). Mean Absolute Error (MAE), presented in Equation (6), provides a linear score where all individual differences are weighted equally (Willmott & Matsuura, 2005). Root Mean Square Error (RMSE), calculated using Equation (7), penalizes larger errors more heavily, highlighting significant deviations during price spikes (Chai & Draxler, 2014). Finally, the coefficient of determination ($R^2$) shown in Equation (8), evaluates the model's ability to explain variance in cement price fluctuations (Chicco et al., 2021).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \qquad (04)$$

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\left|\frac{y_i-\hat{y}_i}{y_i}\right| \quad (05)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i-\hat{y}_i| \quad (06)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2} \quad (07)$$

$$R^2 = 1-\frac{\sum(y_i-\hat{y}_i)^2}{\sum(y_i-\bar{y})^2} \quad (08)$$

# 4. RESULTS AND DISCUSSIONS

This section presents and critically analyses the forecasting performance of the econometric baseline and Deep Learning architectures during the high-volatility period of the Sri Lankan economic crisis. The evaluation proceeds in four stages: feature refinement, sequence length sensitivity, structural break behaviour, and final out-of-sample testing performance.

## 4.1 FEATURE SELECTION AND CORRELATION ANALYSIS

A Pearson correlation analysis was conducted to examine the relationship between cement prices and selected macroeconomic variables. The initial set of variables was identified based on industry evidence reported in the Tokyo Cement Company (Lanka) PLC Annual Report 2024/25, which indicates that cement prices are influenced by factors such as inflation, policy interest rates, exchange rate movements, global freight costs, and energy prices. These variables affect cement production, import, transportation, and distribution costs, making them potential drivers of cement price fluctuations. Based on these industry insights and data availability, the study selected Inflation, Standing Deposit Facility (SDF), Standing Lending Facility (SLF), Exchange Rate (LKR/USD), Average Weighted Lending Rate (AWLR), Producer Price Index for Deep Sea Freight Transportation (PPI-DFT), Diesel Price, and Global Coal Prices (GCP) as candidate explanatory variables.

Pearson correlation analysis was then performed to quantify the strength of the linear relationships between these macroeconomic indicators and cement prices. In this study, correlation coefficients above 0.70 were interpreted as strong positive relationships, values between 0.30 and 0.70 as moderate relationships, and values below 0.30 as weak relationships. As illustrated in Figure 3, strong positive correlations were observed between cement prices and key cost-related variables, particularly the Exchange Rate (0.97) and Diesel Price (0.98), confirming the import-dependent and energy-intensive structure of Sri Lanka's cement supply chain.

The correlation heatmap further indicates that freight-related and fuel-linked variables exhibit relatively high associations with cement prices, whereas the Average Weighted Lending Rate (AWLR) shows a weak and slightly negative correlation (−0.10). Given its minimal explanatory contribution and potential to introduce noise into the forecasting models, AWLR was excluded from the final feature set. Consequently, the refined input variables used for model development included Inflation, SDF, SLF, Exchange Rate (LKR/USD), PPI-DFT, Diesel Price, and GCP. Furthermore, the selected variables were supported by prior construction economics literature and industry evidence regarding cement price formation. This feature selection process improves model parsimony while

retaining the macroeconomic factors most strongly associated with cement price dynamics.

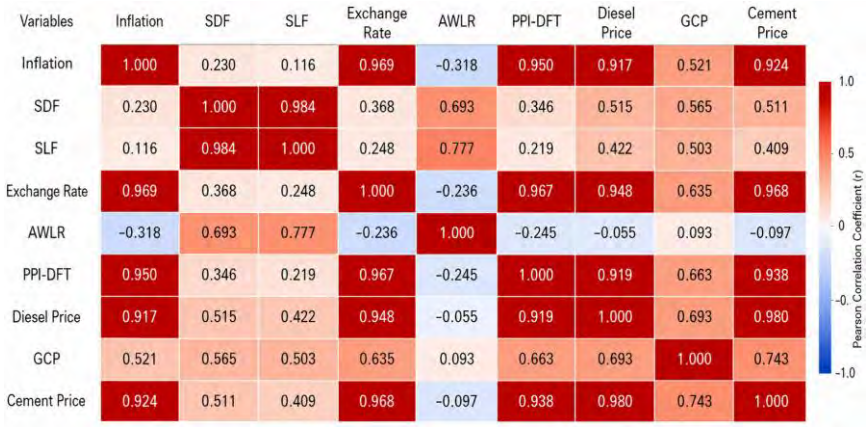



*Figure 3: Feature correlation heatmap*

## 4.2 PERFORMANCE ANALYSIS ACROSS SEQUENCE LENGTHS

To determine the optimal historical context for forecasting cement prices under volatile market conditions, forecasting experiments were conducted using multiple sequence lengths (look-back windows) ranging from 3 to 24 months, where sequence length represents the number of previous monthly observations used as model inputs. For each sequence configuration, the models were trained and used to generate out-of-sample forecasts for the testing period (2022–2025). The resulting predictions were then compared with the actual observed cement prices, and the forecasting errors were calculated. The detailed performance results for each sequence length are presented in Tables 1 to 4. Dark yellow shading indicates the best-performing result, while light yellow shading indicates the second-best result.

Four evaluation metrics were used to assess model performance: MAPE, MAE, RMSE, and $R^2$. Among these metrics, MAPE is emphasized in the analysis because it expresses forecasting error as a percentage, allowing easier comparison across different models and sequence configurations. While MAE and RMSE provide absolute error magnitudes and $R^2$ measures explanatory power, MAPE offers a more interpretable indicator of relative prediction accuracy in time-series forecasting studies.

*Table 1: Mean Absolute Percentage Error (MAPE) analysis across sequence lengths (3 to 24 months)*

| Months / Model | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
|---|---|---|---|---|---|---|---|---|
| **ARIMAX** | 40.52 | 40.52 | 40.52 | 40.52 | 40.52 | 40.52 | 40.52 | 40.52 |
| **LSTM** | 12.89 | 15.52 | 20.49 | 22.97 | 24.18 | 32.41 | 32.39 | 22.91 |
| **GRU** | 13.97 | 13.84 | 10.71 | 11.06 | 13.34 | 15.00 | 7.39 | 15.03 |
| **ATT-LSTM** | 28.46 | 44.11 | 44.85 | 10.22 | 11.7 | 25.23 | 39.07 | 37.41 |

*Table 2: Mean Absolute Error (MAE) analysis across sequence lengths (3 to 24 months)*

| Months / Model | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
|---|---|---|---|---|---|---|---|---|
| **ARIMAX** | 965.3 | 965.3 | 965.3 | 965.3 | 965.3 | 965.3 | 965.3 | 965.3 |
| **LSTM** | 296.73 | 470.54 | 674.63 | 765.91 | 552.92 | 498.39 | 695.81 | 642.4 |
| **GRU** | 330.92 | 373.05 | 317.61 | 296.46 | 232.26 | 487.39 | 212.51 | 361.01 |
| **ATT-LSTM** | 794.37 | 900.59 | 958.72 | 833.23 | 354.27 | 310.94 | 639.76 | 1020.94 |

*Table 3: Root Mean Square Error (RMSE) analysis across sequence lengths (3 to 24 months).*

| Months / Model | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
|---|---|---|---|---|---|---|---|---|
| **ARIMAX** | 1038.22 | 1038.22 | 1038.22 | 1038.22 | 1038.22 | 1038.22 | 1038.22 | 1038.22 |
| **LSTM** | 535.33 | 698.32 | 714.5 | 495.49 | 348.51 | 663.45 | 638.06 | 817.76 |
| **GRU** | 502.15 | 486.59 | 552.01 | 431.84 | 321.49 | 138.78 | 272.57 | 279.78 |
| **ATT-LSTM** | 1145.07 | 1171.48 | 1160.47 | 588.17 | 341.87 | 584.97 | 791.95 | 838.09 |

*Table 4: R-squared ($R^2$) analysis across sequence lengths (3 to 24 months).*

| Months / Model | 3 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
|---|---|---|---|---|---|---|---|---|
| **ARIMAX** | -5.55 | -5.55 | -5.55 | -5.55 | -5.55 | -5.55 | -5.55 | -5.55 |
| **LSTM** | -0.92 | -3.33 | -2.01 | -2.12 | -0.98 | -0.80 | -1.51 | -4.75 |
| **GRU** | -0.30 | -1.17 | -1.32 | -0.02 | -2.38 | 0.55 | 0.19 | 0.54 |
| **ATT-LSTM** | -8.56 | -10.92 | -6.59 | -0.35 | 0.22 | -0.05 | -3.44 | -5.87 |

As shown in Table 1, the ARIMAX model records a constant MAPE value of 40.52% across the experiment. Table 3 further reports an RMSE of 1038.22 LKR, while Table 4 indicates an $R^2$ value of −5.55. Unlike the deep learning models, the ARIMAX model does not rely on sliding-window input sequences; instead, it operates using predefined autoregressive and moving average lag structures. Consequently, its performance remains unchanged across the sequence-length experiments, which were specifically designed for the deep learning architectures. The negative $R^2$ values indicate that ARIMAX struggled to capture the sudden and severe price fluctuations experienced during the economic crisis.

The standard LSTM achieved its optimal performance at a 3-month sequence length, producing a MAPE of 12.89%, MAE of 296.73 LKR, and RMSE of 535.33 LKR, as shown in Tables 1 to 3. However, the $R^2$ remained negative −0.92, indicating limited variance explanation despite reduced magnitude error. As sequence length increased, performance deteriorated, with MAPE rising to 32.41% at 18 months. This suggests that LSTM benefits from short-term dependency structures rather than extended historical memory in volatile environments.

The GRU architecture demonstrated superior stability at longer windows. While initial performance at 3 months produced a MAPE of 13.97%, accuracy improved significantly as the window extended. At 21 months, GRU achieved its optimal results, with MAPE 7.39%, MAE 212.51 LKR, RMSE 272.57 LKR, and a positive $R^2$ of 0.19, as shown in Tables 1 to 4. Additionally, GRU achieved higher $R^2$ values at 18 months 0.55 and 24 months 0.54, indicating improved variance explanation when longer temporal contexts were incorporated. These findings suggest that changes in macroeconomic conditions influence cement prices over several months, and the GRU model was better able to capture these delayed effects.

The ATT- LSTM achieved its best configuration at 12 months, with a MAPE of 10.22%, MAE of 833.23 LKR, RMSE of 588.17 LKR, and $R^2$ of −0.35. Although attention mechanisms theoretically enhance temporal weighting, the model exhibited instability across windows, with MAPE fluctuating from 28.46% at 3 months to 44.85% at 9 months and increasing again to 39.07% at 21 months. This indicates that the ATT-LSTM model was highly sensitive to prolonged economic shocks, leading to less stable forecasts.

## 4.3 STRUCTURAL BREAK BEHAVIOUR DURING THE 2022 CRISIS

A critical observation from Table 4 is that several configurations yielded negative $R^2$ values, particularly for ARIMAX (−5.55) and LSTM (−0.92 at optimal window). These results reflect the unprecedented magnitude of the 2022 hyper-inflationary surge, during which cement prices increased by nearly 3,000 LKR within a short time frame. RMSE values consistently exceed MAE values across all models, confirming that large-magnitude peak errors disproportionately influenced evaluation metrics due to the squared error penalty.

The temporal prediction shift is further illustrated in Figure 4, where model-predicted peaks occur later than the actual mid-2022 market peak. This lag arises because macroeconomic variables such as the Exchange Rate and Diesel Price remained elevated into late 2022. Given the sliding window structure, cumulative macroeconomic shocks continued influencing model outputs into early 2023.

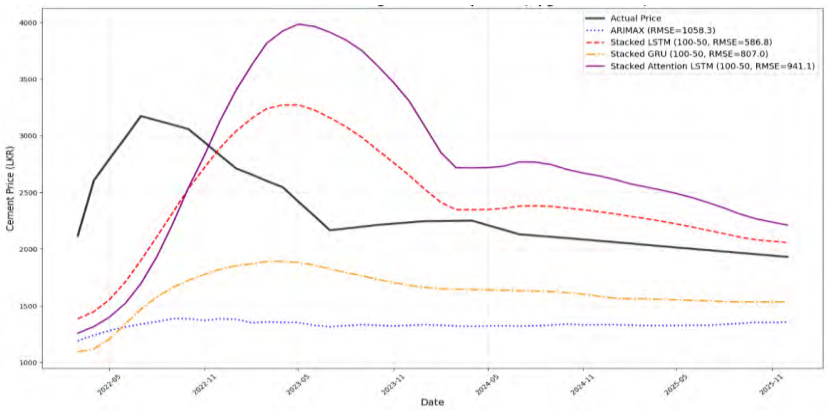



*Figure 4 :Visualization of market reality vs. computational forecasting*

The ATT-LSTM exhibited pronounced overshooting behaviour, reaching nearly 4,000 LKR, reflecting over-sensitivity to prolonged currency depreciation. In contrast, GRU demonstrated smoother adjustment dynamics, while LSTM provided a more moderated trajectory.

### 4.4 OUT-OF-SAMPLE TESTING PERFORMANCE (2022–2025)

The forecasting performance during the 2022–2025 testing window was evaluated by comparing the predicted cement prices with the actual observed values. The resulting error metrics are summarized in Table 5. Yellow shading indicates the best-performing result.

*Table 5: Summary of final performance metrics for ARIMAX, LSTM, GRU, and ATT-LSTM (2022–2025 Testing Period).*

| Model | MAE (LKR) | MAPE (%) | RMSE (LKR) | R2 |
|---|---|---|---|---|
| **ARIMAX** | 1005.05 | 41.93 | 1070.81 | -7.6752 |
| **LSTM** | 462.51 | 18.99 | 586.82 | -1.6053 |
| **GRU** | 705.72 | 28.94 | 806.96 | -3.9266 |
| **ATT-LSTM** | 822.56 | 35.03 | 941.1 | -5.7008 |

ARIMAX recorded a MAPE of 41.93%, MAE of 1005.05 LKR, RMSE of 1070.81 LKR, and $R^2$ of −7.6752, confirming limited predictive capability under structural instability. Among deep learning models, LSTM achieved the lowest testing MAPE of 18.99% and RMSE of 586.82 LKR, outperforming GRU, MAPE 28.94%, RMSE 806.96 LKR and ATT-LSTM, MAPE 35.03%, RMSE 941.10 LKR. Although GRU exhibited superior performance under optimal window experimentation, LSTM demonstrated comparatively greater stability during the extended crisis testing period. This distinction indicates that optimal experimental accuracy does not necessarily translate into long-horizon crisis robustness.

### 4.5 OVERALL MODEL ASSESSMENT

The results reveal two key insights:

- GRU provides the best performance under optimized sequence-length configuration, achieving the lowest overall MAPE 7.39% and positive $R^2$ 0.19.
- LSTM demonstrates more balanced and stable behaviour during prolonged crisis testing, achieving the lowest out-of-sample MAPE 18.99%.

Therefore, model suitability depends on forecasting objective. For optimized short-to-medium term forecasting under controlled conditions, GRU is preferable. For extended crisis-period robustness, LSTM exhibits greater stability. Overall, the findings show that deep learning models can provide more reliable cement price forecasts than traditional econometric methods during periods of economic instability. From a practical perspective, improved forecasting accuracy can support contractors, suppliers, and quantity surveyors in procurement planning, budgeting, and cost-risk management. From a policy perspective, the identified influence of exchange rate and energy-related variables highlights the importance of macroeconomic stability for construction material price management.

## 5. CONCLUSIONS

This study developed and evaluated a macroeconomically driven forecasting framework for cement prices in Sri Lanka by integrating selected macroeconomic variables with advanced deep learning architectures. Pearson correlation analysis confirmed that cement

price movements are strongly associated with cost-driven variables, particularly the Exchange Rate and Diesel Price, while the Average Weighted Lending Rate exhibited weak explanatory power and was therefore excluded from the final feature set. The refined dataset ensured that the forecasting models concentrated on economically meaningful external shocks linked to import dependency, energy intensity, and distribution costs within the construction sector. Comparative analysis between the econometric baseline and deep learning models revealed substantial differences in their ability to handle extreme market volatility. The ARIMAX model produced a MAPE of 41.93%, during the 2022–2025 testing period, indicating limited capacity to capture non-linear price surges associated with the economic crisis. In contrast, deep learning architectures demonstrated superior adaptability. Under optimized sequence-length experimentation, the GRU model achieved the best overall performance, recording a minimum MAPE of 7.39% and a positive $R^2$ of 0.19 at a 21-month window. However, during extended out-of-sample crisis testing, the standard LSTM exhibited greater stability, achieving the lowest testing MAPE of 18.99%. The ATT-LSTM showed sensitivity to prolonged macroeconomic shocks and occasional overshooting of peak values.

A temporal prediction lag was observed during the 2022 economic crisis, as prolonged increases in macroeconomic variables such as the Exchange Rate and Diesel Price caused forecasted cement price peaks to extend into early 2023. Several model configurations produced negative $R^2$ values, highlighting the difficulty of predicting unprecedented market disruptions using models trained primarily on stable pre-crisis data. Overall, deep learning models outperformed the ARIMAX baseline, with GRU achieving the highest forecasting accuracy and LSTM demonstrating greater stability during prolonged economic volatility. These findings suggest the potential value of adaptive or hybrid forecasting approaches for improving performance under extreme economic shocks.

## 6. ACKNOWLEDGEMENT

This research was supported by the Senate Research Committee, University of Moratuwa under Grant No. SRC/LT/2025/23. The authors gratefully acknowledge this financial support.

## 7. REFERENCES

Abdelalim, A. M., Salem, M., Salem, M., Al-Adwani, M., & Tantawy, M. (2024). An analysis of factors contributing to cost overruns in the global construction industry. *Buildings, 15*(1), 18. https://doi.org/10.3390/buildings15010018

Alzubi, Y. (2023). Comparison of various machine learning models for estimating construction projects sales valuation using economic variables and indices. *Journal of Soft Computing in Civil Engineering, 8*(1), .1-32. https://doi.org/10.22115/scce.2023.364221.1536

Box, G. E. P., Jenkins, G. M., & Reinsel, G. C. (2008). *Time Series analysis. In Wiley series in probability and statistics*. John Wiley & Sons, Inc. https://doi.org/10.1002/9781118619193

Central Bank of Sri Lanka. (2021). *Annual report 2021*. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-reports/annual-report-%202021%20

Chai, T., & Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development*, 7(3), 1247–1250. https://doi.org/10.5194/gmd-7-1247-2014

Chicco, D., Warrens, M. J., & Jurman, G. (2021). The coefficient of determination R-squared is more informative than SMAPE, MAE, MAPE, MSE and RMSE in regression analysis evaluation. *PeerJ Computer Science*, *7*, e623. https://doi.org/10.7717/peerj-cs.623

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). *Applied multiple regression/correlation analysis for the behavioral sciences* (3rd ed.). Lawrence Erlbaum Associates. https://doi.org/10.4324/9780203774441

Fortune Business Insights [FBI]. (2026). *Cement market size, share & industry analysis by type (Portland, blended, and others), by application (residential and non-residential), and regional forecast, 2026-2034*. https://www.fortunebusinessinsights.com/industry-reports/cement-market-101825

Gunawardhana, S. R. C. L. (2023). Forecasting the unemployment rate in Sri Lanka using selected macroeconomic variables: A comparative study of machine learning/deep learning and econometric models. *Staff Studies*, *53*, 52–77. https://doi.org/10.4038/ss.v53i1.4735

Han, J., Kamber, M., & Pei, J. (2011). *Data mining: Concepts and techniques* (3rd ed.). Morgan Kaufmann. https://doi.org/10.1016/C2009-0-61819-5

Hewapathirana, I. U. (2025). Advancing tourism demand forecasting in Sri Lanka: Evaluating the performance of machine learning models and the impact of social media data integration. *Journal of Tourism Futures*, *11*(2), 261–285. https://doi.org/10.1108/JTF-06-2023-0149

Hyndman, R. J., & Athanasopoulos, G. (2021). *Forecasting: Principles and practice* (3rd ed.). OTexts. https://otexts.com/fpp3/

Kim, S., & Kim, H. (2016). A new metric of absolute percentage error for intermittent demand forecasts. *International Journal of Forecasting*, *32*(3), 669–679. https://doi.org/10.1016/j.ijforecast.2015.12.003

Lanka News Web. (2022, April 24). *Sri Lanka's construction industry faces a threat of collapse*. Lanka News Web. https://lankanewsweb.net/archives/9610/sri-lankas-construction-industry-faces-a-threat-of-collapse/

Liao, Y., Lin, R., Zhang, R., & Wu, G. (2023). Attention-based LSTM (AttLSTM) neural network for seismic response modeling of bridges. *Computers & Structures*, *275*, 106915. https://doi.org/10.1016/j.compstruc.2022.106915

Ma, M., Tam, V. W. Y., Le, K. N., & Osei-Kyei, R. (2024). A systematic literature review on price forecasting models in construction industry. *International Journal of Construction Management*, *24*(11), 1191–1200. https://doi.org/10.1080/15623599.2023.2241761

Mienye, I. D., Swart, T. G., & Obaido, G. (2024). Recurrent neural networks: A comprehensive review of architectures, variants, and applications. *Information*, *15*(9), 517. https://doi.org/10.3390/info15090517

Osman, E. G. A., & Otaibi, F. A. (2025). Integrating deep learning and econometrics for stock price prediction: A comprehensive comparison of LSTM, transformers, and traditional time series models. *Machine Learning with Applications*, *22*, 100730. https://doi.org/10.1016/j.mlwa.2025.100730

Petrova, V. (2024). Innovations in cement production: the road to sustainability and a circular economy. *The Eurasia Proceedings of Science Technology Engineering and Mathematics*, *29*, 295–303. https://doi.org/10.55549/epstem.1573538

Shiha, A., & El-adaway, I. H. (2024). Forecasting construction material prices using macroeconomic indicators of trading partners. *Journal of Management in Engineering*, *40*(5), 04024036. https://doi.org/10.1061/JMENEA.MEENG-6106

Shiwakoti, R. K., Limcharoen, P., & Uduwage, D. N. L. S. (2025). Short-term electricity demand forecasting in Sri Lanka using statistical and deep learning models. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *13th World Construction Symposium*—2025 (pp. 1260–1272). Department of Building Economics & CIOB.

Tokyo Cement Company (Lanka) PLC. (2025). *Annual report 2024/25*. https://tokyocement.com/financial-reports/

Willmott, C. J., & Matsuura, K. (2005). Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate Research*, *30*(1), 79–82. https://doi.org/10.3354/cr030079

Xiong, S., Nie, C., Lu, Y., & Zheng, J. (2025). Research on price prediction of construction materials based on VMD-SSA-LSTM. *Applied Sciences*, *15*(4), 2005. https://doi.org/10.3390/app15042005

Zhang, H., Liu, X., Gao, X., & Liu, Z. (2025). Hybrid ARIMAX model integrating optimal time-lag selection and markov chain error correction for residential heating load forecasting. *Energy Reports, 14*, 5259–5273. https://doi.org/10.1016/j.egyr.2025.11.082

Zhang, Z., Feng, F., & Huang, T. (2022). FNNS: An effective feedforward neural network scheme with random weights for processing large-scale datasets. *Applied Sciences, 12*(23), 12478. https://doi.org/10.3390/app122312478

Jayanandana, U., Tennakoon, G.A., Kodituwakku, D. and Chan, M 2026. Managing end-of-life impacts of solar photovoltaic systems: A Sri Lankan perspective. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1109-1122. DOI: https://doi.org/10.31705/WCS.2026.81. Available from: https://ciobwcs.com/papers/

# MANAGING END-OF-LIFE IMPACTS OF SOLAR PHOTOVOLTAIC SYSTEMS: A SRI LANKAN PERSPECTIVE

**Ushara Jayanandana[1], G.A. Tennakoon[2], Dasuni Kodituwakku[3] and Melissa Chan[4]**

## *ABSTRACT*

*The rapid expansion of Solar Photovoltaic (PV) systems as part of the global transition toward renewable energy has raised increasing concerns regarding the environmental impact of their End-Of-Life (EOL). Although solar PV technology contributes significantly to renewable electricity generation and has been widely adopted in Sri Lanka, the management of PV systems that have reached their EOL remains insufficiently explored in the local context. With projections indicating that global PV panel waste could reach approximately 78 million tonnes by 2050, effective EOL management strategies have become increasingly important. This study investigates how the EOL management of solar PV systems can be improved to minimise their environmental impact. A qualitative research approach was adopted, using semi-structured interviews, with participants selected through purposive sampling based on their professional experience in the local solar PV sector and their knowledge of EOL practices. The collected data were analysed using thematic analysis. The findings revealed ten strategies for improving EOL management, grouped into five key categories: government leadership, recycling infrastructure, circularity in design, extended producer responsibility, and awareness building. Government leadership emerged as a significant contributor, highlighting the need for supportive regulations, incentives for recycling, and the establishment of collection schemes for EOL solar PV systems. Moreover, the study emphasised integrating circularity principles into solar PV system design, including the use of recyclable and sustainable materials, modular components, and less material-intensive components. The findings provide practical insights for strengthening EOL management and supporting the sustainable expansion of solar PV systems in Sri Lanka.*

***Keywords:*** *End-of-life (EOL); Environmental Sustainability; Renewable Energy; Solar Photovoltaic (PV); Sri Lanka.*

[1] Junior Quantity Surveyor, Commercial Department, ALEC Engineering and Contracting LLC, Abu Dhabi, United Arab Emirates, ushara.jayanandana99@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradhat@uom.lk
[3] Quantity Surveyor, AtkinsRéalis Pps Limited, Dubai, United Arab Emirates, dasuni.kodituwakku@atkinsrealis.com
[4] Senior Lecturer, Institute for Sustainable Industries & Liveable Cities (ISILC); and College of Sport, Health and Engineering, Victoria University, Melbourne, Australia, melissa.chan@vu.edu.au

# 1. INTRODUCTION

With the evolving discussions around environmental sustainability, the use of renewable energy sources has grown significantly in recent years. This is evident through the increase in the share of renewable energy in the global energy mix from 7.4% in 2016 to 12.8% in 2021 (Yolcan, 2023). Among the different sources of renewable energy, solar PV systems occupy a prominent place. As of 2022, solar PV systems accounted for 3.6% of global electricity generation and 31% of renewable energy capacity (Pourasl et al., 2023). The use of solar power as a renewable energy source began in the 19$^{th}$ century, with the first demonstration of the conversion of solar energy to electricity by French Physicist Alexandre Edmond Becquerel with his invention of solar PV cells in 1839 (Lameirinhas et al., 2022). Moving forward, in 1940s and early 1950s, the development of silicon based solar cells was a significant milestone which increased efficiency and commercial viability of solar power usage (Jones & Bouamane, 2012). Currently, silicon based solar cells are the dominant technology in the solar PV market, accounting for approximately 95% of global solar cell production (Zhu et al., 2022). With the increasing concerns regarding environmental degradation and climate change impacts associated with the usage of fossil fuels, renewable energy sources, more specifically solar energy, has gained widespread attention, both globally and in Sri Lanka, and the demand for solar PV systems is expected to grow into the future (Yolcan, 2023; Thennakoon et al., 2023).

From a local perspective, Sri Lanka has embraced the adoption of solar PV technology as part of its renewable energy strategy. The country's solar PV sector is managed under the "Soorya Bala Sangramaya" (Battle for Solar Energy) programme launched in 2016 by the Sri Lankan Government (Thennakoon et al., 2023). Following the initiation of this programme, the solar PV sector in the country has grown significantly and it is expected that the sector will contribute 1.5 GWs of electricity to the national grid by 2030 (Sri Lanka Sustainable Energy Authority, n.d.). Further, the country's tropical climate with higher solar irradiation levels have provided a favourable environment for electricity generation through solar PV systems (Mendis et al., 2019). Although solar PV systems make a substantial contribution to both global and local renewable energy transitions, the potential environmental impacts associated with their life cycle, from manufacturing to EOL disposal, require careful consideration. Previous studies have identified several negative environmental impacts linked to solar PV systems, including the release of hazardous substances such as heavy metals, high water consumption and contamination of water resources, GreenHouse Gas (GHG) emissions, and degradation of ecosystems leading to habitat loss and decline in biodiversity (Bošnjaković et al., 2023). Given these environmental challenges alongside the critical role of solar PV in achieving renewable energy targets, increasing attention has been given towards mitigating such impacts while sustaining the use of solar PV technologies.

Within this background, EOL management of solar PV systems has emerged as a pressing concern. Projections indicate that global PV panel waste, which is primarily composed of glass, could reach approximately 78 million tonnes by 2050, while the recoverable materials from EOL PV panels could be valued at over USD 15 billion (International Energy Agency (IEA), n.d.). As the adoption of solar PV systems continues to grow, the volume of associated waste streams is expected to increase correspondingly, thereby intensifying the need for effective and sustainable EOL management strategies. Recognising both the environmental risks and the economic opportunities associated with EOL solar PV systems, several countries have introduced regulatory and technological

measures to improve EOL management of such systems. For instance, the United Kingdom has implemented the Waste Electrical and Electronic Equipment (WEEE) Directive, which places responsibility on manufacturers and suppliers for the collection, recycling, and disposal of PV panels (Umar et al., 2025). According to the authors, Japan has advanced chemical recycling techniques to recover silicon, a key component of solar cells. Similarly, Germany has integrated PV waste into its electronic waste management framework, while states such as California in the USA have undertaken initiatives to regulate PV disposal and improve recycling efficiency (Umar et al., 2025). Despite growing global interest in the EOL management of solar PV systems, this issue remains underexplored in the Sri Lankan context, particularly from a research standpoint. Existing studies in Sri Lanka have predominantly focused on PV adoption, policy mechanisms, and general environmental benefits, with limited attention given to EOL management considerations (Danthurebandara & Rajapaksha, 2019; Thushara et al., 2019). While the use of solar PV systems has been actively encouraged through government policy interventions, comparatively little emphasis has been placed on addressing the environmental impacts associated with their EOL phase. This gap is particularly significant given that many PV systems installed following the introduction of net metering in Sri Lanka in 2010 are expected to reach their EOL within the next decade (Thennakoon et al., 2023).

Against this backdrop, the present study looks at answering the question "*How can the end-of-life management of solar photovoltaic systems be improved to minimise their environmental impact.*" The study aimed to investigate strategies for improving the EOL management of solar PV systems to minimise their environmental impacts in the Sri Lankan context. The findings of this study are expected to support the environmentally sustainable and economically viable renewable energy transition efforts in the country.

Solar PV systems can be broadly categorised into different installation types, including rooftop systems, Building-Integrated PhotoVoltaics (BIPV), and utility-scale solar farms. These categories differ significantly in terms of system scale, design integration, material composition, and operational context, which in turn influence their environmental impacts and End-Of-Life (EOL) management requirements. For instance, rooftop systems are decentralised and typically involve lower material use and reduced environmental burdens per unit capacity compared to ground-mounted utility-scale systems, which require extensive supporting infrastructure and land use (Roy & Pearce, 2023). In contrast, BIPV systems are integrated directly into building components, which can complicate dismantling processes and create additional challenges for material recovery due to their structural coupling with buildings (Zhou & Li, 2025). Furthermore, previous research indicates that EOL management processes including collection, transportation, recycling, and disposal vary depending on installation type and scale, highlighting the need for tailored approaches across the PV value chain (Biyouki et al., 2024). Despite these variations, the solar PV sector in Sri Lanka remains at a relatively early stage of development in terms of EOL management practices, with limited regulatory differentiation across PV system types. As a result, this study adopts a generalised perspective on EOL management, focusing on identifying common strategies applicable across different PV installation categories. Section 2 provide a brief literature review on the use of solar PV systems in Sri Lanka. Section 3 provides an explanation regarding the study methodology, followed by Section 4 outlining the study findings. Finally, Section 5 presents the conclusions and recommendation of the study.

# 2. LITERATURE REVIEW

## 2.1 SOLAR PV SYSTEMS IN SRI LANKA

Solar PV systems have attracted significant interest in Sri Lanka as a response to the country's increasing energy demand. Owing to its tropical climate, Sri Lanka benefits from consistently high levels of solar irradiation, making solar energy a technically suitable and environmentally sustainable alternative for electricity generation and for reducing reliance on fossil fuels (Mittal, 2023). Recognising this potential, the Sri Lankan government has prioritised the adoption of solar PV systems within its national energy strategy and introduced a range of incentives aimed at lowering fossil fuel dependency while harnessing renewable energy sources such as solar (Koswatte et al., 2024). Among the key initiatives supporting this transition is the net metering scheme introduced in 2010, which enables households and organisations to export surplus electricity generated from solar PV systems to the national grid (Thennakoon et al., 2023). Beyond providing direct financial benefits to system owners, this mechanism has also played an important role in encouraging wider adoption of solar PV technologies. In addition, fiscal measures such as tax exemptions and grant schemes for solar equipment have reduced upfront investment costs, thereby improving affordability for both residential and commercial users (Kannan & Asharp, 2023).

The regulatory environment has also evolved to facilitate the uptake of solar PV systems, notably through policy instruments such as the National Policy for Renewable Energy (NPRE) introduced in 2010. Initiatives, including the "Soorya Bala Sangramaya" (Battle for Solar Energy) programme implemented by the Sustainable Energy Authority of Sri Lanka, have further reinforced national efforts to accelerate the transition towards solar-based electricity generation (Thennakoon et al., 2023).

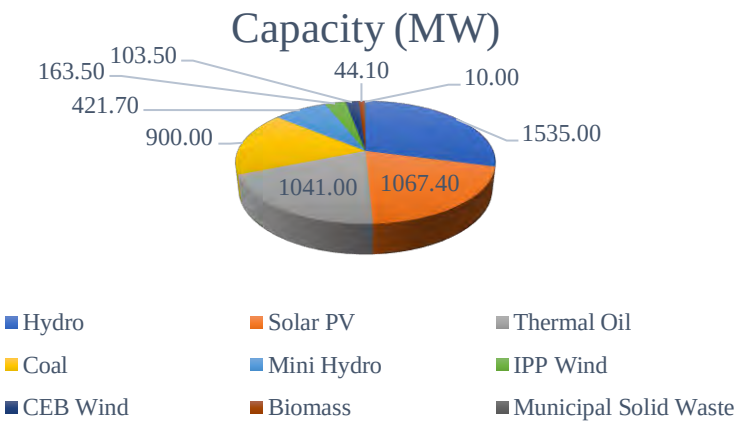



*Figure 1: Energy capacity mix (Adapted from: Public Utilities Commission of Sri Lanka)*

Consequently, solar energy now accounts for a notable component of Sri Lanka's energy mix (refer Figure 1), with an installed capacity exceeding 1000 MW, thereby contributing to national energy security and supporting long-term sustainability objectives. Notwithstanding these advancements, the diffusion of solar PV systems continues to be limited by administrative complexities and extended approval processes, which remain key challenges for prospective users. More critically, despite the strong policy emphasis on expanding solar PV use, limited attention has been directed towards the EOL

management of solar PV systems. The absence of structured policies and regulatory provisions governing the disposal and recycling of decommissioned PV system components raises concerns regarding their potential environmental impacts (Rabaia et al., 2021). Existing studies indicate that EOL considerations for solar PV systems are largely absent from Sri Lanka's current policy framework. Against this backdrop, providing greater attention towards effective EOL management of solar PV systems is essential to ensure that the transition to solar energy in the country aligns with broader principles of environmental sustainability and circular resource use.

## 2.2 ENVIRONMENTAL IMPACTS OF SOLAR PV SYSTEMS

The global environmental impact of solar PV systems is increasingly recognised as a critical factor in the transition towards sustainable energy systems. Solar PV systems play an important role in the mitigation of Greenhouse gases through the generation of renewable energy, and it is expected that they can reduce about 2.3 Giga Tons of CO2 each year (Jan et al., 2023). However, the production process of solar PV systems is not without their impacts on the environment including the use of scarce materials, hazardous materials and notable levels of water usage (Basit et al., 2022). In addition, the life cycle assessments of solar PV systems show that although they have many environmental benefits during the operational phase, their manufacturing and decommissioning phases present negative environmental impacts that need to be carefully evaluated. Therefore, understanding the environmental impacts of solar PV systems is essential for maximising its benefits while minimising its adverse effects on the environment.

### 2.2.1 Impacts During the Manufacturing Phase

Manufacturing of solar PV systems is an energy and material intensive process, which affects their overall environmental impact. PV manufacturing has demonstrated varying energy intensities across different manufacturing stages, particularly in production of silicon wafers and module assembly. For instance, the energy required to extract Silicon from the raw materials for crystalline Silicon solar cells is significant and makes up a considerable part of the carbon footprint of the solar cells (Akhter et al., 2024). While second generation thin film PV technologies typically consume less energy in production than the first generation, they also have their own environmental challenges, specifically related to material inputs and toxicity. Apart from silicon, the manufacturing process of solar PV systems requires other raw materials such as cadmium and tellurium, the mining of which can cause significant environmental degradation in terms of the destruction of habitats, soil erosion and water pollution (Adekanmbi & Wolf, 2024). As the demand for renewable energy evolves, new materials and manufacturing techniques will be required to enhance the environmental sustainability of solar PV systems.

### 2.2.2 Impacts During the Operational Phase

While the environmental impacts of solar PV systems during the operational phase are a minimum, there are several concerns related specifically to large-scale solar farms, primary among them being the excessive land use and habitat disruption (Dhar et al., 2020). Utility scale solar farms consume large land areas and can therefore result in the displacement of local flora and fauna (Karban et al., 2024). According to the authors, this is a particular concern in ecologically sensitive regions that already have their biodiversity under threat. In addition, the competition for lands between the large-scale solar farms and farming for food concerns raise concerns regarding, food security as well as land

scarcity, especially where land availability is low. Several mitigation measures to address these concerns are already emerging, with technologies such as agrivoltaics, which allows combined production of solar energy with agricultural work (Muñoz-García & Hernández-Callejo, 2021).

### 2.2.3 Impacts During the End-Of-Life Phase

Prior research has shown that environmental impacts related to poor end-of-life management of solar PV systems is crucial (Mao et al., 2024). Due to the rapid increase in the adoption of solar technology, there is a considerably high volume of end-of-life solar panels and system components that will produce a significant amount of waste in the next few decades (Mao et al., 2024). Specially, if the PV panels and components like batteries are not properly disposed, heavy metals such as lead and cadmium can leach into the environment, which is highly hazardous (Nain & Kumar, 2020). Furthermore, the current recycling practices for solar panels are still in their infancy, with many systems lacking effective recovery methods for valuable materials (Nain & Kumar, 2020). This lack of recycling of used solar PV systems coupled with the growth in the focus on renewable energy means that there would be a higher demand for virgin materials used in manufacturing PV systems anew, contributing to further depletion of natural resources and increasing the overall environmental footprint of solar PV systems. Therefore, in terms of different phases of the solar PV system lifecycle, the EOL phase is to be considered as a crucial determinant of the overall sustainability of solar PV systems, as failure in effective management of this phase may offset the environmental benefits achieved during the other phases. Hence, there is an urgent need for focusing on managing the environmental impacts of the EOL phase of solar PV systems to ensure that they create a net positive environmental impact.

## 3. METHODOLOGY

The methodology establishes the overall framework through which the study was designed and conducted to achieve its stated aim. A critical component of methodological design is the selection of an appropriate research approach. Broadly, research approaches can be classified as quantitative, qualitative, or mixed methods (Saunders et al., 2019). Each approach offers distinct advantages and is suitable for addressing different types of research questions and contexts, thereby influencing the robustness and validity of the research outcomes. Quantitative research primarily focuses on numerical measurement and statistical analysis, whereas qualitative research seeks to develop an in-depth understanding of phenomena through non-numerical methods, such as interviews and observations. Mixed-methods research integrates both approaches to capture both quantitative and qualitative insights, especially for complex research problems that require detailed analysis.

Given the relative novelty of EOL management of solar PV systems within the Sri Lankan context, the need for in-depth exploratory insights, and the difficulty in conducting a large-scale quantitative study due to limited domain-specific expertise, this study adopted a qualitative research approach. Qualitative research typically uses data collection methods such as interviews, focus groups, and observations to gain detailed insights into the phenomenon under investigation. For this study, interviews were selected as the primary data collection method. Observational methods were considered unsuitable for the research problem, while focus group discussions were deemed unnecessary as the

study did not seek to establish group consensus on specific issues. Interviews can be broadly categorised as structured, semi-structured, or unstructured. Semi-structured interviews were used in this study to balance consistency across participants with flexibility to explore emerging themes. The interviews aimed to identify potential strategies for improving the EOL management of solar PV systems. An interview guideline was developed based on the findings of the literature review, while allowing for probing questions to clarify responses and explore issues in greater depth.

Participants were selected using purposive sampling, based on their professional involvement in the Sri Lankan solar PV sector and their knowledge of EOL management practices. As EOL management of solar PV systems remains an emerging area in Sri Lanka, the number of interviews was limited to eight. Even though the number of interviews was limited to eight, qualitative research does not aim for statistical generalisation yet rather depth of understanding. Methodology literature suggest that smaller sample sizes are appropriate when participants possess high levels of expertise and when the study focuses on a narrowly defined topic. The adequacy of the sample size was determined based on the principle of data saturation, which refers to the point at which no new themes, insights, or patterns emerge from the data. Accordingly, during the data collection process, it was observed that after the sixth interview, recurring themes began to stabilise, and subsequent interviews largely confirmed previously identified insights rather than introducing new concepts. The final two interviews were conducted to ensure consistency and confirm saturation, thereby strengthening the reliability of the findings. This indicates that sufficient depth and coverage of the research topic had been achieved despite the relatively small sample size. The interviewees selected possessed extensive experience related to the study domain, and the interviews yielded rich insights into the EOL management of solar PV systems. The profiles of the interviewees are presented in Table 1.

*Table 1: Profile of interview participants*

| Interviewee Code | Designation | Experience | Qualifications |
|---|---|---|---|
| I1 | Professor | 20+ years | Professor in Building Economics at a Sri Lankan leading university with research expertise related to circular economy, disaster management and resilience |
| I2 | Solar PV Consultant | 10+ years | Worked as a Solar PV Consultant in Sri Lanka and abroad with expertise in solar panel installation and energy optimization strategies |
| I3 | R&D Engineer | 7+ years | Research and Development Engineer specializing in solar energy systems with experience in designing energy-efficient solutions for residential and commercial clients. |
| I4 | Chief Executive Officer | 15+ years | Chief Executive Officer at a leading solar technology company in Sri Lanka with substantial experience in the production of solar panels and renewable energy solutions |
| I5 | Electrical Engineer | 6+ years | Electrical engineer specializing in solar power systems with experience in both grid-connected and off-grid solar systems |

| Interviewee Code | Designation | Experience | Qualifications |
|---|---|---|---|
| I6 | Solar Operations Manager | 12+ years | Solar Operations Manager at a renewable energy firm in Sri Lanka, overseeing large-scale solar installations and maintenance operations |
| I7 | Policy Advisor | 9+ years | Policy advisor focusing on renewable energy policies in Sri Lanka, with a background in environmental law and energy regulation |
| I8 | Project Manager | 7+ years | Project Manager in a leading solar energy firm in Sri Lanka, responsible for overseeing solar energy project implementation, from planning to execution |

The qualitative data collected were analysed using thematic analysis, with the coding and interpretation process conducted primarily through manual methods, supported by Microsoft Excel.

# 4. FINDINGS

The interview findings revealed a range of strategies that could be implemented for improving EOL management of solar PV systems to minimise their environmental impact. These individual strategies are explained in detail under the following sub-topics.

## 4.1 GOVERNMENT LEADERSHIP

The interview findings revealed that the government has a key role to play in terms of improving the end-EOL management of solar PV systems. Herein, the interviewees emphasized that the government should be actively involved in setting up **supportive regulations** that drives the use of solar PV systems in a responsible manner. Such regulations should focus on aspects such as setting up requirements around product returns and material recovery so that EOL solar PV systems are managed responsibly with recoverable resources being brought back into productive use. As noted by I4, the EOL management of solar PV systems in Sri Lanka is currently not regulated. In the absence of proper regulations, private sector entities that are primarily involved in the supply of solar PV systems are highly unlikely to invest in developing recycling infrastructure for these systems, since such investments would eat into their profits.

In addition to regulatory support, I6 recommended that the government could focus on providing **incentives for recycling** EOL solar PV systems, especially the solar panels and battery systems that consist of recyclable glass and rare earth metals, which would drive both users and manufacturers to focus on recycling such systems. The interviewee noted that similar to the tax breaks and subsidies provided for the installation of solar PV systems, financial incentives can be provided to encourage the return and recovery of EOL solar PV systems. However, I2 pointed out that while incentives could encourage responsible EOL management, there is also the need to **develop collection schemes** for effectively collecting system components that have reached the EOL. I2 elaborated on this as follows: "*In addition to providing incentives, we should also set up a good way to collect old solar panels from individuals and companies; it requires setting up collection spots and informing people about the proper way to get rid of their old solar panels. Good logistics are necessary to make sure that the panels are recycled, instead of being thrown*

*away improperly*." As evident through the above extract, there is the need to set up collection centres for collecting the EOL solar PV systems and providing accessible logistics facilities so that such systems are returned to the collection centres. Adding to this, I7 emphasized that such collection schemes should be set up and implemented at the national level, which recognises the need for government leadership and involvement in setting up the collection systems and the relevant logistics infrastructure.

## 4.2 RECYCLING INFRASTRUCTURE

In the quest towards improving the EOL management of solar PV systems, the interviewees reiterated the significance of **setting up recycling infrastructure locally** to recycle EOL solar PV systems. I4, the CEO of a leading solar technology company, pointed out that there is the opportunity to build local recycling facilities with the growing demand for solar PV systems locally as well as in the region. As elaborated by the interviewee, "*Sri Lanka could set up its own recycling plants for solar PV systems – this will help to solve the waste problem and also create new jobs and boost the economy; in fact, we can turn Sri Lanka into a major recycling hub for things like solar panels in South Asia, considering our strategic location in the South Asian region*." According to the above extract, if Sri Lanka can invest in recycling facilities, it can reduce solar PV waste generation, while also recovering valuable materials such as glass, silicon, aluminium and silver, which are required for manufacturing new solar PV systems.

While investments in recycling infrastructure would ideally have to be kick-started by the government until the demand for recycling catches up, the interviewees noted that this might not be viable in a highly cash-crunched economy like Sri Lanka, due to the high upfront costs of setting up recycling infrastructure. Considering this, I6 noted that options such as foreign funding arrangements or public-private partnerships could be considered to initiate the setting up of recycling infrastructure and acquiring the relevant expertise. As noted by I6, "*working together with international companies that specialise in solar panel recycling can introduce the required technologies and knowledge to Sri Lanka, and collaboration between public and private sectors could support the setting up of recycling systems*." However, as noted by the interviewees, investments in recycling infrastructure would not be successful without supportive regulatory or policy initiatives that drives recycling EOL solar PV systems. As explained by I4, "*until there are policies that encourage recycling solar PV systems, companies will not invest in the necessary infrastructure – the government must introduce regulations that require recycling and help drive the return on investment on recycling infrastructure*." As noted by the interviewee, if the regulatory and policy frameworks do not drive the recycling of EOL solar PV systems, people will not be interested in recycling unless there is an economic benefit. This would make recycling facilities idle, which in turn would make it difficult to recover the investment on the recycling facilities, thus discouraging such investments.

## 4.3 CIRCULARITY IN DESIGN

Interestingly, most of the interviewees highlighted that the responsible EOL management of solar PV systems should ideally commence at the design stage itself. As noted by I2, "*if solar panels are designed to be recycled from the start, we can lessen the effect on the environment from the beginning*." Herein, the interviewees identified several circularity principles that can be adopted in the design of solar PV systems. Among them, improving the resource efficiency of solar PV systems was emphasized to make them **less material**

**intensive**. To achieve resource efficiency in design, I3 noted that the design of solar PV systems should be improved to use less materials while also **selecting materials that are comparatively easy to recycle**. This will ensure that the resources committed to the production of solar PV systems are minimized while at the same time, any recyclable materials are recovered and diverted back towards new production processes.

Moving further, I4 advised that the local suppliers of solar PV systems should investigate **modular designs** which would make it possible to replace individual components of the solar PV systems instead of replacing the entire system. For instance, the interviewee pointed out that by making the solar panels modular, any faulty cells could be removed and replaced rather than replacing the entire panel. This would ensure that the solar panels last longer while also cutting down on the waste generated. This aligns with the current trends in product design which urges companies to make products that can be repaired, upgraded or taken apart for recycling. Moreover, I2 noted that the **use of sustainable material** alternatives when manufacturing solar PV systems could also help lower the negative EOL impacts of solar PV systems. As stated by the interviewee, "*it would be better for manufacturers to choose materials that are less harmful to the environment such as recycled aluminium or glass*." This can be specially considered when manufacturing solar panels, since aluminium, which is used as a framing material is highly recyclable, while glass which is used as a transparent layer on top of the solar cells to protect them from exposure to the elements and impact, can also be made using recycled glass since they do not have a direct impact on energy generation through solar panels.

## 4.4 EXTENDED PRODUCER RESPONSIBILITY

Following on from EPR requirements placed on manufacturers of products such as electronics and vehicles, the interview findings revealed that the government could consider **applying EPR requirements for suppliers of solar PV systems**. This was emphasised by I1 who noted that applying EPR requirements would make suppliers responsible for the entire lifecycle of their products, from cradle to grave. The interviewee noted that EPR schemes would encourage suppliers of solar PV systems to design and supply products with recycling and disposal in mind and be responsible for their products after they are used. Implementing such requirements is aligned with what is currently happening globally, where businesses are expected to internalize and be responsible for the negative environmental effects of their products after they are sold.

## 4.5 AWARENESS BUILDING

While implementing the measures, the interview findings also recognised the need for building broader community awareness regarding proper EOL management of solar PV systems. As noted by the interviewees, such awareness building efforts should focus on communicating the negative/harmful effects of poor EOL management of solar PV systems, how EOL solar PV systems should be managed and what are the avenues/options available to responsibly manage such systems that have reached their EOL. Herein, I4 specifically noted that such awareness building efforts should target stakeholders at both the supply and demand sides.

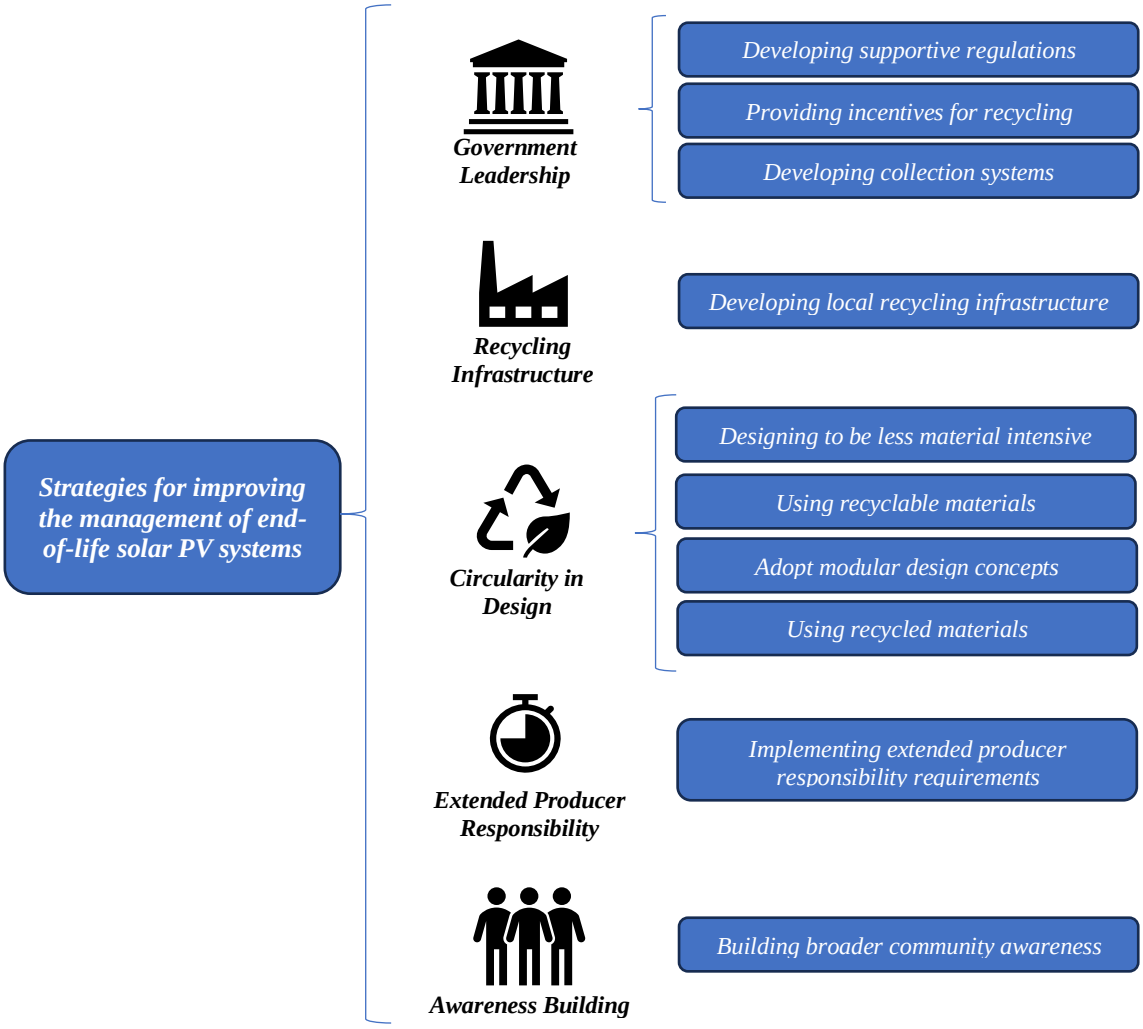



*Figure 2: Summary of findings*

The key findings of the study are summarised in Figure 2.

## 5. DISCUSSION

Recent statistics suggest that Sri Lanka's dependence on solar PV systems is increasing as part of its transition towards more sustainable energy generation. However, the end-of-life (EOL) management of solar PV systems remains underexplored in the local context, indicating a critical gap that the present study seeks to address. The findings emphasise the need for stronger government intervention through appropriate regulations, recycling incentives, formal collection mechanisms, and the development of recycling infrastructure, potentially through public–private partnerships. Although Sri Lanka has actively promoted solar energy adoption, insufficient attention has been given to the eventual disposal and recovery of solar PV systems, many of which will progressively reach their EOL in the coming years (Thennakoon et al., 2023, Koswatte et al., 2024). This is particularly concerning because PV panels are classified as hazardous e-waste, yet Sri Lanka lacks structured recycling and material recovery systems capable of safely managing this waste stream and recovering valuable materials such as silicon, copper, aluminium, and glass (Thennakoon et al., 2023). Existing e-waste collection systems are largely informal, while subsequent recycling and recovery processes remain

insufficiently transparent. In contrast, countries such as Japan and China have begun developing national recycling frameworks and large-scale facilities to manage solar PV waste sustainably (Umar et al., 2025). While Sri Lanka may draw lessons from these approaches, their direct applicability must be assessed in light of local financial and technological constraints. Furthermore, countries such as China benefit from economies of scale as a major global producer of solar PV panels, an advantage that Sri Lanka lacks. However, given Sri Lanka's strategic location in South Asia, the study indicates potential for positioning the country as a regional hub for solar PV recycling, provided that a robust regulatory framework is established to prevent the country from becoming a destination for hazardous waste disposal.

The findings highlight the importance of embedding circularity principles into solar PV system design, including material-efficient designs, modularity, and the use of recycled or recyclable materials. Since most solar PV components used in Sri Lanka are imported, with limited local design or manufacturing capacity (Koswatte et al., 2024), local suppliers should prioritise the importation and promotion of systems designed in accordance with such circularity principles. Closely linked to this is the adoption of EPR schemes, under which suppliers remain accountable for products throughout their lifecycle rather than only until the point of sale. Similar mechanisms have been widely used in the European Union and the United Kingdom through instruments such as the Waste Electrical and Electronic Equipment Directive to encourage EOL recovery of solar PV systems (Umar et al., 2025). Prior studies further suggest that EPR is essential for sustaining recycling schemes, as it creates legal and financial accountability for suppliers who fail to ensure proper lifecycle management (Umar et al., 2025). Accordingly, establishing EPR-based requirements is imperative for the long-term success of EOL solar PV recovery in Sri Lanka. Finally, the study highlights the need for broader awareness-building initiatives. The effectiveness of regulatory, technical, and recovery-oriented strategies will depend heavily on public understanding of proper EOL management and active community participation, a finding consistently supported in previous studies (Thennakoon et al., 2023; Umar et al., 2025).

## 6. CONCLUSIONS

The study findings agree with the existing literature that despite promotion of solar PV systems in Sri Lanka, their EOL management has received comparatively very limited attention, therefore necessitating a closer look at how to improve the management of the EOL environmental impacts of solar PV systems. The findings revealed a range of strategies that could be used to address and overcome the negative environmental impacts of EOL solar PV systems. Interestingly, it was found that the government has a major role to play in this regard. Herein, the findings revealed that the government should focus on enacting supportive regulations that drive product return and material recovery. The government can consider providing financial incentives for recycling EOL solar PV systems, similar to those that are provided for promoting their use. Importantly, it was emphasized that such measures should be complemented by a nation-wide collection scheme for EOL solar PV systems without which there would not be a clear pipeline for collecting EOL solar PV systems for material recovery. While aforementioned measures are being implemented, the study also recognised the significance of setting up recycling infrastructure locally, which could be set up through foreign funding arrangements or public-private partnerships, considering the high initial costs involved in setting up such

infrastructure. If successful, there is the potential for Sri Lanka to be a hub for recycling solar PV systems in the region. Considering the notable impact that system design can have on EOL management, the importance of considering circularity principles in system design was highlighted. Circularity strategies such as using less materials, using recyclable and sustainable materials (e.g., materials with recycled content) and following modular design principles were recognised as avenues for improving the EOL management of solar PV systems at the design stage itself. Further, the study recognised the potential for applying EPR requirements for manufacturers/suppliers of solar PV systems, so that they themselves are held responsible for the EOL impacts of solar PV systems, which in turn would drive them to consider EOL management during design and manufacturing of solar PV systems itself. Finally, the need for building broader community awareness regarding proper EOL management of solar PV systems was emphasised.

## 7. REFERENCES

Adekanmbi, A. O., & Wolf, D. (2024). Solid mineral resources extraction and processing using innovative technology in Nigeria. *ATBU Journal of Science, Technology and Education*, *12*(1), 1–16. https://doi.org/10.13140/RG.2.2.16610.91840

Akhter, M., Al Mansur, A., Islam, Md. I., Lipu, M. S. H., Karim, T. F., Abdolrasol, M. G. M., & Alghamdi, T. A. H. (2024). Sustainable strategies for crystalline solar cell recycling: A review on recycling techniques, companies, and environmental impact analysis. *Sustainability*, *16*(13), 5785. https://doi.org/10.3390/su16135785

Basit, A., Hassan, M., Kanwal, S., Anwar, M., Kazmi, S. A. A., & Ansari, A. A. (2022). Environmental impact assessments of the renewable energy technologies adaptation. *Pakistan Journal of Engineering and Technology*, *5*(2), 100–103. https://doi.org/10.51846/vol5iss2pp100-103

Biyouki, Z. A., Zaman, A., Marinova, D., Minunno, R., & Shayegan, M. A. (2024). Solar photovoltaics value chain and end-of-life management practices: A systematic literature review. *Sustainability*, *16*(16), 7038. https://doi.org/10.3390/su16167038

Bošnjaković, M., Santa, R., Crnac, Z., & Bošnjaković, T. (2023). Environmental impact of PV power systems. *Sustainability 15* (15). https://doi.org/10.3390/su151511888

Danthurebandara, M., & Rajapaksha, L. (2019). Environmental consequences of different electricity generation mixes in Sri Lanka by 2050. *Journal of Cleaner Production*, *210*, 432–444. https://doi.org/10.1016/j.jclepro.2018.10.343

Dhar, A., Naeth, M. A., Jennings, P. D., & Gamal El-Din, M. (2020). Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. *Science of The Total Environment*, *718*, 134602. https://doi.org/10.1016/j.scitotenv.2019.134602

International Energy Agency (IEA). (n.d.). *End-of-Life Solar PV Panels*. International Energy Agency - Photovoltaic Power Systems Programme. Retrieved January 25, 2026, from https://iea-pvps.org/key-topics/irena-iea-pvps-end-of-life-solar-pv-panels-2016/

Jan, A. A., Lai, F. W., Shad, M. K., Ali, S. E. A., & Hamad, S. (2023). Solar photovoltaic technology and its impact on environmental, social and governance (ESG) performance: A review. *KnE Social Sciences*, 759–774. https://doi.org/10.18502/kss.v8i20.14636

Jones, G., & Bouamane, L. (2012). 'Power from Sunshine': A business history of solar energy. *Harvard Business School Working Paper Series*, *12*, 105. http://nrs.harvard.edu/urn-3:HUL.InstRepos:9056763

Kannan, N., & Asharp, T. (2023). Solar energy as a sustainable source of energy for industrial applications in Sri Lanka: A conceptual mini-review. *Vavuniya Journal of Science*, *2*(1), 39–50. https://doi.org/10.4038/vjs.v2i1.20

Karban, C. C., Lovich, J. E., Grodsky, S. M., & Munson, S. M. (2024). Predicting the effects of solar energy development on plants and wildlife in the Desert Southwest, United States. *Renewable and Sustainable Energy Reviews*, *205*, 114823. https://doi.org/10.1016/j.rser.2024.114823

Koswatte, I., Iddawala, J., Kulasekara, R., Ranaweera, P., Dasanayaka, C. H., & Abeykoon, C. (2024). Can Sri Lanka be a net-zero nation by 2050? - Current renewable energy profile, opportunities, challenges, and recommendations. *Cleaner Energy Systems*, *8*, 100126. https://doi.org/10.1016/j.cles.2024.100126

Lameirinhas, R. A. M., Torres, J. P. N., & Cunha, J. P. M. (2022). A photovoltaic technology review: History, fundamentals and applications. *Energies*, *15*(5), 1823. https://doi.org/10.3390/en15051823

Mao, D., Yang, S., Ma, L., Ma, W., Yu, Z., Xi, F., & Yu, J. (2024). Overview of life cycle assessment of recycling end-of-life photovoltaic panels: A case study of crystalline silicon photovoltaic panels. *Journal of Cleaner Production*, *434*, 140320. https://doi.org/10.1016/j.jclepro.2023.140320

Mendis, T., Huang, Z., & Xu, S. (2019). Determination of economically optimised building integrated photovoltaic systems for utilisation on facades in the tropical climate: A case study of Colombo, Sri Lanka. *Building Simulation*, *13*(1), 171–183. https://doi.org/10.1007/s12273-019-0579-4

Mittal, A. (2023). Assessment of SAARC nations' solar energy potential for sustainable development. *Energy & Environment*, *34*(6), 2228–2255. https://doi.org/10.1177/0958305X221120935

Muñoz-García, M. A., & Hernández-Callejo, L. (2021). Photovoltaics and electrification in agriculture. *Agronomy*, *12*(1), 44. https://doi.org/10.3390/agronomy12010044

Nain, P., & Kumar, A. (2020). Identifying issues in assessing environmental implications of solar PVs-related waste. In A. S. Kalamdhad (Ed.), *Recent Developments in Waste Management* (pp. 71–90). Springer Singapore. https://doi.org/10.1007/978-981-15-0990-2_7

Pourasl, H. H., Barenji, R. V., & Khojastehnezhad, V. M. (2023). Solar energy status in the world: A comprehensive review. *Energy Reports*, *10*, 3474–3493. https://doi.org/10.1016/j.egyr.2023.10.022

Rabaia, M. K. H., Abdelkareem, M. A., Sayed, E. T., Elsaid, K., Chae, K.-J., Wilberforce, T., & Olabi, A. G. (2021). Environmental impacts of solar energy systems: A review. *Science of The Total Environment*, *754*, 141989. https://doi.org/10.1016/j.scitotenv.2020.141989

Roy, R., & Pearce, J. M. (2023). Is small or big solar better for the environment? Comparative life cycle assessment of solar photovoltaic rooftop vs. ground-mounted systems. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-023-02254-x

Saunders, M. A., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed). Pearson.

Sri Lanka Sustainable Energy Authority. (n.d.). *Soorya Bala Sangramaya*. Sri Lanka Sustainable Energy Authority. Retrieved January 25, 2026, from https://www.energy.gov.lk/en/soorya-bala-sangramaya

Thennakoon, T. M. T. N., Weerarathna, D. M., Hewage, H. T. M., Jayathma, W. M. V. A., Gamage, D. G. M. L., Sulaksha, L. G. T., Alahakoon, A. M. A. R. B., Senarath, P. G. R. L. P., & Bandara, G. A. I. M. (2023). Overview of solar electricity in Sri Lanka and recycling processes. *Journal of Research, Technology and Engineering*, *4*(2), 125–153. https://www.jrte.org/wp-content/uploads/2023/04/OVERVIEW-OF-SOLAR-ELECTRICITY-IN-SRI-LANKA-AND-RECYCLING-PROCESSES.pdf

Thushara, D. S. M., Hornberger, G. M., & Baroud, H. (2019). Decision analysis to support the choice of a future power generation pathway for Sri Lanka. *Applied Energy*, *240*, 680–697. https://doi.org/10.1016/j.apenergy.2019.02.074

Umar, T., Ahmed, S. and Rana, M.Q. (2025). Sustainable solar: Addressing the growing need for PV panel recycling. In K.G.A.S. Waidyasekara, H.S. Jayasena, P.L.I. Wimalaratne, & G.A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium, Colombo*, 15-16 August 2025. (pp. 1288-1301). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2025.96

Yolcan, O. O. (2023). World energy outlook and state of renewable energy: 10-Year evaluation. *Innovation and Green Development*, *2*(4), 100070. https://doi.org/10.1016/j.igd.2023.100070

Zhou, C., & Li, S. (2025). Reverse logistics network optimization for retired BIPV panels in smart city energy systems. *Buildings*, *15*(14), 2549. https://doi.org/10.3390/buildings15142549

Zhu, L., Zou, S., Ni, M., Ding, J., Wu, C., Lu, Z., Zeng, Y., Ye, X., Wang, X., Fan, R., Sun, H., Liao, B., Xu, Y., Shen, M., & Su, X. (2022). Ultrafast random-pyramid texturing for efficient monocrystalline silicon solar cells. *Solar RRL*, *6*(7), 2200204. https://doi.org/10.1002/solr.202200204

Sanmargaraja, S., Olanrewaju, A., Ali, M. A., Chu, H.C., Khor, S.C., Ponniah, V. and Kanniyapan, G., 2026. Managing foreign labour in Malaysia's construction sector: Practices and constraints. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1123-1135. DOI: https://doi.org/10.31705/WCS.2026.82. Available from: https://ciobwcs.com/papers/

# MANAGING FOREIGN LABOUR IN MALAYSIA'S CONSTRUCTION SECTOR: PRACTICES AND CONSTRAINTS

**Shalini Sanmargaraja[1], Abdul Lateef Olanrewaju[2], Muhammad Adnan Ali[3], Hui Chen Chu[4], Soo Cheen Khor[5], Vignes Ponniah[6] and Gunavathy Kanniyapan[7]**

## *ABSTRACT*

*The Malaysian construction sector is heavily dependent on foreign labour, making effective labour management a critical factor for project success. Despite their essential contributions to construction delivery and industry growth, foreign labourers often face challenges related to inadequate governance, weak enforcement, and suboptimal on-site management, exposing them to poor housing, low wages, unsafe conditions, and limited labour rights. These issues not only undermine worker well-being but also negatively impact productivity and project performance. This study investigates foreign labour management practices in Malaysia through a survey of 282 construction labourers using a 46-item questionnaire. The results indicate strong performance in workplace safety, supportive supervision, and accommodation management, while mid-level ratings were observed for job clarity, fair compensation, and training opportunities. High scores reflect better-performing sampled sites and do not mean issues are absent Weaknesses were identified in worker participation in decision-making and awareness of policies and labour rights. The findings underscore the need to enhance communication, participatory management, and policy awareness to improve worker satisfaction, compliance, and overall project outcomes. Strengthening these labour management practices is essential not only for protecting foreign labourers' well-being but also for optimizing productivity and ensuring the effective execution of construction projects in Malaysia.*

***Keywords:*** *Foreign Workforce Integration; Human Resource Coordination; Industry Productivity; Regulatory Compliance; Workforce Governance.*

[1] Assistant Professor, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, shalinis@utar.edu.my
[2] Associate Professor, Department of Construction Management, University Tunku Abdul Rahman, Malaysia, olanrewaju@utar.edu.my
[3] PhD Student, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, muhammadadnan1108@gmail.com
[4] Lecturer, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, chuhc@utar.edu.my
[5] Assistant Professor, Department of Construction Management, Universiti Tunku Abdul Rahman, Malaysia, khorsc@utar.edu.my
[6] Lecturer, Trafford College Group, United Kingdom, VPonniah@tmc.ac.uk
[7] Assistant Professor, Department of Real Estate, Tunku Abdul Rahman Universiti of Management and Technology, Malaysia, gunavathyk@tarc.edu.my

# 1. INTRODUCTION

Malaysia's dependence on foreign labourers can be traced back to the colonial period, when imported labour was brought in to address shortages in agriculture and infrastructure; today, the construction sector continues this legacy, relying heavily on labourers from Indonesia, Bangladesh, Myanmar, and Nepal, similar to trends seen across Southeast Asia (Saari et al., 2025; Yusop et al., 2025). . While this reliance helps keep labour costs low and projects affordable, it also creates socio-economic challenges, including wage pressure on local labourers, limited career progression, and weak skill transfer, ultimately reinforcing a segmented workforce with restricted opportunities for advancement (Saari et al., 2025; Yusop et al., 2025). Malaysia currently employs around 2.1 million documented foreign labourers, representing about 13% of the national workforce. However, the true scale of undocumented migrants remains uncertain. Previous estimates suggest that their numbers may be comparable to the documented workforce, potentially doubling the actual presence of foreign labourers in the country (Rizam et al., 2024; Mazlan et al., 2024).

The construction sector plays a vital role in driving national economic growth, but its activities depend heavily on the availability of a sufficient workforce. Due to the shortage of local labour, the industry increasingly relies on foreign labourers, who have become the preferred choice for many contractors. While this approach helps sustain project delivery, it also contributes to higher unemployment among local citizens and leads to an outflow of national income as foreign labourers remit their earnings to their home countries (Saari et al., 2024; Najib et al., 2019). Based on the research conducted by Jamalulil et al. (2022), reliance on foreign labourers stems largely from limited interest among local labourers in joining the industry. Zakaria & Zain (2021) argued that although foreign labourers have helped address labour shortages in Malaysia's construction sector, excessive reliance on them and the resulting negative consequences have evolved into a significant social concern.

Despite extensive research on foreign labour in construction, most studies have been conducted in other regional contexts, and limited empirical evidence exists focusing specifically on Malaysian construction sites. Furthermore, existing studies often rely on secondary data or limited case studies, with fewer employing direct primary data collection from active construction sites across both building and infrastructure projects. This indicates a geographical and methodological gap, which this study aims to address.

# 2. LITERATURE REVIEW

Many local labourers are selective about the types of jobs they are willing to accept and often avoid physically demanding, high-risk, or unstable roles such as those in the construction industry. Consequently, employers tend to rely more on foreign labourers to fill these positions and ensure project continuity. Foreign labourers are attracted to Malaysia's construction sector due to consistent employer demand, comparatively better wages and working conditions, and limited employment prospects in their home countries (Zainal et al., 2023). Foreign workers often face multiple workplace challenges, including human rights concerns, work permit issues, language barriers, inadequate compensation and insurance, unequal treatment, and poor working conditions. However, fear of losing their jobs or being repatriated prevents many from voicing complaints or expressing dissatisfaction to management. (Wei & Yazdanifard, 2015; Uddin & Mohammed, 2020).

According to Bariono & Kamaruding (2025), foreign labourers in the construction industry face significant safety and productivity challenges. Inadequate training, low safety awareness, limited protective equipment, and fear of deportation increase their risk of workplace accidents. Additionally, inefficient recruitment processes and language barriers (Sanmargaraja et al., 2024; Ne' Matullah et al., 2021) delay hiring, disrupt project timelines, and lead to misunderstandings about safety and job requirements. These issues highlight the need for stronger safety enforcement, proper training, and improved administrative systems to enhance overall project performance.

Migrant labourers have long contributed to Malaysia's economy, but many still face inadequate and overcrowded housing conditions that can affect their health and safety. To address this issue, the Malaysian government introduced the Employees' Minimum Standards of Housing, Accommodations and Amenities Act 1990 (Act 446) to protect the housing rights and welfare of both migrant and local labourers (Nasir et al., 2023). The treatment of foreign labourers in the construction industry is often inadequate, as they face numerous challenges in their working environment. Poor working conditions and insufficient welfare support can negatively impact labourers' productivity and lead to delays in project timelines. Therefore, it is important to ensure that foreign construction labourers receive fair wages, safe working conditions, adequate welfare facilities, and proper support for their general well-being (Fateh et al., 2021).

According to Putul & Mia (2018), exploitation of foreign labourers frequently occurs at construction sites in Malaysia, which can significantly affect labourers' morale and motivation in their jobs. These exploitative practices include confiscation of labourers' passports, physical and psychological abuse, forced labour, sexual harassment, unfair salary deductions, discrimination, poor living conditions, and burdens related to the levy system. In some cases, labourers also face harassment from authorities. Such practices are often used to restrict labourers' freedom of movement, prevent them from changing jobs, and discourage them from reporting poor working conditions or exploitation.

Furthermore, exploitation in the context of labourers takes the form of wages that are not commensurate with the work they perform. This type of exploitation is usually carried out by employers within an organization, particularly in the construction sector. Exploitation of foreign labourers occurs due to weak administration, lax laws, and employers' lack of attention to managing migrant labourers from other countries to work in Malaysia. Employers often neglect proper management of foreign labourers, even when these labourers enter Malaysia through unauthorized channels (Marjuki, 2018). While concerns such as exploitation and human rights issues are discussed in the literature, this study operationalises these concerns through measurable workplace indicators such as working conditions, accommodation quality, and compensation practices.

## 3. METHODOLOGY

This study employed a quantitative survey approach to examine strategies for enhancing worker protection, productivity, and general performance in Malaysia's construction sector. The research was guided by a pragmatic research philosophy and adopted both descriptive and explanatory approaches to better understand foreign labour practices at construction sites. The respondents comprised foreign construction labourers from

Bangladesh, Pakistan, and Indonesia, selected through a non-probability convenience sampling technique.

Data were collected using both structured face-to-face questionnaires administered and online questionnaires through Google Form at several active construction sites located in Malaysia. The selected construction projects consist of both building and infrastructure developments. The construction sites were selected using a non-probability convenience sampling approach based on several considerations, including: (i) active project status during the data collection period, (ii) accessibility and permission granted by site management, and (iii) representation of both building and infrastructure projects to capture diverse construction practices. This approach ensured that the selected sites were relevant to the study objectives and provided practical access to foreign workers for data collection. The questionnaire instrument was developed based on insights from relevant literature, particularly the work of Sanmargaraja et al. (2025) and Olanrewaju et al. (2024). It consisted of both Likert-scale and categorical questions, designed to capture labourers' perceptions and experiences related to labour management practices in Malaysian construction sites.

The questionnaire covered three main sections: (i) demographic and background characteristics of the respondents, (ii) labour management practices at construction sites, and (iii) potential interventions aimed at improving working conditions. However, this research focuses specifically on the findings related to foreign labour management practices in Malaysia at construction sites. Responses were measured using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The collected data were analysed using descriptive statistical techniques and explanatory approach with IBM SPSS Statistics (version 31.0.0.0).

Specifically, the descriptive approach was employed to systematically characterize foreign labour practices at construction sites, including aspects such as working conditions, communication challenges, and employment arrangements. This was achieved using the structured survey instruments and descriptive statistical analysis (e.g., frequencies, means, and standard deviations).

# 4. RESULTS AND DISCUSSION

A total of 282 valid questionnaires were collected from 11 construction sites across Malaysia between September 2025 and February 2026. The names of the projects are kept anonymous to maintain confidentiality and protect the privacy of the sites involved.

## 4.1 RESPONDENT PROFILE

A total of 300 questionnaires were distributed both online through Google Forms and in physical form. From this distribution, 282 completed responses were received, yielding a response rate of 94%. The demographic profile of the respondents is presented in Table 1.

*Table 1: Respondent profile and employment status*

| Variable | Category | Frequency (N) | Percent (%) |
|---|---|---|---|
| ***Site*** | Site A | 21 | 7.4 |

| Variable | Category | Frequency (N) | Percent (%) |
|---|---|---|---|
| | Site B | 6 | 2.1 |
| | Site C | 6 | 2.1 |
| | Site D | 12 | 4.3 |
| | Site E | 83 | 29.4 |
| | Site F | 59 | 20.9 |
| | Site G | 19 | 6.7 |
| | Site H | 20 | 7.1 |
| | Site I | 20 | 7.1 |
| | Site J | 26 | 9.2 |
| | Site K | 10 | 3.5 |
| ***Years of Experience*** | Less than 1 year | 13 | 4.6 |
| | 1-3 years | 159 | 56.4 |
| | 4-6 years | 59 | 20.9 |
| | 7-10 years | 35 | 12.4 |
| | Over 10 years | 15 | 5.3 |
| ***Nationality*** | Bangladesh | 214 | 75.9 |
| | Indonesia | 6 | 2.1 |
| | Nepal | 7 | 2.5 |
| ***Highest education*** | No formal education | 109 | 38.7 |
| | Primary | 82 | 29.1 |
| ***Current employment*** | Full-time | 79 | 28.1 |
| | Contract-based | 135 | 47.9 |
| | Daily wages | 65 | 23 |
| ***Monthly income range (RM)*** | 1000-1499 | 6 | 2.1 |
| | 1500-1999 | 122 | 43.3 |
| | 2000-2999 | 94 | 33.4 |
| | 3000-3999 | 35 | 12.4 |
| ***Types of construction*** | Residential buildings | 125 | 44.3 |
| | Commercial buildings | 120 | 42.6 |
| | Infrastructure | 5 | 1.8 |
| | Industrial facilities | 22 | 7.8 |
| ***Living in company accommodation*** | Yes | 262 | 92.9 |
| ***Language spoken at the site*** | ***Bengali*** | ***206*** | ***73*** |
| | Nepali | 8 | 2.8 |
| | Hindi | 4 | 1.4 |
| | Indonesian | 1 | 0.4 |
| | Urdu | 25 | 8.9 |

| Variable | Category | Frequency (N) | Percent (%) |
|---|---|---|---|
| ***Trade/skill area*** | General labourer | 73 | 25.9 |
| | Masonry/brickwork | 16 | 5.7 |
| | Carpentry | 18 | 6.4 |
| | Electrical | 5 | 1.8 |
| | Plumbing | 128 | 45.4 |
| | Painting | 5 | 1.8 |
| | Heavy machinery operator | 2 | 0.7 |
| | Others: aircon, fire plumber, scaffolder, etc | 32 | 11.3 |
| ***Formal certification/training*** | Yes-local (Malaysia) | 160 | 56.7 |
| | Yes-From home country | 69 | 24.5 |
| | No | 49 | 17.4 |
| ***Recruitment method*** | Local employment agency | 129 | 45.7 |
| | Home country agency | 81 | 28.7 |
| | Directly by the employer | 37 | 13.1 |
| | Referred by other labourers | 31 | 11 |
| ***Frequency of overtime*** | Very often | 92 | 32.7 |
| | Quite often | 139 | 49.3 |
| | Often | 31 | 31 |
| | Occasionally | 16 | 16 |
| ***Reasons for overtime*** | To meet the project deadline | 55 | 19.5 |
| | To earn more income | 209 | 74.1 |
| | The project is on extension of time (EOT) | 12 | 4.3 |
| | Others: being forced, etc. | 1 | 0.4 |

## 4.2 RESULTS OF FOREIGN LABOUR MANAGEMENT PRACTICES IN MALAYSIA

The reliability analysis indicates that the 46-item questionnaire has outstanding internal consistency, with a Cronbach's Alpha of 0.955 and 0.964 for standardized items (Table 2). These results confirm that the instrument consistently measures the intended constructs, and the slightly higher standardized value further demonstrates that the items maintain strong reliability even after standardization, underscoring the robustness of the measurement tool.

*Table 2: Reliability statistics*

| Cronbach's Alpha | Cronbach's Alpha Based on Standardized Items | N of Items |
|---|---|---|
| .955 | .964 | 46 |

The KMO suggests a very high degree of shared variance among the 46 constructs which means that the variables are not isolated measures but are likely influenced by common underlying factors or governance mechanisms in labour management (Table 3). In practical terms, this implies construct are suitable to collectively measure labour practices. The significant Bartlett's Test further confirms that relationships among variables are not random, indicating a well-structured correlation matrix. This strengthens the conceptual validity of the instrument and suggests that foreign labour management in the Malaysian construction industry is systemically interconnected rather than fragmented, supporting deeper interpretation, such as identifying key dimensions, policy gaps, or managerial clusters.

*Table 3: KMO and Bartlett's test*

| **Kaiser-Meyer-Olkin Measure of Sampling** | | |
|---|---|---|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy. | | .928 |
| Bartlett's Test of Sphericity | Approx. Chi-Square | 6618.607 |
| | df | 1035 |
| | Sig. | .000 |

Table 4 presents the descriptive statistics for labour management practices, including the mean, standard deviation, and ranking of each statement. The findings indicate that respondents generally perceive labour management practices at construction sites positively, as reflected by the high mean scores ranging from 4.23 to 4.38 on a five-point scale. This suggests that most labourers agree that appropriate management practices are implemented at their workplace.

*Table 4: Descriptive analysis of labour management practices in Malaysia*

| Labour Management Practices | Mean | Standard Deviation | Rank |
|---|---|---|---|
| My job responsibilities are clearly defined and well-managed. | 4.38 | 0.647 | 1 |
| The site environment is clean, safe, and well-organized. | 4.36 | 0.676 | 2 |
| My employer provides regular updates on contract renewal and permit status. | 4.36 | 0.719 | 3 |
| I have experienced fair treatment during recruitment and onboarding. | 4.34 | 0.623 | 4 |
| I always have access to personal protective equipment (PPE). | 4.33 | 0.662 | 5 |
| When labourers are mistreated, it affects the overall performance of the project. | 4.32 | 1.99 | 6 |

| Labour Management Practices | Mean | Standard Deviation | Rank |
|---|---|---|---|
| There is clarity about how wages and deductions are calculated. | 4.32 | 0.569 | 7 |
| I feel proud to work at my current site due to good management practices. | 4.32 | 0.698 | 8 |
| I receive clear instructions before starting a new task. | 4.31 | 0.709 | 9 |
| I always have access to proper safety gear and equipment. | 4.31 | 0.683 | 10 |
| I feel safe from harassment or abuse at my workplace. | 4.3 | 0.723 | 11 |
| I am fairly compensated for overtime work. | 4.28 | 0.681 | 12 |
| I am given sufficient rest breaks during the workday. | 4.28 | 0.639 | 13 |
| I think adequate signposts with graphical illustrations are provided on the site. | 4.28 | 0.728 | 14 |
| I am treated fairly regardless of my nationality. | 4.27 | 0.701 | 15 |
| The work environment is safe and well-managed. | 4.26 | 0.674 | 16 |
| The accommodation provided is clean, safe, and not overcrowded. | 4.25 | 0.762 | 17 |
| Poor labour practices can lead to legal fines, disputes, or project delays. | 4.25 | 0.661 | 18 |
| Management listens to and responds to worker complaints or grievances. | 4.24 | 0.619 | 19 |
| My supervisor is approachable and supportive. | 4.23 | 0.688 | 20 |
| My work performance is regularly reviewed and discussed. | 4.23 | 0.649 | 21 |
| The supervisors treat labourers with respect and professionalism. | 4.23 | 0.701 | 22 |
| I have access to drinking water and basic sanitation facilities on site. | 4.23 | 0.766 | 23 |
| I receive fair and transparent treatment from supervisors. | 4.23 | 0.62 | 24 |
| The way work is assigned and managed contributes positively to project productivity. | 4.22 | 0.602 | 25 |
| I receive safety training before starting high-risk tasks. | 4.22 | 0.6 | 26 |
| I am informed about my legal rights as a foreign worker in Malaysia. | 4.22 | 0.635 | 27 |
| I am informed in advance if there are changes in work schedules. | 4.2 | 0.599 | 28 |
| Labour management systems help improve work productivity on site. | 4.19 | 0.672 | 29 |
| I am informed of company policies and procedures. | 4.19 | 0.663 | 30 |

| Labour Management Practices | Mean | Standard Deviation | Rank |
|---|---|---|---|
| I understand the safety procedures and emergency protocols on-site. | 4.19 | 0.602 | 31 |
| I am aware of the company's policies related to worker rights and welfare. | 4.19 | 0.747 | 32 |
| Supervisors are trained to handle cultural and language differences. | 4.18 | 0.71 | 33 |
| Communication between foreign labourers and management is effective. | 4.18 | 0.683 | 34 |
| The company offers opportunities for skill development or training. | 4.17 | 0.7 | 35 |
| My feedback is taken seriously by management. | 4.17 | 0.73 | 36 |
| I feel that labour policies are applied equally to foreign and local labourers. | 4.15 | 0.726 | 37 |
| There are transparent and fair processes for conflict resolution. | 4.15 | 0.644 | 38 |
| There are clear procedures for reporting complaints or grievances. | 4.15 | 0.699 | 39 |
| The construction company provides stable and secure employment for foreign labourers. | 4.14 | 0.788 | 40 |
| The company has systems in place to prevent abuse or exploitation of foreign labourers. | 4.13 | 0.745 | 41 |
| My working hours are reasonable and comply with labour laws. | 4.13 | 0.629 | 42 |
| Labourers are involved in decisions or discussions that affect their jobs. | 4.11 | 0.716 | 43 |
| The working hours are fair and comply with employment regulations. | 4.1 | 0.613 | 44 |
| My wages are paid on time and according to what was promised. | 4.06 | 0.843 | 45 |
| My job responsibilities are clearly explained to me. | 4.05 | 0.605 | 46 |

The highest-ranked variable recorded a mean score of 4.38 (SD = 0.647), indicating a strong level of agreement among respondents. This suggests that labourers generally experience clear task organization and structured job management, which contributes to better coordination and efficiency in construction activities. The second-ranked variable obtained a mean score of 4.36 (SD = 0.676), reflecting respondents' positive perception of workplace conditions. A well-maintained and organized site environment is important in construction projects as it supports worker safety, operational efficiency, and project performance. The present study found that improved safety measures are perceived as essential for enhancing worker welfare. This finding aligns with the work of Zulkeflee et al. (2023), who reported that inadequate enforcement of safety procedures remains a significant challenge in Malaysian construction sites.Similarly, the third-ranked variable also recorded a mean score of 4.36 (SD = 0.719), suggesting that respondents perceive effective communication regarding employment-related matters. The role of site

supervisors or team leaders who share the same native language (e.g., Bengali) and are able to communicate effectively in basic or functional Malay is critical in bridging communication gaps between foreign workers and local management. These supervisors often act as intermediaries, translating instructions and facilitating communication between management and workers. As a result, even though many workers may have limited proficiency in Malay, they generally possess a working understanding of commonly used terms and instructions, which supports day-to-day site communication.This finding corroborates previous research by Dainty et al. (2007), which identified language barriers as a major obstacle to safety compliance and operational efficiency in multicultural construction environments.The fourth-ranked variable achieved a mean score of 4.34 (SD = 0.623), indicating that respondents generally perceive fair and appropriate processes during the early stages of employment. Fair recruitment and onboarding practices are essential for building trust and maintaining ethical labour management. Meanwhile, the fifth-ranked variable reported a mean score of 4.33 (SD = 0.662), demonstrating that respondents widely acknowledge the availability of necessary safety resources at the workplace. Ensuring access to safety equipment is a critical aspect of labour management as it helps reduce workplace risks and promotes a safer working environment.

The remaining variables recorded mean scores ranging from 4.10 to 4.38, indicating a generally high level of agreement among respondents regarding the implementation of labour management practices at construction sites. These variables collectively reflect positive perceptions related to workplace safety, fair employment practices, communication between labourers and management, and the provision of welfare facilities. The results suggest that respondents acknowledge the presence labour management systems that support worker protection, productivity, and project performance.

Variables related to safety management, fair treatment, access to welfare facilities, and effective supervision demonstrate consistently high mean scores above 4.20, indicating that these practices are relatively well implemented across the surveyed construction projects. Furthermore, aspects associated with communication, worker rights awareness, grievance handling mechanisms, and training opportunities also received favourable responses, suggesting that labourers generally perceive management efforts to maintain transparent and supportive working conditions.

The findings indicate that providing adequate welfare support, including safe accommodation, fair remuneration, and effective occupational safety measures, is essential for enhancing the well-being of foreign construction workers. These findings are consistent with previous studies that emphasised the importance of welfare provisions in improving worker productivity, job satisfaction, and retention (Olanrewaju et al., 2024). Furthermore, the results support the observations of Zulkeflee et al. (2023), who reported that inadequate safety practices and poor living conditions remain persistent challenges among foreign workers in the Malaysian construction sector.

However, several variables with comparatively lower mean scores, although still above 4.00, indicate potential areas for improvement. These include aspects related to worker participation in decision-making, wage management consistency, and clarity of job explanations. While the overall perception remains positive, enhancing these areas could

further strengthen labour management effectiveness and improve worker satisfaction within the construction sector.

Although the overall mean scores suggest generally positive labour management practices, these findings should be interpreted with caution, as they likely reflect site-specific conditions and may not fully capture the broader challenges within the Malaysian construction industry. The results indicate relatively strong performance in areas such as safety, fair treatment, and structured work management; however, improvements in communication, worker engagement, and employment transparency remain necessary to support more sustainable labour practices and enhance project performance.

## 5. CONCLUSIONS

The findings should be interpreted as reported perceptions of labour management practices within the surveyed sites, shaped by the study context and potential response constraints, rather than as a definitive representation of industry-wide conditions. Overall, respondents perceived labour management practices positively, with most variables recording mean scores above 4.00, indicating a high level of agreement on the presence of structured systems. Key aspects such as task organization, workplace safety, fair recruitment, access to protective equipment, and communication were viewed as important contributors to a well-managed work environment. These perceptions suggest that effective labour management practices may support worker welfare and project performance, although the results should be interpreted with caution.

First, the sample size of 282 respondents may limit the generalizability of the findings, and future research could involve a larger number of participants across more construction projects to obtain broader insights. Second, access to construction sites was challenging, as some project management teams were reluctant to allow survey activities, possibly due to concerns that issues regarding the treatment of foreign labourers might be exposed. Third, foreign labourers may have been hesitant to provide their true perceptions, as supervisors were often present during survey sessions, which could have led respondents to hide their dissatisfaction for fear of losing their jobs or facing wage penalties. While the findings indicate generally positive perceptions, the possibility of response bias due to workers' reluctance to express dissatisfaction should be considered, and thus the results may reflect a more conservative estimate of existing challenges.

The use of online survey tools such as Google Forms was limited because many labourers do not always carry mobile phones or have access to high-speed data. The presence of site supervisors during data collection may have influenced respondents to provide more favourable answers due to perceived workplace hierarchy. Although measures such as anonymity assurance were implemented, this may still have introduced some degree of response bias.

From a practical perspective, the findings highlight the need for construction firms to strengthen communication mechanisms, enhance worker engagement, and improve transparency in employment practices. From a policy standpoint, the results emphasize the importance of enforcing labour standards and strengthening monitoring systems to safeguard foreign worker welfare. Theoretically, this study contributes to the body of knowledge by providing empirical insights into labour management practices within the Malaysian construction context. Future research should adopt broader and more

representative sampling approaches, incorporate qualitative methods for deeper understanding, and utilize independent or anonymous data collection strategies.

## 6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by Universiti Tunku Abdul Rahman (UTAR) under the UTAR Research Fund 2025 through the project IPSR/RMC/UTARRF/2025-C1/S01 and vote number 6565/1S01.

## 7. REFERENCES

Bariono, N.S.E. & Kamaruding, M. (2025). Initiatives to overcome the issues and negative impacts on the involvement of foreign labourers in the Malaysian construction industry. *Jurnal Kejuruteraan*, 37(2), 855–867. https://doi.org/10.17576/jkukm-2025-37(2)-24

Dainty, A., Moore, D., & Murray, M. (2007). *Communication in construction: Theory and practice.* Routledge. https://doi.org/10.4324/9780203358641

Fateh, M. A. M., Arshad, R. A., & Hamzah, F. H. (2021). The unfair welfare practices towards foreign labourers in the Malaysian construction industry. *International Journal of Infrastructure Research and Management, 8*(1), 23–46. https://doi.org/10.63646/j.ijirm.2020.080103

Jamalulil, S.N.N.S., Hussin, S.N., Salleh, N.M., Kamar, I.F.M. & Rizam, K.N. (2022). High dependence on foreign workforce in Malaysian construction industry. *International Journal of Academic Research in Business & Social Sciences*, 12(9), 399–405. https://doi.org/10.6007/ijarbss/v12-i9/14488

Marjuki, M.A. (2018). Exploitation of foreign labourers, obstacles and challenges in the construction sector. *Trends in Undergraduate Research*, 1(1), 55–59. https://doi.org/10.33736/tur.1186.2018

Mazlan, S.N.S., Sarpin, N., Omar, R., Khalid, Z. & Ismayatim, N. (2024). The impact of illegal employment of foreign labourers in construction project: Contractor's perspective. *Research in Management of Technology and Business*, 5(2), 493–502. https://publisher.uthm.edu.my/periodicals/index.php/rmtb/article/view/18137

Nasir, N.H., Haque, M.M. & Awang, M.B. (2023). The challenges in providing adequate housing for migrant labourers in Terengganu, Malaysia. *Malaysian Journal of Social Sciences and Humanities*, 8(4), 1–12. https://doi.org/10.47405/mjssh.v8i4.2265

Najib, I.Z.M., Nordin, R.M., Ahnuar, E.M. & Sukor, K.M. (2019). Malaysian as the component of labour force for the construction industry in Malaysia. IConBEE 2018, Malaysia. https://doi.org/10.1051/matecconf/201926601007

Ne'Matullah, K.F., Pek, L.S. & Roslan, S.A. (2021). Investigating communicative barriers on construction industry productivity in Malaysia: An overview. *International Journal of Evaluation and Research in Education*, 10(2), 476–482. https://doi.org/10.11591/ijere.v10i2.21163

Olanrewaju, A., Sanmargaraja, S., Tan, S.Y. & Chu, H.C. (2024). Evaluation of the benefits of the implementation of digital twins in sustainable construction projects. Proceedings of the 12th *World Construction Symposium*, (pp. 446–457). https://doi.org/10.31705/wcs.2024.35

Putul, S.J. & Mia, M.T. (2018). Exploitation of migrant labourers in Malaysia and protection under domestic laws. In *Proceedings of the International Law Conference (iN-LAC 2018)* (pp. 125–131). https://doi.org/10.5220/0010054801250131

Rizam, K.R., Jamalulil, S.N.N.S., Hussin, S.N., Muhamad, N.H. & Salleh, N.M. (2024). Strategies to lessen dependency on foreign labourers in the Malaysian construction industry. *International Journal of Business and Technology Management*, 6(S1), 422–430. https://mysitasi.mohe.gov.my/journal-website/get-meta-article?artId=2f307c5c-2e94-11f0-8f88-005056b163df&formatted=true

Saari, M. N., Shuib, M. S. & Ajis, M.N. (2024). Navigating policy challenges in Malaysia's construction sector: The governmental dilemma on the issue of foreign labour shortage in Malaysia. *International Journal of Asian Social Science*, 14(12), 437–444. https://doi.org/10.55493/5007.v14i12.5266

Saari, M. N., Shuib, M. S. & Ajis, M.N. (2025). Foreign labor dynamics in Malaysia's construction industry: Policy impacts and economic consequences. *International Journal of Innovative Research and Scientific Studies*, 8(2), 4308–4321. https://doi.org/10.53894/ijirss.v8i2.6304

Sanmargaraja, S., Bandirau, J.R., Olanrewaju, A., Ponniah, V., Mathalamuthu, A.D. & Kanniyapan, G. (2024). Issues on foreign labourers productivity on green buildings in Selangor, Malaysia. Proceedings of the 12th *World Construction Symposium*, (pp. 687–697). https://doi.org/10.31705/WCS.2024.54

Sanmargaraja, S., Olanrewaju, A., Lakhiar, M.T., Lim, C.H., Ponniah, V. & Mathalamuthu, A.D. (2025). Sustainable design criteria for green office buildings. *Malaysian Construction Research Journal*, 45(1), 71–83. https://www.cream.my/data/cms/files/MCRJ%20Volume%2045,%20No_1,%202025.pdf?iframe

Uddin, M.S. & Mohammed, A.A. (2020). Exploration of migrants' social life: A case study on Bangladeshi temporary contract labourers in Malaysia. *International Journal on Human Resources Studies*, 10(1), 186–200. https://doi.org/10.5296/ijhrs.v10i1.16172

Wei, W. M., & Yazdanifard, R. (2015). The review of challenges foreign workers face in construction industry of Malaysia. *Global Journal of Management and Business Research: A Administration and Management*, *15*(4), 13–16. https://journalofbusiness.org/index.php/GJMBR/article/view/1617

Yusop, N., Ismail, N.H., Ismail, W.N.W., Isa, S.S.M., Jenuwa, N. & Ali, S. (2025). Practical strategies for the language barriers of foreign labourers at Malaysian construction sites. *International Journal of Business and Technology Management*, 7(7), 322–334. https://doi.org/10.55057/ijbtm.2025.7.7.25

Zainal, M.H.H., Nor, N.M., Ali, M.F.M., Saliah, S.N.M., Ismail, S.I.H. & Zadawa, A.N. (2023). The need to educate foreign labourers based on the performance factor in a construction project especially in a highly populated area in Johor, Malaysia. *Jurnal Kejuruteraan*, 35(6), 1443–1453. https://doi.org/10.17576/jkukm-2023-35(6)-17

Zakaria, M.A.A. & Zain, F.M.Y. (2021). Issues in foreign labourers management in construction project. *QS Colloquium 2020*, Universiti Teknologi Mara. https://ir.uitm.edu.my/id/eprint/57717/1/57717.pdf

Zulkeflee, A., Faisol, N., Ismail, F., Ismail, N. A. A., & Qurtubi, Q. (2023). Hesitance to change behaviour: key factors of construction foreign workers' safety non-compliances. *Malaysian Construction Research Journal*, 19(2), 35–49. https://pure.hw.ac.uk/ws/portalfiles/portal/107228210/MCRJ_Special_Issue_Volume_19_No_2_2023.pdf

Ogungbe, M.A., Aigbavboa, C.O., Oke, A.E, Ikuabe, M.O., Aregbesola, G.T. and Ogunade, T.V., 2026. Mapping infrastructure finance research in Africa's built environment: A bibliometric review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1136-1149. DOI: https://doi.org/10.31705/WCS.2026.83. Available from: https://ciobwcs.com/papers/

# MAPPING INFRASTRUCTURE FINANCE RESEARCH IN AFRICA'S BUILT ENVIRONMENT: A BIBLIOMETRIC REVIEW

**Mayowa Adedapo Ogungbe[1], Clinton Ohis Aigbavboa[2] Ayodeji Emmanuel Oke[3], Matthew Ikuabe[4], Ganiu Tunde Aregbesola[5] and Toluwanimi Victoria Ogunade[6]**

## *ABSTRACT*

*Infrastructure development plays a critical role in economic growth, urbanisation, and sustainable development across Africa. However, the persistent infrastructure deficit in many African countries has intensified the need for innovative financing mechanisms to support the delivery of built environment projects. Despite increasing scholarly attention to infrastructure financing, the structure, evolution, and knowledge domains of this research area remain fragmented. This study therefore presents a bibliometric review that maps the intellectual landscape of infrastructure finance research in Africa with specific relevance to the built environment and construction sector. Bibliographic data were retrieved from the Elsevier Scopus database, covering peer-reviewed publications on infrastructure financing in Africa. Bibliometric techniques including publication trend analysis, co-authorship networks, country collaboration patterns, keyword co-occurrence mapping, and citation analysis were conducted using VOSviewer and Bibliometrix. The analysis identifies the most influential authors, journals, and institutions contributing to the field, as well as emerging thematic clusters. The findings reveal significant growth in infrastructure finance research over the past decade, with dominant themes centred on public–private partnerships, infrastructure investment gaps, sustainable infrastructure financing, and policy frameworks for infrastructure development. The study also highlights limited cross-regional collaboration within Africa and identifies emerging research areas such as green infrastructure financing and digital infrastructure investment. The study contributes by providing a structured overview of research trends and identifying future research directions for infrastructure financing in Africa's built environment.*

***Keywords:*** *Africa; Built Environment; Infrastructure Finance; PPP; Development.*

---

[1] Dr., Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, ogungbemayowa@yahoo.com
[2] Professor, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, caigbavboa@uj.ac.za
[3] Professor, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, emayok@gmail.com
[4] Senior Lecturer, School of Construction Economics and Management, University of Witwatersrand, Johannesburg, South Africa, ikuabematthew@gmail.com
[5] Dr., Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, aregbesolatunde13@gmail.com
[6] PhD Candidate, Department of Construction Management and Quantity Surveying, University of Johannesburg, South Africa, ogunadetoluwanimi@gmail.com

# 1. INTRODUCTION

Infrastructure development is widely recognised as a fundamental driver of economic growth, urban development, and social welfare. Adequate infrastructure systems including transportation networks, energy supply, water systems, and urban facilities are essential for supporting productive economic activities and improving the quality of life of citizens. In the context of developing economies, particularly in Africa, infrastructure plays a critical role in facilitating regional integration, trade expansion, and sustainable development (Calderón & Servén, 2014; Chuku et al., 2023). However, many African countries continue to face a substantial infrastructure deficit that constrains economic performance and development outcomes.

Historically, infrastructure development across many African countries was largely financed and delivered by the public sector, particularly during the post-independence period of the 1960s and 1970s. Governments assumed primary responsibility for financing and managing infrastructure projects through national budgets and state-owned enterprises. However, economic crises and fiscal constraints in the 1980s and 1990s significantly weakened the capacity of governments to sustain infrastructure investment (Estache, 2010; Kirkpatrick & Smith, 2011). As a result, many countries experienced declining infrastructure quality and growing investment gaps. In response to these challenges, the late 1990s and early 2000s witnessed a global shift toward alternative infrastructure financing mechanisms aimed at mobilising private sector participation in infrastructure development. One of the most prominent approaches was the adoption of Public–Private Partnerships (PPPs), which involve collaborative arrangements between public authorities and private entities for financing, constructing, and operating infrastructure projects. International financial institutions such as the World Bank and the African Development Bank actively promoted PPPs and other innovative financing mechanisms across Africa to address the continent's infrastructure investment gap (Ashiagbor et al., 2018; World Bank, 2017). These efforts coincided with growing academic and policy interest in infrastructure financing models, including project finance, blended finance, and private infrastructure investment.

The urgency of addressing Africa's infrastructure deficit has also been reinforced by continental development initiatives such as the Programme for Infrastructure Development in Africa (PIDA), which was launched in 2012 to support large-scale infrastructure projects across the continent. Despite these initiatives, estimates suggest that Africa requires between US$130 billion and US$170 billion annually to meet its infrastructure needs, while a significant financing gap persists (Mjimba & Muavha, 2021). Consequently, infrastructure financing has become a critical research area attracting increasing scholarly attention from fields such as construction management, infrastructure economics, development studies, and public policy. Over the past two decades, the academic literature on infrastructure finance in Africa has expanded considerably, reflecting growing interest in issues such as infrastructure investment gaps, public–private partnership performance, financing models for large-scale infrastructure projects, and institutional frameworks for infrastructure delivery.

However, despite the growing volume of research on infrastructure financing in Africa, the existing body of knowledge remains highly fragmented across multiple disciplines, including construction management, infrastructure economics, development studies, and public policy. This fragmentation makes it difficult to obtain a coherent understanding of

the intellectual structure of the field, the dominant research themes, and the evolution of scholarly contributions over time. While previous studies have employed narrative or systematic review approaches to examine specific aspects of infrastructure financing, these approaches are often limited in their ability to capture large-scale publication patterns, collaboration networks, and the dynamic development of research themes across a broad and multidisciplinary knowledge base.

Given the rapid expansion and interdisciplinary nature of infrastructure finance research, there is a need for a more robust and quantitative approach that can systematically map the structure and evolution of the field. Bibliometric analysis provides such an approach by enabling the quantitative examination of publication trends, citation relationships, and thematic linkages within a large corpus of academic literature (Donthu et al., 2021). Through techniques such as co-authorship analysis, keyword co-occurrence mapping, and citation network analysis, bibliometric methods offer a comprehensive means of identifying influential studies, emerging research fronts, and knowledge gaps that are not easily discernible through conventional review methods. Therefore, adopting a bibliometric approach is particularly appropriate for synthesising the dispersed and rapidly growing body of literature on infrastructure financing in Africa's built environment.

## 2. METHODOLOGY

This study adopts a bibliometric research design to systematically examine the development and thematic trends of infrastructure finance research in the African context. Bibliometric analysis enables the quantitative evaluation of large volumes of scholarly literature through the analysis of publication patterns, citation relationships, and keyword networks, thereby providing insights into the intellectual structure of a research field (Donthu et al., 2021). Bibliographic data were retrieved exclusively from the Scopus database, which is widely recognized for its broad coverage of high-quality peer-reviewed literature across multidisciplinary fields, including construction management, infrastructure studies, economics, and public policy. Compared to other databases such as Web of Science, Scopus provides a larger journal coverage and includes a wider range of publications relevant to emerging and interdisciplinary research areas, particularly those relating to developing regions such as Africa. Previous bibliometric studies have also demonstrated that Scopus offers more comprehensive coverage for social science and infrastructure-related research, making it particularly suitable for studies aiming to map broad research domains. Furthermore, the use of a single, well-curated database enhances data consistency and reduces the risk of duplication and indexing discrepancies that may arise when combining multiple databases. The structured metadata provided by Scopus is also highly compatible with bibliometric analysis tools such as VOSviewer and the Bibliometrix package in R, thereby facilitating robust network and performance analyses. While the exclusion of other databases may limit the inclusion of some publications, the extensive coverage and data reliability of Scopus ensure that the dataset is sufficiently representative for mapping the intellectual structure and trends of infrastructure finance research in Africa.

The search was conducted using the following query: ("infrastructure finance" OR "infrastructure financing" OR "infrastructure investment" OR "public infrastructure finance" OR "infrastructure funding" OR "project finance" OR "public-private partnership" OR PPP OR "blended finance") AND (Africa OR "Sub-Saharan Africa" OR

"North Africa") AND (infrastructure OR construction OR transport OR energy OR water). The initial search yielded 942 documents. After applying filters for publication period (2000–2025), English language, document type, and subject area, the dataset was reduced to 577 documents, with 365 records removed during the filtering process. Subsequently, title and abstract screening was conducted to ensure relevance to infrastructure finance in Africa, leading to the exclusion of 22 documents. Following the eligibility assessment, 555 articles met the inclusion criteria and were retained for the final analysis. The bibliographic records were exported in CSV format and analysed using VOSviewer and the Bibliometrix package in R. VOSviewer was employed to generate visual network maps for co-authorship, keyword co-occurrence, and source analysis, while Bibliometrix was used to conduct descriptive bibliometric analyses such as annual publication trends. The combination of these tools enabled a comprehensive mapping of the research landscape and thematic evolution of infrastructure finance literature.

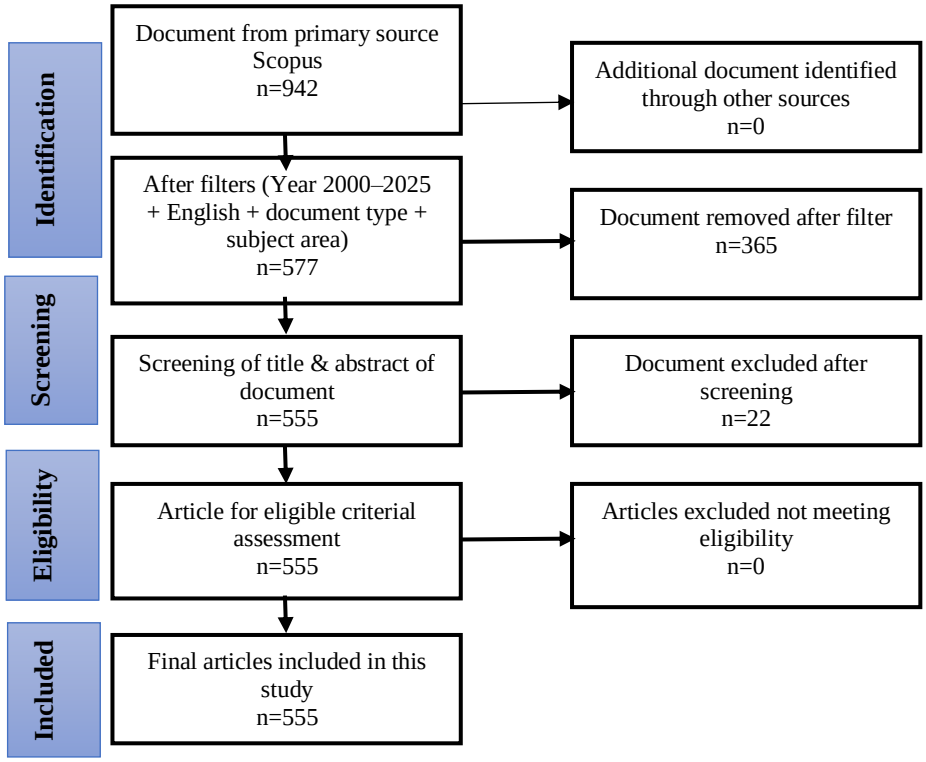



*Figure 1: Study selection results using PRISMA chart*

# 3. RESULT AND DISCUSSION

## 3.1 ANNUAL PUBLICATION TREND OF INFRASTRUCTURE FINANCE RESEARCH IN AFRICA

The annual publication trend as illustrated in figure 2 shows the growth and evolution of scholarly research on infrastructure finance in Africa between 2000 and 2025. The results show that research output in this field remained relatively low and stable during the early years, with fewer than ten publications annually between 2000 and 2008. This period reflects the nascent stage of academic interest in infrastructure finance within the African context, when discussions were largely limited to policy debates on infrastructure

investment and development financing. A gradual increase in publications becomes evident from 2009 to 2015, with the number of studies rising steadily as infrastructure financing gained attention in development discourse. This growth can be associated with increasing global recognition of Africa's infrastructure deficit and the need for innovative financing mechanisms, including public–private partnerships (PPP), project finance, and international development finance. During this period, infrastructure investment was increasingly viewed as a critical driver of economic growth, trade facilitation, and regional integration across African economies.

From 2016 onwards, the field experienced a significant acceleration in research output, indicating a growing scholarly and policy interest in infrastructure finance across the continent. The number of publications increased consistently, reaching approximately 55 publications in 2022, before experiencing a slight decline in 2023, and rising again in 2024. The most notable surge occurs in 2025, where the number of publications reaches the highest level in the dataset, suggesting an expanding research focus on infrastructure financing strategies in Africa. This recent growth may be linked to emerging debates surrounding sustainable infrastructure investment, climate-resilient infrastructure, renewable energy financing, and international development initiatives aimed at addressing Africa's infrastructure financing gap.

Therefore, the upward trajectory of publications demonstrates that infrastructure finance has evolved into a rapidly expanding research domain, reflecting its increasing importance for economic development, urbanisation, and sustainable infrastructure provision across Africa. This rapid growth not only reflects increasing academic interest but also indicates a shift in the research agenda toward addressing complex financing challenges associated with sustainable and climate-resilient infrastructure. The surge in publications after 2016 suggests that infrastructure finance is transitioning from a peripheral topic within development studies to a central research domain with significant implications for policy formulation, investment strategies, and infrastructure governance in Africa.

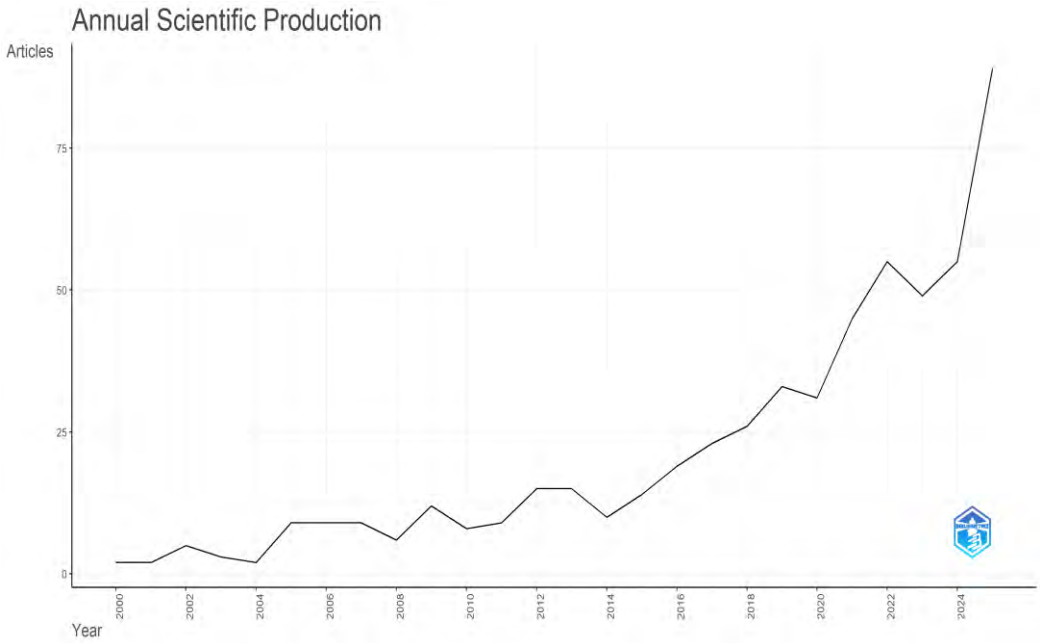



*Figure 2: Annual publication trend*

## 3.2 COUNTRY COLLABORATION NETWORK

The country collaboration network analysis reveals the extent of international research partnerships in infrastructure finance research related to Africa. The VOSviewer visualization in Figure 3 indicates that South Africa emerges as the most central and influential node, suggesting that it plays a dominant role in scholarly collaborations within the field. The prominence of South Africa reflects its relatively advanced research infrastructure, strong academic institutions, and its position as a regional hub for infrastructure development and financing initiatives in Africa. Closely connected to South Africa are major research contributors such as the United States, China, and the United Kingdom, indicating significant cross-continental collaboration in infrastructure finance studies. The presence of these countries highlights the global interest in infrastructure development across Africa, particularly given the role of international financial institutions, development banks, and foreign investment in supporting infrastructure projects on the continent. The network also reveals several collaboration clusters, indicating thematic and regional partnerships among countries. One cluster shows strong linkages between China, Nigeria, Japan, Canada, and the Russian Federation, reflecting the increasing involvement of Asian and emerging economies in infrastructure financing across Africa. Another cluster includes European countries such as Germany, Belgium, Italy, and Spain, which are connected to African countries like Rwanda, Zambia, and Tanzania, suggesting collaboration driven by development cooperation programs and international infrastructure investment initiatives. Additionally, a cluster involving Australia, Ghana, Hong Kong, and Sweden indicates research collaborations related to infrastructure investment and development finance in emerging economies.

Despite the presence of several international partnerships, the network structure suggests that collaboration intensity among African countries themselves remains relatively limited, with most connections occurring between African countries and developed economies. This pattern highlights the continued reliance on external expertise and funding sources in infrastructure finance research and practice across Africa. Strengthening intra-African research collaboration could therefore enhance knowledge exchange, improve context-specific solutions, and support more sustainable infrastructure financing strategies within the continent.

This pattern of externally driven collaboration implies that knowledge production in infrastructure finance is still heavily influenced by global North institutions, which may limit the development of context-specific financing solutions tailored to African realities. Strengthening intra-African collaboration is therefore not only a research necessity but also a strategic requirement for enhancing locally grounded infrastructure financing models.

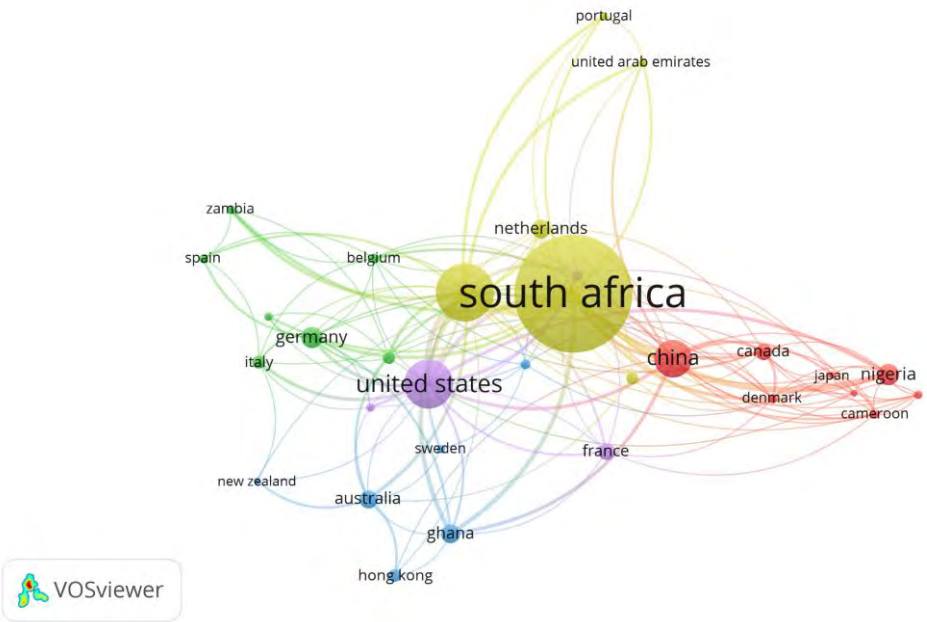



*Figure 3: Country collaboration network map*

## 3.3 KEYWORD CO-OCCURRENCE MAP

The keyword co-occurrence analysis was conducted using VOSviewer to identify the major research themes and emerging topics within the infrastructure finance literature related to Africa. A threshold of a minimum of 5 number of occurrences was set, while the default threshold of VOSviewer is 5. Thus, the implication of this is that the choice of the extraction of a particular keyword is dependent on the minimum of 5 occurrences. As shown in Table 1, the analysis produced 38 keywords grouped into seven clusters, indicating the main thematic areas that have shaped scholarly discussions in this field. The table shows that "public–private partnerships," "Africa," "sub-Saharan Africa," and "infrastructure finance" are among the most prominent and frequently occurring keywords, highlighting the central role of PPP arrangements in financing infrastructure development across the African continent. The strong linkages between these keywords suggest that much of the existing literature focuses on the role of collaborative financing mechanisms between the public and private sectors in addressing Africa's infrastructure deficit.

**Cluster 1- PPP Governance and Infrastructure Service Delivery**

Cluster 1 reflects themes related to PPP governance and infrastructure service delivery, including keywords such as governance, privatization, sustainability, water, Ghana, Africa, and Nigeria. The prominence of governance-related keywords suggests that the literature increasingly recognises the importance of institutional quality, regulatory frameworks, and public-sector capacity in infrastructure financing and delivery. Previous studies have shown that effective governance structures, transparent procurement systems, and institutional accountability are critical to the success of PPP infrastructure projects, particularly in developing economies (World Bank, 2017).

**Cluster 2- Sustainable Infrastructure and Energy-related Development**

Cluster 2 focuses on sustainable infrastructure and energy-related development, with keywords such as renewable energy, sustainable development, electricity, transportation, and poverty. This suggests that infrastructure finance research increasingly intersects with broader sustainable development goals, particularly in sectors critical to economic growth and poverty reduction in African economies. Existing studies have similarly highlighted the importance of sustainable infrastructure investment in promoting economic resilience, energy access, and inclusive development in emerging economies (Bhattacharya et al., 2015; Sachs et al., 2019).

**Cluster 3- Project Finance and Private Sector Participation**

Cluster 3 represents research addressing project finance and private sector participation, including keywords such as project finance, private sector, developing countries, and critical success factors. This indicates the importance of financial structuring and stakeholder involvement in ensuring the successful implementation of infrastructure projects. Prior research has emphasised that private sector participation can improve infrastructure delivery through enhanced access to finance, managerial expertise, and technological innovation (Aigbavboa et al., 2017).

**Cluster 4- Geopolitical and Investment Dynamics**

Cluster 4 highlights geopolitical and investment dynamics, particularly the growing role of emerging economies, as reflected in keywords such as China, BRICS, East Africa, and infrastructure investment. This cluster reflects the increasing influence of international partnerships and foreign investment in financing infrastructure across Africa. Existing literature has shown that China has become a major infrastructure financier across Africa through bilateral agreements and strategic investment initiatives such as the Belt and Road Initiative (Babones et al., 2020).

**Cluster 5- Urbanisation and Environmental Challenges**

Cluster 5 emphasises urbanisation and environmental challenges, with keywords including climate change, urbanization, global south, and infrastructure. This suggests that recent research increasingly addresses the intersection between infrastructure financing and urban sustainability challenges in developing regions. Rapid urbanisation across Africa has intensified pressure on transportation, housing, water, and energy infrastructure systems, thereby increasing the demand for sustainable and climate-resilient infrastructure investments (Kirkpatrick & Smith, 2011).

**Cluster 6- Infrastructure Finance and the Belt and Road Initiative (BRI)**

Cluster 6 capture emerging topic such as "infrastructure finance" and the Belt and Road Initiative (BRI). This cluster highlights the role of China's Belt and Road Initiative in shaping infrastructure finance dynamics in Africa. Existing studies have noted that the BRI has contributed significantly to infrastructure investment across transportation, energy, and logistics sectors in developing economies (Babones et al., 2020).

**Cluster 7- Development and Rural Development**

Cluster 7 capture development and rural development, indicating growing interest in rural infrastructure and inclusive development strategies. Rural infrastructure has been widely recognised as essential for improving agricultural productivity, market accessibility, poverty reduction, and regional economic integration in developing economies (Lenz et al., 2017).

*Table 1: Keyword clusters and quantitative strength*

| Cluster | Theme | No. of Keywords | Representative Keywords | Quantitative Strength |
|---|---|---|---|---|
| Cluster 1 | PPP Governance and Infrastructure Service Delivery | 10 | Africa, governance, Nigeria, Ghana, water, PPP, sustainability, sub-saharan Africa, privatization | Largest cluster dominant theme |
| Cluster 2 | Sustainable Infrastructure and Energy | 8 | economic growth, electricity, renewable energy, Ethiopia, poverty, sustainable development, transportation, Zambia | High frequency cluster |
| Cluster 3 | Project Finance and Private Sector | 6 | project finance, private sector, construction industry, critical success factors, developing countries, Kenya | Moderate cluster strength |
| Cluster 4 | Geopolitical Investment Dynamics | 5 | China, BRICS, infrastructure investment, East Africa, infrastructure development | Emerging but influential |
| Cluster 5 | Urbanisation and Environmental Challenges | 5 | climate change, urbanization, global south, infrastructure, South Africa | Moderate strength |
| Cluster 6 | Infrastructure Finance and BRI | 2 | BRI, infrastructure finance | Emerging (low frequency) |
| Cluster 7 | Development and Rural Development | 2 | rural development, development | Least developed cluster |

The identification of these thematic clusters provides important academic and practical insights into the structure and evolution of infrastructure finance research in Africa. From an academic perspective, the clustering reveals that the field is not monolithic but is organised around interconnected domains of governance, sustainability, financial structuring, and geopolitical investment dynamics. This contributes to the literature by offering a structured understanding of how infrastructure finance research has evolved across disciplinary boundaries and by highlighting emerging areas such as climate-related infrastructure financing and sustainability-oriented investment models. From a practical and policy perspective, the findings suggest several critical priorities. The dominance of PPP-related research underscores the need for policymakers to strengthen institutional and regulatory frameworks to enhance the effectiveness of PPP arrangements. The growing emphasis on sustainable infrastructure and renewable energy financing highlights the importance of integrating environmental considerations into infrastructure investment decisions. Additionally, the prominence of international investment and geopolitical themes indicates the need for African countries to develop strategic frameworks that balance foreign investment opportunities with long-term economic sustainability and financial independence. Finally, the emerging focus on rural and

inclusive development suggests that infrastructure financing strategies must extend beyond urban centres to support equitable development across the continent.

These findings provide important insights into the infrastructure financing challenges highlighted in the introduction. The dominance of PPP-related themes confirms that collaborative financing mechanisms have become central to addressing Africa's infrastructure deficit. However, the strong emphasis on governance and institutional factors suggests that many of the persistent challenges in infrastructure delivery are rooted in regulatory inefficiencies and weak institutional capacity rather than purely financial constraints. Similarly, the increasing focus on sustainability and climate-related infrastructure reflects a shift in response to emerging global and regional challenges, including climate vulnerability and the need for resilient infrastructure systems. Despite these advances, the limited representation of intra-African collaboration and locally driven financing models in the literature indicates a critical gap in developing context-specific solutions to Africa's infrastructure financing needs.

## 3.4 MOST INFLUENTIAL JOURNALS/DOCUMENTS

The analysis of publication sources reveals that research on infrastructure finance in Africa is distributed across journals in development economics, infrastructure policy, sustainability, and sector-specific infrastructure studies. Table 2 presents the most influential journal within the dataset, highlighting representative publications and their contribution to the literature. The classification of "most influential" journals in this study is based primarily on the number of publications within the dataset, which reflects the productivity and contribution of each source to the field. Journals with higher publication counts are considered more influential in shaping the development of infrastructure finance research in Africa. While citation-based metrics are commonly used to assess impact, this study emphasises source productivity due to the objective of mapping the structure and evolution of the research domain. Representative documents were selected from these journals to illustrate key thematic contributions and are included based on their relevance to the identified research clusters rather than citation ranking alone.

Among these, World Development emerges as the most influential outlet, with eight publications in the dataset. A notable example is the study by Lenz et al. (2017) titled "Does Large-Scale Infrastructure Investment Alleviate Poverty? Impacts of Rwanda's Electricity Access Roll-Out Program," which examines the socio-economic effects of infrastructure investment on poverty reduction in Rwanda. The prominence of this journal underscores the strong linkage between infrastructure finance and broader development outcomes in African economies.

Similarly, the Journal of Infrastructure, Policy and Development and Development Southern Africa each contributed seven publications, indicating their relevance in discussions surrounding infrastructure financing and regional economic development. For instance, Wang and Xu (2023) explore issues of debt sustainability and infrastructure financing in Africa, particularly in relation to China–Africa infrastructure cooperation. Meanwhile, Ngepah et al. (2023) investigate the employment impacts of freight infrastructure investment in South Africa, highlighting the economic benefits associated with infrastructure development. These studies demonstrate the importance of infrastructure investment not only as a financing issue but also as a driver of employment and economic growth.

Other notable outlets include ENR (Engineering News-Record) and Water SA, each with six publications in the dataset. These journals provide sector-specific insights into infrastructure markets and service delivery. For example, Ruiters and Matji (2016) propose a conceptual framework for financing water services infrastructure in South Africa through public–private partnerships, reflecting the growing emphasis on PPP models for infrastructure delivery. Likewise, Sustainability (Switzerland) contributes six publications, including Chaitarin et al. (2025), which investigates the relationship between transport infrastructure and trade flows, reflecting the increasing integration of sustainability and infrastructure financing debates.

The dataset also highlights the contributions of regionally focused journals such as the South African Journal of Economics, which includes influential studies such as Perkins et al. (2005) on economic infrastructure investment in South Africa. In addition, conference proceedings such as the Proceedings of the International Conference on Industrial Engineering and Operations Management feature research examining PPP financing models for transit-oriented development in South Africa (Aigbavboa et al., 2017). Journals such as Global Policy and Energy for Sustainable Development further contribute to the discourse by addressing the role of international development finance and governance risks in infrastructure investment across Sub-Saharan Africa (Babones et al., 2020; Falchetta et al., 2021).

Therefore, the distribution of publication sources indicates that infrastructure finance research in Africa is highly interdisciplinary, spanning development economics, infrastructure policy, sustainability, and sector-specific studies such as energy, transport, and water infrastructure. The presence of both international development journals and regionally focused outlets reflects the growing academic and policy interest in addressing Africa's infrastructure financing gap through innovative financing mechanisms, public–private partnerships, and international investment collaborations.

*Table 2: Top sources of infrastructure finance research in Africa*

| Journal | Paper Title | Authors/Year | Number of Publications within the dataset |
|---|---|---|---|
| World Development | Does Large-Scale Infrastructure Investment Alleviate Poverty? Impacts of Rwanda's Electricity Access Roll-Out Program | Lenz et al. (2017) | 8 |
| Journal of Infrastructure, Policy and Development | China and Africa: A new narrative on debt sustainability and infrastructure financing | Wang and Xu (2023) | 7 |
| Development Southern Africa | The impact of freight infrastructure investment on employment in South Africa | Ngepah et al. (2023) | 7 |

| Journal | Paper Title | Authors/Year | Number of Publications within the dataset |
|---|---|---|---|
| ENR (Engineering News-Record) | European, U.S. firms still dominate Africa infrastructure market | Oirere (2013) | 6 |
| Water SA | Public–private partnership conceptual framework for financing water services infrastructure in South Africa | Ruiters and Matji (2016) | 6 |
| Sustainability (Switzerland) | When Does Air Transport Infrastructure and Trade Flows Matter? | Chaitarin et al. (2025) | 6 |
| South African Journal of Economics | An analysis of economic infrastructure investment in South Africa | Perkins et al. (2005) | 5 |
| Proceedings of the International Conference on Industrial Engineering and Operations Management | Public–private partnerships: An effective finance model for transit-oriented development in South Africa? | Ndebele et al. (2017) | 5 |
| Global Policy | China's Role in Global Development Finance: China Challenge or Business as Usual? | Babones et al. (2020) | 5 |
| Energy for Sustainable Development | The role of regulatory, market and governance risk for electricity access investment in Sub-Saharan Africa | Falchetta et al. (2021) | 5 |

# 4. KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS

The findings of this study reveal several key gaps in the literature on infrastructure finance in Africa. First, although public–private partnerships (PPP) dominate the research landscape, there is limited focus on context-specific financing models tailored to African institutional and socio-economic conditions. Second, while governance emerges as a central theme, there is insufficient empirical evidence on how institutional capacity and regulatory frameworks influence infrastructure financing outcomes. Third, the analysis shows limited collaboration among African countries, indicating a gap in regionally driven knowledge production and context-specific solutions. Fourth, although there is growing attention to sustainable and climate-resilient infrastructure, research on the practical implementation and financing of green infrastructure in Africa remains underdeveloped. Finally, emerging areas such as rural infrastructure development and inclusive financing strategies are relatively underexplored.

Future research should focus on strengthening context-specific financing models and enhancing intra-African research and policy collaboration, as current literature remains limited in addressing locally driven and institutionally grounded solutions to Africa's infrastructure financing challenges. The study is limited to Scopus-indexed publications and does not include grey literature from institutions such as the World Bank and African Development Bank. As these organisations produce significant policy and practice-oriented reports on infrastructure financing in Africa, their exclusion may limit the comprehensiveness of the findings. Future studies could incorporate such sources to provide a more holistic perspective.

## 5. CONCLUSIONS

This study presents a bibliometric mapping of infrastructure finance research in Africa based on publications indexed in the Scopus database between 2000 and 2025. The findings reveal a rapidly growing and interdisciplinary body of literature, reflecting the increasing importance of infrastructure financing in addressing Africa's infrastructure deficit. The results show that research in this field is largely structured around themes such as public–private partnerships (PPP), sustainable infrastructure development, and international investment dynamics. While PPPs dominate the literature as a key financing mechanism, the prominence of governance-related themes indicates that infrastructure financing challenges in Africa are not only financial but also institutional in nature. The collaboration analysis further reveals strong global partnerships but limited intra-African collaboration, suggesting a gap in context-specific knowledge development. These findings contribute to the literature by providing a structured overview of the intellectual landscape of infrastructure finance research in Africa and highlighting emerging areas such as sustainability and climate-resilient infrastructure. From a practical perspective, the results underscore the need for stronger institutional frameworks, increased regional collaboration, and more locally grounded financing strategies to effectively address Africa's infrastructure challenges. Overall, the study bridges the gap between the identified infrastructure financing challenges and existing research by showing how current scholarly efforts align with, and in some cases overlook, critical areas necessary for sustainable infrastructure development in Africa.

## 6. ACKNOWLEDGEMENTS

Special thanks to the University of Johannesburg, the SARChI Chair in Sustainable Construction Management and Leadership in the Built Environment, and the Director, Professor Clinton Aigbavboa, for their invaluable support and leadership.

## 7. REFERENCES

Aigbavboa, C., Ndebele, R., & Ogra, A. (2017). Public Private Partnerships (PPPs): an effective and legitimate finance model for TOD in South Africa? *In 7th Annual International Conference on Industrial Engineering and Operations Management*. https://doi.org/10.46254/AN07.20170450

Ashiagbor, D., Deiana, R., Kappeler, A., Minsat, A. and Nguyen-Quoc, T. (2018), "Financing infrastructure in Africa", Banking in Africa: Delivering on Financial Inclusion, Supporting Financial Stability, 4th ed., European Investment Bank, pp. 201–224.

Babones, S., Åberg, J. H. S., & Hodzi, O. (2020). China's role in global development finance: China challenge or business as usual? *Global Policy*, *11*(3), 326-335. https://doi.org/10.1111/1758-5899.12802

Bhattacharya, A., Oppenheim, J., & Stern, N. (2015). Driving sustainable development through better infrastructure: key elements of a transformation program. Global Economy and Development, 1–38. https://www.brookings.edu/wp-content/uploads/2016/07/07-sustainable-development-infrastructure-v2.pdf.

Calderón, C., & Servén, L. (2014). Infrastructure, Growth, and Inequality An overview. In *World Bank Group* (pp. 6526–6534). World Bank Group. https://openknowledge.worldbank.org/server/api/core/bitstreams/602e2fd1-8047-526a-a195-21cb8742fc97/content

Chaitarin, W., Maneejuk, P., Sriboonchitta, S., & Yamaka, W. (2025). When does air transport infrastructure and trade flows matter? Threshold effects on economic growth in ASEAN countries. *Sustainability (Switzerland)*, *17*(16), Article 7406. https://doi.org/10.3390/su17167406

Chuku, C., Simpasa, A., & Ekpo, A. (2023). Catalysing regional integration in Africa: The role of infrastructure. *World Economy*, *46*(2), 472-495. https://doi.org/10.1111/twec.13364

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285-296. https://doi.org/https://doi.org/10.1016/j.jbusres.2021.04.070

Estache, A. (2010). Infrastructure finance in developing countries: An overview. *EIB Papers*, *15*(2), 60-88.

Falchetta, G., Dagnachew, A. G., Hof, A. F., & Milne, D. J. (2021). The role of regulatory, market and governance risk for electricity access investment in sub-Saharan Africa. *Energy for Sustainable Development*, *62*, 136-150. https://doi.org/10.1016/j.esd.2021.04.002

Kirkpatrick, L. O., & Smith, M. P. (2011). The infrastructural limits to growth: Rethinking the urban growth machine in times of fiscal crisis. *International Journal of Urban and Regional Research*, *35*(3), 477-503. https://doi.org/https://doi.org/10.1111/j.1468-2427.2011.01058.x

Lenz, L., Munyehirwe, A., Peters, J., & Sievert, M. (2017). Does large scale infrastructure investment alleviate poverty? Impacts of Rwanda's electricity access roll-out program. *World Development*, *89*, 88-110. https://doi.org/10.1016/j.worlddev.2016.08.003

Mjimba, V., & Muavha, A. (2021). 'Good'Aid Conditionality for the African Continental Free Trade Area. *Africa Insight*, *51*(2-3), 53-68.

Ngepah, N., Nkosi, P. N., Mouteyica, A. E. N., & Saba, C. S. (2023). The impact of freight infrastructure investment on employment in South Africa. *Development Southern Africa*, *40*(1), 133-151. https://doi.org/10.1080/0376835X.2021.1980374

Oirere, S. (2013). European, U.S. Firms still dominate africa infrastructure market. *ENR (Engineering News-Record)*, *271*(26). https://www.scopus.com/inward/record.uri?eid=2-s2.0-84892426848&partnerID=40&md5=51e3799b3bfc337a3ee475d57dd003a5

Perkins, P., Fedderke, J., & Luiz, J. (2005). An analysis of economic infrastructure investment in South Africa. *South African Journal of Economics*, *73*(2), 211-228. https://doi.org/10.1111/j.1813-6982.2005.00014.x

Ruiters, C., & Matji, M. P. (2016). Public–private partnership conceptual framework and models for the funding and financing of water services infrastructure in municipalities from selected provinces in South Africa. *Water SA*, *42*(2), 291-305. https://doi.org/10.4314/wsa.v42i2.13

Sachs, J. D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., & Rockström, J. (2019). Six Transformations to achieve the Sustainable Development Goals. *Nature Sustainability*, *2*(9), 805-814. https://doi.org/10.1038/s41893-019-0352-9

Wang, Y., & Xu, Y. (2023). China and Africa: A new narrative on debt sustainability and infrastructure financing. *Journal of Infrastructure, Policy and Development*, *7*(1), Article 2181. https://doi.org/10.24294/jipd.v7i1.2181

World Bank, G. (2017). *World development report 2017: Governance and the law*. World Bank Publications. https://www.worldbank.org/en/publication/wdr2017

Madhushani, S.J.L., Ranadewa, K.A.T.O. and Perera B.A.K.S., 2026. Maritime infrastructure impacts on marine socio-ecological systems: A literature review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1150-1165. DOI: https://doi.org/10.31705/WCS.2026.84. Available from: https://ciobwcs.com/papers/

# MARITIME INFRASTRUCTURE IMPACTS ON MARINE SOCIO-ECOLOGICAL SYSTEMS: A LITERATURE REVIEW

**S.J.L. Madhushani[1], K.A.T.O. Ranadewa[2], and B.A.K.S. Perera[3]**

## *ABSTRACT*

*Maritime infrastructure plays a pivotal role in supporting economic development, energy transition, and global maritime connectivity. However, its interactions with Marine Socio-Ecological Systems (MSES) are complex and multifaceted. While previous studies have examined ecological or socio-economic impacts in isolation, there is a paucity of research integrating these impacts within the broader context of MSES. This study addresses this gap through a comprehensive literature review and synthesis of empirical and theoretical studies on maritime infrastructure. Findings indicate that maritime infrastructure provides numerous positive impacts on MSES, including enhanced biodiversity, fisheries productivity, habitat complexity, renewable energy generation, coastal protection, and socio-economic resilience. Simultaneously, it generates negative impacts, including habitat loss, ecological fragmentation, disruption of major ecological processes, pollution, and reduced adaptive capacity of coastal communities. The study underscores the need for integrated, nature-inclusive design and governance strategies to balance economic development with ecological sustainability, thereby ensuring the long-term resilience and multifunctionality of MSES.*

***Keywords:*** *Marine Socio-ecological Systems; Maritime Infrastructure; Negative Impacts; Positive Impacts.*

## 1. INTRODUCTION

It is well recognised that human well-being and economic development are fundamentally dependent on natural ecosystems (Heslinga et al., 2017). Many studies highlight that humans constantly rely on natural systems, emphasising the concept of 'humans-in-nature' (Petrosillo et al., 2015). However, human activities are increasingly transforming natural ecosystems in complex and uncertain ways (Fischer et al., 2015), resulting in multiple environmental problems, including biodiversity loss and resource depletion. Solving such issues requires integrated perspectives that move beyond traditional disciplinary boundaries (Virapongse et al., 2016). Hence, the concept of Socio-Ecological Systems (SES) has emerged to understand the dynamic relationships between humans and nature (Heslinga et al., 2017). SES refers to interconnected systems in which

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, madhushanisjl.20@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, tharushar@uom.lk
[3] Senior Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk

ecological and social components interact through feedback mechanisms across multiple spatial and temporal scales (Fischer et al., 2015; Virapongse et al., 2016). The ecological component of SES provides essential ecosystem services, including food, energy, water, and raw materials that support humans (Heslinga et al., 2017). On the other hand, human activities influence ecological processes through resource extraction and other anthropogenic pressures (Virapongse et al., 2016). Understanding these interdependencies is therefore essential. Consequently, the SES perspective has been explored in multiple fields, including environmental management (Smith et al., 2025), climate change (Kanan & Giupponi, 2024), marine systems (Lazzari et al., 2026), and agriculture (Salazar-Gálvez et al., 2026). Among these, oceans and marine environments represent one of the most complex socio-ecological systems on the planet (Bugnot et al., 2020). Oceans constitute the largest ecosystem on Earth (Spanier & Kuenzer, 2024). They support diverse biological communities while providing critical ecosystem services (Hryshyna et al., 2021). However, growing anthropogenic pressures place significant stress on marine ecosystems (Banihabib & Assadi, 2023). Thus, MSES have become a central global concern (Glaser & Glaeser, 2014). MSES involves complex interactions between ecological components such as marine habitats and oceanographic processes, and social components including coastal communities and institutions, and economic activities (Ferrol-Schulte et al., 2013; Refulio-Coronado et al., 2021). MSES are influenced by a plethora of ocean-based activities (Villasante et al., 2013), including fisheries, marine tourism, coastal development, marine renewable energy, and marine biotechnology (Bugnot et al., 2020). Among these, maritime infrastructure plays a significant role within the domain of marine and coastal development (Li et al., 2022).

Maritime infrastructure forms a critical component of global maritime development (Zimmerhackel et al., 2023). It encompasses diverse infrastructure types, including ports and harbours, offshore energy infrastructure, coastal defence structures, artificial islands, pipelines, aquaculture facilities, and undersea cables, each characterised by distinct features (Hryshyna et al., 2021; Li & Li, 2007). These infrastructures are considered major enablers that facilitate international trade, support maritime transportation networks, enable offshore industries, and contribute to coastal economic growth (Hooper et al., 2021). Prior studies have consistently emphasised offshore energy infrastructure (offshore wind farms and offshore oil and gas platforms), ports and harbours, and coastal defence infrastructure (seawalls and breakwaters) as significant infrastructure types generating multiple impacts (Allen & Moore, 2016; Banihabib & Assadi, 2023; Dafforn et al., 2015; Marnot, 2025; Watson et al., 2024). Therefore, in the present study, maritime infrastructure primarily refers to these three infrastructure categories. Notably, the development of such infrastructure produces both positive and negative ecological and social impacts on MSES (Airoldi & Bulleri, 2011). Although a growing body of literature has examined MSES (Berkes, 2011; Glaser & Glaeser, 2014; Villasante et al., 2013), studies often focus on specific sectors or isolated environmental impacts. Moreover, seminal studies by Bugnot et al. (2020) primarily focused on mapping the current and projected global extent of marine built structures and assessing their broad seascape-scale ecological modifications and physical footprints. Similarly, Bulleri and Chapman (2010) explored primarily on the ecological consequences of coastal urban infrastructure, particularly artificial shoreline structures, with emphasis on habitat alteration, biodiversity impacts, and ecological engineering approaches. Consequently, the broader implications of maritime infrastructure within the domain of MSES remain insufficiently explored. Therefore, this study aims to contribute to the existing literature by examining

the impacts of maritime infrastructure on MSES through two objectives. These are: (i) to identify the positive impacts of maritime infrastructure on MSES, and (ii) to identify the negative impacts of maritime infrastructure on MSES. The paper's underlying sections include the literature review, methodology, research findings, discussion, and conclusions.

# 2. LITERATURE REVIEW

## 2.1 MARINE SOCIO-ECOLOGICAL SYSTEMS

Tropical marine environments have supported human communities for centuries (Berkes, 2011). The concept of MSES has therefore emerged to understand the multidimensional relationships between people and marine ecosystems (Ferrol-Schulte et al., 2013). As illustrated in Figure 1, MSES consists of interconnected social and ecological components linked through multiple interactions and feedback mechanisms (Elegbede et al., 2023; Villasante et al., 2013). These interactions include resource use, governance decisions, technological interventions, and ecological responses that operate across different spatial and temporal scales (Ellis et al., 2025).

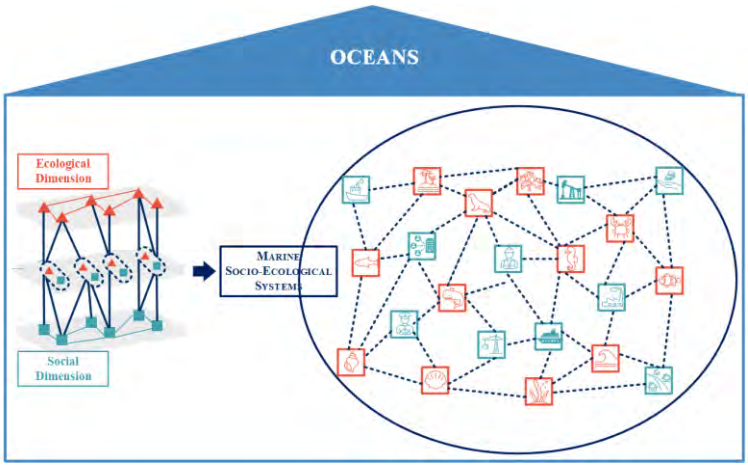



*Figure 1: Marine socio-ecological systems*

As presented in Figure 1, in MSES, ecological conditions influence human livelihoods, while human activities simultaneously influence ecological structures (Berkes, 2011). However, increasing anthropogenic pressures, including overfishing, habitat destruction, and pollution, disrupt the balance between ecological integrity and human use (Berkes, 2011). MSES are, therefore, characterised by high levels of complexity, uncertainty, and vulnerability (Coronado et al., 2021). Thus, effective governance mechanisms and management frameworks play a critical role in securing the overall functioning of MSES (Glaser & Glaeser, 2014). Within the broader spectrum of components and frameworks affecting MSES, maritime infrastructure has emerged as a key driver influencing the MSES (Spanier & Kuenzer, 2024).

## 2.2 MARITIME INFRASTRUCTURE

Maritime infrastructure is generally considered the most prominent anthropogenic modification to the global seascape (Hofstede & Koningsveld, 2024). They refer to the engineering structures and facilities located in marine environments (Hryshyna et al., 2021; Li & Li, 2007). Given the diversity of maritime activities, maritime infrastructure

encompasses a wide range of structural forms and functional purposes (Abdolpour & Marut, 2025). Scholars have therefore categorised maritime infrastructure from several perspectives. One common classification is based on location, distinguishing infrastructure situated in coastal, nearshore, offshore, and inland waterway environments (Amaechi et al., 2022; Gourvenec, 2018; Li & Li, 2007). Another widely used approach categorises infrastructure according to the functional applications, such as maritime transportation, offshore energy, fisheries, tourism, and coastal protection (Banihabib & Assadi, 2023; Marnot, 2025). From an engineering perspective, maritime infrastructure can be classified as fixed, floating, and submerged structures (Mohapatra, 2022). In the context of MSES, maritime infrastructure represents a critical physical link between human activities and marine ecosystems (Bugnot et al., 2020). On one hand, maritime infrastructure supports maritime industries and livelihoods (Whoriskey et al., 2021). On the other hand, the construction and operation of maritime infrastructure can significantly alter marine environments (Airoldi & Bulleri, 2011). Thus, it is noteworthy to explore the potential impacts of maritime infrastructure on MSES.

## 3. RESEARCH METHODOLOGY

A comprehensive literature review is critical for strengthening any research as it critically examines existing knowledge, identifies gaps, and establishes a robust foundation for new contributions (Neubert, 2026). Standalone literature reviews consolidate fragmented findings and develop an integrated perspective (Taherdoost, 2023). Among diverse approaches, narrative literature reviews focus on the critical synthesis of existing studies to develop a coherent understanding of the subject (Sukhera, 2022). Narrative reviews are particularly valuable when the research domain consists of diverse perspectives, heterogeneous evidence, and fragmented relationships that require in-depth conceptual interpretation (Usman et al., 2025). Unlike bibliometric analysis, which primarily emphasises publication patterns and citation structures, or systematic review approaches such as PRISMA, the narrative literature review approach enables a more flexible and holistic exploration of research domain (Belter, 2015; Mishra & Mishra, 2023). Given the interdisciplinary nature of the research topic, existing studies are highly fragmented across environmental science, marine ecology, coastal engineering, maritime development, and socio-economic research domains. Consequently, an in-depth qualitative content analysis and interpretive synthesis are necessary to comprehensively examine the diverse perspectives reported across the literature. Therefore, this study adopts a narrative literature review approach to examine the impacts of maritime infrastructure on MSES. Literature was collected from databases, including Google Scholar, Scopus, and Web of Science. These databases were selected for their comprehensive coverage of multidisciplinary, peer-reviewed literature, ensuring the inclusion of both ecological and socio-economic perspectives (Martín-Martín et al., 2018). Three groups of keywords were identified and combined using Boolean logic appropriate to each database: (i) maritime infrastructure-related terms, (ii) MSES concepts, and (iii) impact-related terms. Accordingly, the key search terms included: ("maritime infrastructure" OR "marine infrastructure" OR "offshore infrastructure" OR "coastal infrastructure") AND ("marine socio-ecological systems" OR "socio-ecological systems" OR "MSES" OR "SES") AND ("impact" OR "effect" OR "benefit" OR "risk" OR "positive" OR "negative" OR "challenge" OR "pressure" OR "trade-off"). Figure 2 presents the research process of the present study.

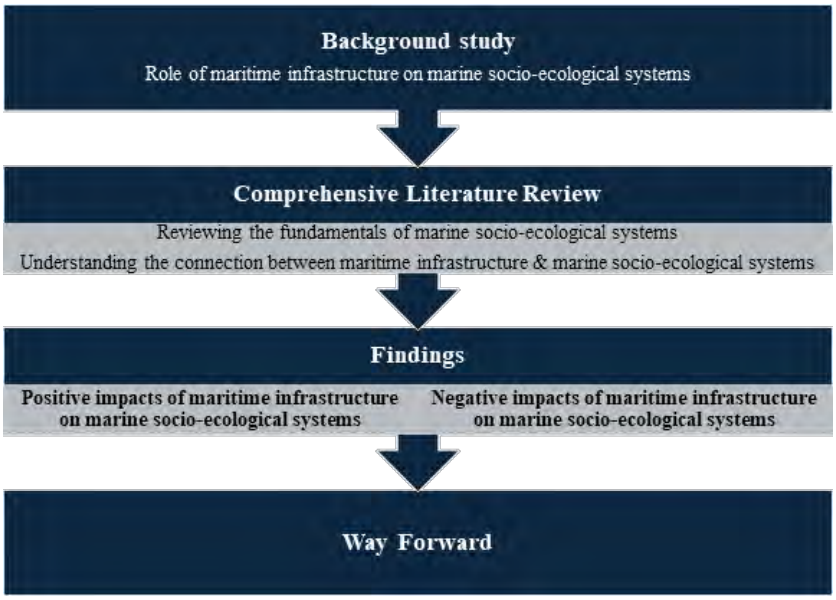



*Figure 2: Research process*

Accordingly, a background study was conducted to understand the role and impacts of maritime infrastructure on MSES. This was followed by a comprehensive literature review of maritime infrastructure and MSES. Data analysis was conducted using manual content analysis, chosen for its ability to sensitively accommodate diverse literature (Anastasiei & Georgescu, 2020). Manual coding was employed to categorise the data into key themes and sub-themes, allowing for a comprehensive understanding of the multidimensional impacts of maritime infrastructure on MSES. Initially, relevant literature extracts were carefully reviewed and segmented to identify recurring concepts and patterns (Vollstedt & Rezat, 2019). These initial codes were then progressively compared and grouped based on conceptual similarity, allowing higher-order categories to emerge through iterative refinement, ensuring broader analytical structures aligned with the research objectives (Williams & Moser, 2019). A three-level coding structure was subsequently developed and applied to enhance clarity, and consistency. Accordingly, Level 1 distinguished the overarching systems as the social system and ecological system. Level 2 classified the direction of impacts into positive and negative impacts. Level 3 further refined the analysis by categorising impacts into environmental, social, and economic subcategories.

# 4. FINDINGS

## 4.1 IMPACTS OF MARITIME INFRASTRUCTURE ON MARINE SOCIO-ECOLOGICAL SYSTEMS

Maritime infrastructure, as a core pillar of coastal and marine environments, generates both positive and negative impacts that influence MSES (Abdolpour & Marut, 2025; Bugnot et al., 2020). Understanding these dual effects is therefore essential to ensure that maritime infrastructure development supports the long-term resilience of MSES.

## 4.2 POSITIVE IMPACTS OF MARITIME INFRASTRUCTURE ON MARINE SOCIO-ECOLOGICAL SYSTEMS

Existing literature increasingly emphasises that maritime infrastructure provides enormous positive impacts on MSES (Bugnot et al., 2020). Table 1 synthesises the positive impacts, illustrating the diverse contributions of maritime infrastructure to MSES. Accordingly, maritime infrastructure offers substantial contributions to the structure, function, and resilience of MSES. Economically, maritime infrastructure supports the development of coastal and offshore regions by enabling ports, and offshore industrial facilities, which collectively strengthen regional livelihoods, enhance community resilience, and facilitate the sustainable integration of human activities within MSES (Hryshyna et al., 2021; Park & Kildow, 2015; Spanier & Kuenzer, 2024). The rapid growth of ocean-based industries highlights the pivotal role of maritime infrastructure in optimising the use of ocean space, promoting employment, and creating economic opportunities (Allen & Moore, 2016; Li et al., 2022). From an energy transition perspective, maritime infrastructure enables renewable and green energy generation, supporting the shift away from fossil-fuel-based systems and contributing to the sustainability of MSES (Bugnot et al., 2018); however, these outcomes depend on design choices, ecological sensitivities, and regulatory frameworks (Bugnot et al., 2020; Spanier & Kuenzer, 2024). Environmentally, maritime structures can enhance MSES functionality by providing habitat complexity, and supporting fisheries productivity (Dafforn et al., 2015; ter Hofstede & van Koningsveld, 2024). By functioning as artificial reefs or colonisation substrates, maritime infrastructures strengthen ecological connectivity and improve the resilience of both ecological and human components of MSES (Hooper et al., 2021). Eco-engineered and nature-inclusive designs further improve ecological resilience and provide coastal protection against erosion and wave energy impacts (Li et al., 2022; Allen & Moore, 2016). From a social perspective, maritime infrastructure contributes to the adaptive capacity of MSES by improving coastal protection, reducing erosion, and enhancing maritime safety (Allen & Moore, 2016; Park, 2014). Moreover, it promotes adaptive capacity in coastal communities (Li et al., 2022). Collectively, these positive impacts demonstrate maritime infrastructure as a critical enabler of multifunctional, resilient, and sustainable MSES. However, compared with environmental impacts, social and economic impacts remain less frequently explored, suggesting a gap in understanding the socio-economic dimensions of maritime infrastructure impacts in MSES. Despite these widely recognised positive impacts, maritime infrastructure also generates negative impacts on MSES.

## 4.3 NEGATIVE IMPACTS OF MARITIME INFRASTRUCTURE ON MARINE SOCIO-ECOLOGICAL SYSTEMS

Despite multiple positive impacts, a growing body of literature highlights that maritime infrastructure generates significant adverse impacts on MSES (Afzal et al., 2022). Physical alterations of seabed morphology, intensive dredging (Fernandes et al., 2023), and land reclamation (Shan & Li, 2020) disrupt the natural dynamics of MSES (Watson et al., 2024). Thus, maritime infrastructure is increasingly recognised as a key anthropogenic driver of habitat loss, and deterioration of marine environmental quality (Chen & Wang, 2023). Accordingly, Table 1 synthesises the diverse perspectives within the existing literature, presenting a comprehensive overview of the negative impacts of maritime infrastructure on MSES.

*Table 1: Positive and negative impacts of marine infrastructure on marine socio-ecological systems*

| Ecological System | | Social System | |
|---|---|---|---|
| **Positive Impacts of Marine Infrastructure on Marine Ecological Systems** | **Negative Impacts of Marine Infrastructure on Marine Ecological Systems** | **Positive Impacts of Marine Infrastructure on Marine Social System** | **Negative Impacts of Marine Infrastructure on Marine Social System** |
| **Environmental Impacts**<br>• Enable the generation of renewable and green energy from marine resources [1],[2],[3],[4],[5],[6],[7],[8]<br>• Support the transition from fossil-based systems to sustainable energy pathways [1],[2],[3],[4],[5],[6],[7]<br>• Enhance fisheries productivity by providing habitat for marine organisms [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11]<br>• Provide effective coastal protection by reducing wave energy and shoreline erosion [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11]<br>• Enhance ecological connectivity and support species dispersal under changing climatic conditions [1],[2],[3],[4],[5],[6],[7],[8]<br>• Increase marine biodiversity by functioning as artificial reefs and colonisation substrates [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12],[13] | **Environmental Impacts**<br>• Disruption of ecosystems previously supported by offshore platforms during decommissioning or dismantling [1],[6],[7],[8],[10],[11],[30],[31],[49],[51]<br>• Degradation, destruction, and fragmentation of critical marine habitats [1],[6],[7],[8],[10],[11],[12],[13],[30],[31],[32],[33],[34],[35],[36],[37],[38],[39],[40],[41],[50]<br>• Loss of ocean wilderness and reduced ecosystem resilience [7],[11],[30],[31]<br>• Alteration of physical and chemical properties of water, including hydrodynamics, and sediment characteristics [13],[30],[31],[32],[33],[34],[35],[36],[37],[38],[49],[50]<br>• Disruption of ecological processes (organism movement, food webs, propagule dispersal, and energy flow) [1],[13],[36],[37],[38],[39],[40],[44],[45],[46]<br>• Spread of non-indigenous/ invasive species, altering local ecosystem dynamics [1],[6],[7],[8],[10],[11],[12],[13],[30],[31],[32],[33],[34],[51]<br>• Increased suspended sediments and turbidity during dredging, affecting water quality and marine life [1],[6],[7],[8],[10],[11],[12],[13],[30],[31],[40],[43]<br>• Shoreline erosion, overtopping, and armour stone instability impacting habitats [1],[6],[7],[8],[10],[11],[30],[31],[42],[50] | **Social Impacts**<br>• Improve food security through increased availability of marine biological resources [1],[2],[3],[4],[5],[6],[7]<br>• Improve maritime safety by creating calm waters for harbour operations [1],[2],[3]<br>• Support recreation, tourism, and environmental education activities [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12],[13],[14],[15]<br>• Support integrated ocean governance and strategic marine policy implementation [1],[2],[3],[4],[5],[6],[7],[8]<br><br>**Economic Impacts**<br>• Promote economic development through ports and offshore industrial facilities [1],[2],[3],[4],[5],[6],[7],[8],[9],[10]<br>• Strengthen global maritime connectivity and facilitate international trade [1],[2],[3],[4]<br>• Enable offshore exploration and production of oil and gas resources in deep-water [1],[2],[3],[4],[5] | **Social Impacts**<br>• Reduced adaptive capacity of coastal communities to sea level rise increasing vulnerability of settlements and livelihoods [1],[6],[7],[30],[31],[44],[45],[46]<br><br>**Economic Impacts**<br>• Cumulative environmental degradation (overexploitation of fisheries and depletion of marine resources), affecting food security and local economies [1],[6],[7],[8],[10],[11],[12], [30],[31]<br>• Economic losses to coastal communities resulting from infrastructure failures [1],[6],[7],[8],[10],[30],[31],[47],[48] |

| Ecological System | | Social System | |
|---|---|---|---|
| **Positive Impacts of Marine Infrastructure on Marine Ecological Systems** | **Negative Impacts of Marine Infrastructure on Marine Ecological Systems** | **Positive Impacts of Marine Infrastructure on Marine Social System** | **Negative Impacts of Marine Infrastructure on Marine Social System** |
| • Improve ecological resilience through eco-engineered and nature-inclusive designs [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12],[13]<br>• Deliver ecosystem services; pollution reduction and water quality improvement [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12]<br>• Allow versatile application across coastal, offshore, and deep-sea environments through diverse structural types [1],[2],[3],[4],[5],[6] | • Habitat loss and modification due to land reclamation and artificial islands [6],[7],[30],[31],[51]<br>• Pollution from untreated discharges, production wastes, or human activity affecting surrounding ecosystems [1],[6],[7],[30],[31],[32],[33],[34],[35],[36],[41]<br>• Replacement of natural habitats with built structures, modifying seascapes and environmental conditions [1],[6],[7],[8],[36],[37],[38],[39],[40],[47],[48],[51]<br>• Sub-lethal biological impacts, including reduced reproduction, disorientation [1],[6],[7],[8],[10],[11],[12],[13],[30],[31],[32],[33] | • Support efficient utilisation of ocean space for energy recovery [1],[2],[3],[4],[5],[6],[7]<br>• Facilitate the development of emerging marine industries [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11]<br>• Promote long-term marine infrastructure development and continuous technological advancement [1],[2],[3],[4],[5],[6],[7],[8],[9]<br>Optimise local resource efficiency and support regional socio-economic development [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12] | |

[1] (Allen & Moore, 2016), [2] (Bugnot et al., 2018), [3] (Park & Kildow, 2015), [4] (Abdolpour & Marut, 2025), [5] (Park, 2014), [6] (Spanier & Kuenzer, 2024), [7] (Li & Li, 2007), [8] (Hryshyna et al., 2021), [9] (Sadeghi, 2008), [10] (ter Hofstede & van Koningsveld, 2024), [11] (Dafforn et al., 2015), [12] (Li et al., 2022), [13] (Bulleri & Chapman, 2010), [14] (Griffin et al., 2019), [15] (Paxton, Lester, et al., 2025), [16] (Whoriskey et al., 2021), [17] (Paxton, Runde, et al., 2025), [18] (Banerjee et al., 2018), [19] (Pioch et al., 2011), [20] (Zimmerhackel et al., 2023), [21] (Wang et al., 2020), [22] (Gao et al., 2020), [23] (Cisneros-Montemayor & Sumaila, 2010), [24] (Hooper et al., 2021), [25] (Sutton-Grier et al., 2015), [26] (Perkol-Finkel & Sella, 2014), [27] (Korbee & Van Tatenhove, 2013), [28] (Glykas et al., 2010), [29] (Li, 2023), [30] (Bugnot et al., 2020), [31] (Nassar & Elbisy, 2024), [32] (Morris et al., 2018), [33] (Bueger & Liebetrau, 2023), [34] (Fowler et al., 2018), [35] (McKibbin et al., 2024), [36] (Wilson et al., 2015), [37] (Lennox et al., 2025), [38] (Dreizis et al., 2019), [39] (Komyakova et al., 2022), [40] (Valdez et al., 2016), [41] (Chen & Wang, 2023), [42] (Anton et al., 2019), [43] (El Gohary & Hassan, 2012), [44] (Yuan et al., 2023), [45] (Kuşku et al., 2018), [46] (Lopes et al., 2025), [47] (Del Grosso, 2001), [48] (Ware & Callaway, 2019), [49] (Sheehan et al., 2020), [50] (Airoldi & Bulleri, 2011), [51] (van Elden et al., 2025)

As presented in Table 1, existing literature consistently highlights maritime infrastructure as a major driver of disturbances within MSES, particularly from an environmental perspective. Empirical studies demonstrate that activities including dredging, land reclamation, and offshore installations cause degradation, fragmentation, and permanent loss of critical marine habitats (Ware & Callaway, 2019). Consequently, they reduce the resilience of both ecological and social components of MSES (Spanier & Kuenzer, 2024; ter Hofstede & van Koningsveld, 2024). Physical modifications associated with maritime infrastructure activities erode shorelines and destabilise protective coastal structures, collectively impairing water quality and ecosystem functions (Allen & Moore, 2016; Nassar & Elbisy, 2024). Moreover, maritime infrastructure disrupts vital ecological processes that sustain MSES, including organism movement, propagule dispersal, energy flow, and food-web connectivity (Bugnot et al., 2020; Li & Li, 2007). These disruptions can facilitate the spread of invasive or non-indigenous species, further disturb local ecosystem dynamics and undermine the adaptive capacity of coastal communities (Sheehan et al., 2020). Beyond environmental impacts, the literature also emphasises social and economic impacts, although these dimensions receive comparatively less attention. From a social perspective, environmental degradation and ecosystem disturbances can reduce the adaptive capacity of coastal communities to climate-related pressures such as sea-level rise, increasing the vulnerability of settlements and livelihoods (Spanier & Kuenzer, 2024; Yuan et al., 2023). Economically, cumulative environmental degradation, including overexploitation of fisheries, depletion of marine resources, and pollution from untreated discharges, can negatively affect food security and local economies reliant on marine resources within MSES (Kuşku et al., 2018; Yuan et al., 2023). In addition, infrastructure failures and ecosystem degradation may lead to economic losses for coastal communities dependent on fisheries, tourism, and other marine-based industries (Ware & Callaway, 2019). Overall, the literature demonstrates that the negative impacts of maritime infrastructure on MSES are multidimensional, encompassing environmental, social, and economic dimensions. However, the synthesis indicates that existing studies predominantly focus on environmental impacts. In contrast, social and economic consequences are comparatively less explored, despite their critical implications for coastal livelihoods and long-term socio-ecological resilience. This collectively emphasise the need for holistic and integrated approaches to mitigate negative impacts while enhancing positive impacts.

Notably, maritime infrastructure generates simultaneous trade-offs and synergies across ecological, social, and economic dimensions. For instance, offshore renewable energy infrastructure and coastal defence structures may enhance coastal protection, renewable energy generation, and economic development, while simultaneously contributing to habitat fragmentation, altered hydrodynamics, and social vulnerability within coastal communities. These interactions reflect the interconnected and dynamic nature of MSES, where ecological and social systems continuously influence one another through feedback mechanisms, adaptive processes, and governance structures. The review further emphasises that the balance between benefits and adverse impacts is highly context-dependent and influenced by factors including infrastructure type, scale, geographical location, ecological sensitivity, governance effectiveness, stakeholder participation, and the extent of nature-inclusive design integration.

## 5. CONCLUSIONS AND FUTURE DIRECTIONS

This study aimed to examine the impacts of maritime infrastructure on MSES through a narrative review approach. The findings demonstrate that maritime infrastructure generates complex and interconnected environmental, social, and economic impacts across both ecological and social systems. While maritime infrastructure contributes positively to renewable energy generation, coastal protection, maritime connectivity, fisheries productivity, and regional economic development, it simultaneously creates substantial challenges including habitat degradation, ecological fragmentation, biodiversity disturbance, pollution, and increased socio-economic vulnerability within coastal communities. These findings emphasise maritime infrastructure as an integral component of dynamic MSES characterised by continuous interactions, trade-offs, and feedback between human and ecological systems. The study further highlights that the impacts of maritime infrastructure are highly context-dependent and influenced by infrastructure type, spatial scale, governance arrangements, ecological sensitivity, and the extent of nature-inclusive design integration. The implications of this study extend across multiple domains. From a theoretical perspective, this study contributes to the existing MSES literature by synthesising fragmented knowledge on maritime infrastructure impacts into a structured approach encompassing ecological and social systems, positive and negative impacts, and environmental, social, and economic dimensions. For society, the study illustrates the direct links between maritime infrastructure, coastal ecosystem services, and community well-being, emphasising the importance of participatory governance and sustainable ocean management to ensure equitable benefits and minimise adverse impacts. For industry, the findings highlight the need for ecologically informed infrastructure design and operational strategies, including eco-engineered structures, cumulative impact assessments, and integration of renewable energy, to enhance economic productivity while reducing ecological harm. Future research is recommended to adopt in-depth case study approaches to comprehensively examine the socio-economic dimensions of maritime infrastructure within MSES through the integration of economic models such as the blue economy, thereby supporting sustainable ocean management. Future research should prioritise identifying the underlying drivers and root causes of both positive and negative impacts of maritime infrastructure on MSES, thereby enabling the development of more innovative, sustainable, and nature-based design solutions that minimise ecological and social disruptions. This study has several limitations, primarily due to its reliance on a literature review, which may overlook recent research or unpublished studies, potentially resulting in an incomplete understanding of maritime infrastructure impacts. Furthermore, the selection of search terms and literature sources may influence the findings, limiting their generalisability. Despite these limitations, this study provides a comprehensive benchmark for future in-depth research and contributes to advancing knowledge on sustainable maritime infrastructure development within MSES.

## 6. ACKNOWLEDGEDMENT

The authors acknowledge the financial support provided by the Senate Research Committee of the University of Moratuwa under the Grant SRC/ST/2026/27.

# 7. REFERENCES


Abdolpour, H., & Marut, M. (2025). Parametric design for sustainable marine infrastructure. *Bulletin of the Polish Academy of Sciences: Technical Sciences, 73*(5). https://doi.org/10.24425/bpasts.2025.154289

Afzal, M. S., Tahir, F., & Al-Ghamdi, S. G. (2022). Recommendations and strategies to mitigate environmental implications of artificial island developments in the Gulf. *Sustainability, 14*(9), 5027. https://doi.org/10.3390/su14095027

Airoldi, L., & Bulleri, F. (2011). Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. *PLoS ONE, 6*(8), e22985. https://doi.org/10.1371/journal.pone.0022985

Allen, S. N., & Moore, G. A. C. (2016). 4 - Construction methodologies and challenges for marine concrete structures. In M. Alexander & J. M. W. Mackechnie (Eds.), *Marine concrete structures* (pp. 115–133). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100081-6.00004-0

Amaechi, C. V., Reda, A., Butler, H. O., Ja'e, I. A., & An, C. (2022). Review on fixed and floating offshore structures. Part I: Types of platforms with some applications. *Journal of Marine Science and Engineering, 10*(8), 1074. https://doi.org/10.3390/jmse10081074

Anastasiei, I.-D., & Georgescu, M. R. (2020). Automated vs manual content analysis – A retrospective look. *Scientific Annals of Economics and Business, 67*(SI), 57–67. https://doi.org/10.47743/saeb-2020-0025

Anton, I. A., Panaitescu, M., Panaitescu, F.-V., & Ghiţă, S. (2019). Impact of coastal protection systems on marine ecosystems. *E3S Web of Conferences, 85*, 07011. https://doi.org/10.1051/e3sconf/20198507011

Banerjee, O., Boyle, K., Rogers, C. T., Cumberbatch, J., Kanninen, B., Lemay, M., & Schling, M. (2018). Estimating benefits of investing in resilience of coastal infrastructure in small island developing states: An application to Barbados. *Marine Policy, 90*, 78–87. https://doi.org/10.1016/j.marpol.2018.01.004

Banihabib, R., & Assadi, M. (2023). Towards a low-carbon future for offshore oil and gas industry: A smart integrated energy management system with floating wind turbines and gas turbines. *Journal of Cleaner Production, 423*, 138742. https://doi.org/10.1016/j.jclepro.2023.138742

Belter, C. W. (2015). Bibliometric indicators: Opportunities and limits. *Journal of the Medical Library Association, 103*(4), 219–221. https://doi.org/10.3163/1536-5050.103.4.014

Berkes, F. (2011). Restoring unity: The concept of marine social-ecological systems. In R. E. Ommer, R. I. Perry, K. Cochrane, & P. Cury (Eds.), In *World fisheries: A social-ecological analysis* (pp. 9–28). Blackwell Publishing. https://doi.org/10.1002/9781444392241.ch2

Bueger, C., & Liebetrau, T. (2023). Critical maritime infrastructure protection: What's the trouble? *Marine Policy, 155*, 105772. https://doi.org/10.1016/j.marpol.2023.105772

Bugnot, A. B., Mayer-Pinto, M., Airoldi, L., Heery, E. C., Johnston, E. L., Critchley, L. P., Strain, E. M. A., Morris, R. L., Loke, L. H. L., Bishop, M. J., Sheehan, E. V., Coleman, R. A., & Dafforn, K. A. (2020). Current and projected global extent of marine built structures. *Nature Sustainability, 4*, 33–41. https://doi.org/10.1038/s41893-020-00595-1

Bugnot, A. B., Mayer-Pinto, M., Johnston, E. L., Schaefer, N., & Dafforn, K. A. (2018). Learning from nature to enhance blue engineering of marine infrastructure. *Ecological Engineering, 120*, 611–621. https://doi.org/10.1016/j.ecoleng.2018.03.012

Bulleri, F., & Chapman, M. G. (2010). The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology, 47*(1), 26–35. https://doi.org/10.1111/j.1365-2664.2009.01751.x

Chen, Z., & Wang, H. (2023). Variance analysis of negative impacts of offshore construction on marine environment. *Proceedings of the 2023 8th international conference on engineering management (ICEM 2023)*, (pp. 97–106). Atlantis Press. https://doi.org/10.2991/978-94-6463-308-5_11

Cisneros-Montemayor, A. M., & Sumaila, U. R. (2010). A global estimate of benefits from ecosystem-based marine recreation: Potential impacts and implications for management. *Journal of Bioeconomics, 12*(3), 245–268. https://doi.org/10.1007/s10818-010-9092-7

Dafforn, K. A., Mayer-Pinto, M., Morris, R. L., & Waltham, N. J. (2015). Application of management tools to integrate ecological principles with the design of marine infrastructure. *Journal of Environmental Management*, *158*, 61–73. https://doi.org/10.1016/j.jenvman.2015.05.001

Del Grosso, A. E. (2001). Monitoring of infrastructures in the marine environment. *Structural Control for Civil and Infrastructure Engineering*, 107–117. https://doi.org/10.1142/9789812811707_0014

Dreizis, Y., Bondareva, E., & Vershinina, G. (2019). The environmental impact of the reconstruction and development of the coastal marine transport infrastructure. *E3S Web of Conferences*, *91*, 07005. https://doi.org/10.1051/e3sconf/20199107005

El Gohary, R., & Hassan, N. A. A. (2012). Environmental Impact Assessment (EIA) of marine structures — A case study. *KSCE Journal of Civil Engineering*, *16*(5), 689–698. https://doi.org/10.1007/s12205-012-1347-5

Elegbede, I. O., Fakoya, K. A., Adewolu, M. A., Jolaosho, T. L., Adebayo, J. A., Oshodi, E., Hungevu, R. F., Oladosu, A. O., & Abikoye, O. (2023). Understanding the social–ecological systems of non-state seafood sustainability scheme in the blue economy. *Environment, Development and Sustainability*, *27*(2), 2721–2752. https://doi.org/10.1007/s10668-023-04004-3

Ellis, J., Macpherson, E., Thrush, S., Fisher, K., Pilditch, C., Jorgensen, E., Low, J., Stephenson, F., Allison, A., Geange, S., & Hewitt, J. (2025). Scale and ecosystem-based management: Navigating mismatches between socio-ecological systems. *Biological Conservation*, *302*, 111000. https://doi.org/10.1016/j.biocon.2025.111000

Fernandes, L. D. A., Corte, G. N., Moura, L., Reis, C., Matos, T., Moreno, D., Cortez, P. S. A., de Carvalho, W. F., Monteiro-Ribas, W., Gonçalves, J. E. A., Ribeiro, F., Thomazelli, F., Rizzini-Ansari, N., Neto, E. B. F., Gaelzer, L. R., de Souza Martins, E., Lobão, M. M., Baeta-Neves, M. H., & Coutinho, R. (2023). Effects of dredging activities and seasonal variation on coastal plankton assemblages: Results from 10 years of environmental monitoring. *Environmental Monitoring and Assessment*, *195*(2), 261. https://doi.org/10.1007/s10661-022-10867-2

Ferrol-Schulte, D., Wolff, M., Ferse, S., & Glaser, M. (2013). Sustainable livelihoods approach in tropical coastal and marine social–ecological systems: A review. *Marine Policy*, *42*, 253–258. https://doi.org/10.1016/j.marpol.2013.03.007

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., Hill, R., Hughes, T. P., Luthe, T., Maass, M., Meacham, M., Norström, A. V, Peterson, G., Queiroz, C., Seppelt, R., Spierenburg, M., & Tenhunen, J. (2015). Advancing sustainability through mainstreaming a social–ecological systems perspective. *Current Opinion in Environmental Sustainability*, *14*, 144–149. https://doi.org/10.1016/j.cosust.2015.06.002

Fowler, A. M., Jørgensen, A., Svendsen, J. C., Macreadie, P. I., Jones, D. O., Boon, A. R., Booth, D. J., Brabant, R., Callahan, E., Claisse, J. T., Dahlgren, T. G., Degraer, S., Dokken, Q. R., Gill, A. B., Johns, D. G., Leewis, R. J., Lindeboom, H. J., Linden, O., May, R., … Coolen, J. W. (2018). Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, *16*(10), 571–578. https://doi.org/10.1002/fee.1827

Gao, S., Sun, H., Zhao, L., Cao, G., & Liu, W. (2020). Research on the comprehensive benefits and driving forces of various typical types of marine development in Jiangsu province. *IOP Conference Series: Earth and Environmental Science*, *569*, 012034. https://doi.org/10.1088/1755-1315/569/1/012034

Glaser, M., & Glaeser, B. (2014). Towards a framework for cross-scale and multi-level analysis of coastal and marine social-ecological systems dynamics. *Regional Environmental Change*, *14*(6), 2039–2052. https://doi.org/10.1007/s10113-014-0637-5

Glykas, A., Papaioannou, G., & Perissakis, S. (2010). Application and cost–benefit analysis of solar hybrid power installation on merchant marine vessels. *Ocean Engineering*, *37*(7), 592–602. https://doi.org/10.1016/j.oceaneng.2010.01.019

Gourvenec, S. (2018). Nearshore structures. In P. Bobrowsky & B. Marker (Eds.), *Encyclopedia of Engineering Geology (Encyclopedia of Earth Sciences Series)*. Springer. https://doi.org/10.1007/978-3-319-12127-7_210-1

Griffin, E., Coote, A., & Crompvoets, J. (2019). A marine spatial data infrastructure in New Zealand: A systematic review on the cost-benefits. *Journal of Spatial Science*, *64*(1), 33–47. https://doi.org/10.1080/14498596.2017.1372227

Heslinga, J. H., Groote, P., & Vanclay, F. (2017). Using a social-ecological systems perspective to understand tourism and landscape interactions in coastal areas. *Journal of Tourism Futures, 3*(1), 23–38. https://doi.org/10.1108/JTF-10-2015-0047

Hooper, T., Armstrong, A., & Vlaswinkel, B. (2021). Environmental impacts and benefits of marine floating solar. *Solar Energy, 219*, 11–14. https://doi.org/10.1016/j.solener.2020.10.010

Hryshyna, L., Pogoryelova, E., Karas, P., Mihai, N., & Khmarska, I. (2021). Financial and investment processes in ensuring the development of marine infrastructure. *MATEC Web of Conferences, 339*, 01021. https://doi.org/10.1051/matecconf/202133901021

Kanan, A. H., & Giupponi, C. (2024). Coastal socio-ecological systems adapting to climate change: A global overview. *Sustainability, 16*(22), 10000. https://doi.org/10.3390/su162210000

Komyakova, V., Jaffrés, J. B. D., Strain, E. M. A., Cullen-Knox, C., Fudge, M., Langhamer, O., Bender, A., Yaakub, S. M., Wilson, E., Allan, B. J. M., Sella, I., & Haward, M. (2022). Conceptualisation of multiple impacts interacting in the marine environment using marine infrastructure as an example. *Science of The Total Environment, 830*, 154748. https://doi.org/10.1016/j.scitotenv.2022.154748

Korbee, D., & Van Tatenhove, J. P. M. (2013). Environmental governance for marine infrastructure: Enabling and constraining conditions for ecodynamic development and design in marine infrastructural projects. *Journal of Environmental Policy & Planning, 15*(4), 533–550. https://doi.org/10.1080/1523908X.2013.807211

Kuşku, H., Yiğit, M., Ergün, S., Yiğit, Ü., & Taylor, N. (2018). Acoustic noise pollution from marine industrial activities: Exposure and impacts. *Aquatic Research, 1*(4), 148–161. https://doi.org/10.3153/AR18017

Lazzari, N., Martín-López, B., Gelcich, S., & Martinez-Harms, M. J. (2026). Exploring multiscale social-ecological dynamics for enhanced coastal and marine management. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.6169977

Lennox, R. J., Birnie-Gauvin, K., Bate, C., Cooke, S. J., Haraldstad, T., Berhe, S., Penney, H. D., Bangley, C. W., Vollset, K. W., & Piczak, M. L. (2025). Marine fish passage—Underappreciated threats to connectivity within the marine environment. *Marine Ecology, 46*(1). https://doi.org/10.1111/maec.12859

Li, D. (2023). The impact of marine industrial structure rationalization on marine economic growth. *Journal of Sea Research, 196*, 102455. https://doi.org/10.1016/j.seares.2023.102455

Li, H., Liu, Y., Liang, B., Liu, F., Wu, G., Du, J., Hou, H., Li, A., & Shi, L. (2022). Demands and challenges for construction of marine infrastructures in China. *Frontiers of Structural and Civil Engineering, 16*(5), 551–563. https://doi.org/10.1007/s11709-022-0839-8

Li, Y., & Li, L. (2007). Marine structures and materials. In J. C. J. Nihoul & C.-T. A. Chen (Eds.), *Encyclopedia of Life Support Systems (EOLSS): III*. UNESCO. http://www.eolss.net/sample-chapters/c01/e6-18-08-02.pdf

Lopes, L., Dauari, H., Mendonça, P., & Almeida, M. (2025). Marine plastic waste in construction: A systematic review of applications in the built environment. *Polymers, 17*(13), 1729. https://doi.org/10.3390/polym17131729

Marnot, B. (2025). The permanent adjustment process: A theoretical approach to structural change in commercial ports from the nineteenth century onwards. *The Journal of Transport History, 46*(3), 291–314. https://doi.org/10.1177/00225266241295482

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & Delgado López-Cózar, E. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Journal of Informetrics, 12*(4), 1160–1177. https://doi.org/10.1016/j.joi.2018.09.002

McKibbin, O., Vergés, A., Pottier, P., & Mayer Pinto, M. (2024). Marine infrastructure support fewer producers and more filter feeders than natural habitats: A review and meta-analysis. *Environmental Research Letters, 19*(11), 113005. https://doi.org/10.1088/1748-9326/ad7ee1

Mishra, V., & Mishra, M. (2023). PRISMA for review of management literature – Method, merits, and limitations: An academic review. In S. Rana, J. Singh, & S. Kathuria (Eds.), *Advancing methodologies of conducting literature review in management domain* (Review of Management Literature, Vol. 2). Emerald Publishing Limited.

Mohapatra, S. C. (2022). Application of flexible structure in marine engineering. *Journal of Marine Science and Engineering*, *10*(12), 1893. https://doi.org/10.3390/jmse10121893

Morris, R. L., Porter, A. G., Figueira, W. F., Coleman, R. A., Fobert, E. K., & Ferrari, R. (2018). Fish-smart seawalls: A decision tool for adaptive management of marine infrastructure. *Frontiers in Ecology and the Environment*, *16*(5), 278–287. https://doi.org/10.1002/fee.1809

Nassar, A. H., & Elbisy, A. M. (2024). A machine learning approach to predict time delays in marine construction projects. *Engineering, Technology & Applied Science Research*, *14*(5), 16125–16134. https://doi.org/10.48084/etasr.8173

Neubert, M. (2026). Literature review fundamentals for researchers. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.6004194

Park, K. S. (2014). *The estimation of the ocean economy and coastal economy in South Korea*. Center for the Blue Economy, Middlebury Institute of International Studies at Monterey. https://cbe.miis.edu/cgi/viewcontent.cgi?params=/context/cbe_working_papers/article/1029/&path_info=10.29.14.park_.kwangseo.the_estimation_of_the_ocean_economy_and_coastal_economy_in_korea_draft_wp.pdf

Park, K. S., & Kildow, J. T. (2015). Rebuilding the classification system of the ocean economy. *Journal of Ocean and Coastal Economics*, *2014*(1). https://doi.org/10.15351/2373-8456.1001

Paxton, A. B., Lester, S. E., Smith, C. S., Narayan, S., Angelini, C., Runde, B. J., Saunders, M. I., Gittman, R. K., Allgeier, J., Vozzo, M. L., Steward, D. N., Lemoine, H. R., Valdez, S. R., Morris, R. L., Nowacek, D. P., Seaman, W., Halpin, P. N., & Silliman, B. R. (2025). Recommendations for built marine infrastructure that supports natural habitats. *Frontiers in Ecology and the Environment*, *23*(6). https://doi.org/10.1002/fee.2840

Paxton, A. B., Runde, B. J., Smith, C. S., Lester, S. E., Vozzo, M. L., Saunders, M. I., Steward, D. N., Lemoine, H. R., Valdez, S. R., Gittman, R. K., Narayan, S., Allgeier, J., Morris, R. L., Nowacek, D. P., Seaman, W., Halpin, P. N., Angelini, C., & Silliman, B. R. (2025). Leveraging built marine structures to benefit and minimize impacts on natural habitats. *BioScience*, *75*(2), 172–183. https://doi.org/10.1093/biosci/biae135

Perkol-Finkel, S., & Sella, I. (2014). Ecologically active concrete for coastal and marine infrastructure: Innovative matrices and designs. In W. Allsop & K. Burgess (Eds.), *From sea to shore – meeting the challenges of the Sea* (pp. 1139–1149). ICE Publishing. https://doi.org/10.1680/fsts.59757.124

Petrosillo, I., Aretano, R., & Zurlini, G. (2015). Socioecological systems. In B. Fath (Ed.), *Encyclopedia of ecology* (pp. 419–425). Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09518-X

Pioch, S., Saussola, P., Kilfoyleb, K., & Spieler, R. (2011). Ecological design of marine construction for socio-economic benefits: Ecosystem integration of a pipeline in coral reef area. *Procedia Environmental Sciences*, *9*, 148–152. https://doi.org/10.1016/j.proenv.2011.11.023

Refulio-Coronado, S., Lacasse, K., Dalton, T., Humphries, A., Basu, S., Uchida, H., & Uchida, E. (2021). Coastal and marine socio-ecological systems: A systematic review of the literature. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.648006

Sadeghi, K. (2008). Significant guidance for design and construction of marine and offshore structures. *GAU Journal of Social & Applied Sciences*, *4*(7), 67–92. https://www.researchgate.net/publication/250310894_Significant_Guidance_for_Design_and_Construction_of_Marine_and_Offshore_Structures

Salazar-Gálvez, B., Quintas-Soriano, C., Piedra-Muñoz, L., & Aguilera, P. A. (2026). Insects contribution to people: Functional diversity and social welfare in regenerative agriculture social-ecological systems. *Ecosystems and People*, *22*(1). https://doi.org/10.1080/26395916.2025.2604339

Shan, J., & Li, J. (2020). Valuing marine ecosystem service damage caused by land reclamation: Insights from a deliberative choice experiment in Jiaozhou Bay. *Marine Policy*, *122*, 104249. https://doi.org/10.1016/j.marpol.2020.104249

Sheehan, E. V, Cartwright, A. Y., Witt, M. J., Attrill, M. J., Vural, M., & Holmes, L. A. (2020). Development of epibenthic assemblages on artificial habitat associated with marine renewable infrastructure. *ICES Journal of Marine Science*, *77*(3), 1178–1189. https://doi.org/10.1093/icesjms/fsy151

Smith, G., Atkins, J., Gregory, A., & Elliott, M. (2025). The minimum complexity necessary: The value of a simple social-ecological systems analysis in holistic marine environmental management. *Sustainable Futures*, *9*, 100476. https://doi.org/10.1016/j.sftr.2025.100476

Spanier, R., & Kuenzer, C. (2024). Marine infrastructure detection with satellite data — A review. *Remote Sensing*, *16*(10), 1675. https://doi.org/10.3390/rs16101675

Sukhera, J. (2022). Narrative reviews: Flexible, rigorous, and practical. *Journal of Graduate Medical Education*, *14*(4), 414–417. https://doi.org/10.4300/JGME-D-22-00480.1

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *51*, 137–148. https://doi.org/10.1016/j.envsci.2015.04.006

Taherdoost, H. (2023). Towards nuts and bolts of conducting literature review: A typology of literature review. *Electronics*, *12*(4), 800. https://doi.org/10.3390/electronics12040800

ter Hofstede, R., & van Koningsveld, M. (2024). Defining operational objectives for nature-inclusive marine infrastructure to achieve system-scale impact. *Frontiers in Marine Science*, *11*. https://doi.org/10.3389/fmars.2024.1358851

Usman, A. C., Al-Hendawi, M., & Bulut, S. (2025). Approaches to qualitative research: A narrative literature review. *Advances in Medicine, Psychology, and Public Health*, *2*(2), 81–95. https://hal.science/hal-04745107v1

Valdez, B., Ramirez, J., Eliezer, A., Schorr, M., Ramos, R., & Salinas, R. (2016). Corrosion assessment of infrastructure assets in coastal seas. *Journal of Marine Engineering & Technology*, *15*(3), 124–134. https://doi.org/10.1080/20464177.2016.1247635

van Elden, S., Fasca, H., & Meeuwig, J. J. (2025). Conservation implications of dominant species associated with ocean infrastructure: The genus Tubastraea (Dendrophyllidae). *Marine Pollution Bulletin*, *214*, 117789. https://doi.org/10.1016/j.marpolbul.2025.117789

Villasante, S., Macho, G., Antelo, M., Rodríguez-González, D., & Kaiser, M. J. (2013). Resilience and challenges of marine social–ecological systems under complex and interconnected drivers. *Ambio*, *42*(8), 905–909. https://doi.org/10.1007/s13280-013-0450-2

Virapongse, A., Brooks, S., Metcalf, E. C., Zedalis, M., Gosz, J., Kliskey, A., & Alessa, L. (2016). A social-ecological systems approach for environmental management. *Journal of Environmental Management*, *178*, 83–91. https://doi.org/10.1016/j.jenvman.2016.02.028

Vollstedt, M., & Rezat, S. (2019). An introduction to grounded theory with a special focus on axial coding and the coding paradigm. In G. Kaiser & N. Presmeg (Eds.), *Compendium for early career researchers in mathematics education (ICME-13 Monographs)* (pp. 81–100). Springer. https://doi.org/10.1007/978-3-030-15636-7_4

Wang, S., Xing, L., & Chen, H. (2020). Impact of marine industrial structure on environmental efficiency. *Management of Environmental Quality: An International Journal*, *31*(1), 111–129. https://doi.org/10.1108/MEQ-06-2019-0119

Ware, J., & Callaway, R. (2019). Public perception of coastal habitat loss and habitat creation using artificial floating islands in the UK. *PLoS ONE*, *14*(10), e0224424. https://doi.org/10.1371/journal.pone.0224424

Watson, S. C. L., Somerfield, P. J., Lemasson, A. J., Knights, A. M., Edwards-Jones, A., Nunes, J., Pascoe, C., McNeill, C. L., Schratzberger, M., Thompson, M. S. A., Couce, E., Szostek, C. L., Baxter, H., & Beaumont, N. J. (2024). The global impact of offshore wind farms on ecosystem services. *Ocean & Coastal Management*, *249*, 107023. https://doi.org/10.1016/j.ocecoaman.2024.107023

Whoriskey, F., Barbier, M., Mazur, M., Hahn, T., Kritzer, J., & Vallee, R. (2021). Maximizing benefits from punctual ocean infrastructure: An ethical perspective. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.733822

Williams, M., & Moser, T. (2019). The art of coding and thematic exploration in qualitative research. *International Management Review*, *15*(1), 45–55.

Wilson, A. M. W., Mugerauer, R., & Klinger, T. (2015). Rethinking marine infrastructure policy and practice: Insights from three large-scale marina developments in Seattle. *Marine Policy*, *53*, 67–82. https://doi.org/10.1016/j.marpol.2014.11.020

Yuan, B., Cui, Y., An, D., Jia, Z., Ding, W., & Yang, L. (2023). Marine environmental pollution and offshore aquaculture structure: Evidence from China. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.979003

Zimmerhackel, J. S., Clifton, J., Ackermann, F., Burton, M. P., Elrick-Barr, C. E., Hill, G., & Harvey, E. S. (2023). A framework for the integrated assessment of social and economic values associated with man-made marine structures. *Marine Policy*, *152*, 105612. https://doi.org/10.1016/j.marpol.2023.105612

De Silva, C. P., 2026. Material innovation as a cultural material practice: Coconut based product design for regenerative futures. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1166-1179. DOI: https://doi.org/10.31705/WCS.2026.85. Available from: https://ciobwcs.com/papers/

# MATERIAL INNOVATION AS A CULTURAL MATERIAL PRACTICE: COCONUT BASED PRODUCT DESIGN FOR REGENERATIVE FUTURES

**C.P. De Silva[1]**

## *ABSTRACT*

*The growing recognition that sustainability alone may be insufficient to address contemporary ecological and social crises has led to increased attention toward regeneration as an expanded design paradigm. While sustainable design has focused largely on efficiency and harm reduction, regenerative approaches seek to restore, renew, and strengthen the living systems upon which the built environment depends. However, translating regenerative principles to the level of materials and products remains underdeveloped, particularly within design education. This paper examines how regeneration can be cultivated through a practice based and participatory material exploration process. Using Culture Code 2025, a design led educational initiative centred on coconut-based product innovation in Sri Lanka, the study investigates how regeneration can emerge through observation, experimentation, prototyping, and collaboration with craftspeople. Based on the ecological and cultural context of the coconut palm (Cocos nucifera), the project engages students in hands on exploration that emphasises material intelligence, circularity, and cultural continuity. The findings suggest that practice led material innovation offers a viable pathway for approaching regeneration in the built environment, demonstrating how educational settings can nurture regenerative thinking and action at the scale of everyday products. The findings further suggest that this approach offers a replicable educational model for embedding regenerative thinking within design curricula. By demonstrating how locally rooted, practice-based engagement with natural materials can generate regenerative outcomes, the study contributes to the growing body of knowledge on sustainable built environment practice at the intersection of material culture, design education and ecological stewardship.*

***Keywords:*** *Coconut Based Materials; Design Education; Material Innovation; Practice-led Design; Regenerative Practice.*

## 1. INTRODUCTION

Sustainability has shaped built environment conversations for decades, guiding efforts to reduce environmental impact, conserve resources, and improve efficiency. Yet despite significant progress in standards, certifications, and technological optimisation, global ecological degradation and interconnected social crises continue to intensify. Increasingly, scholars argue that harm reduction alone cannot address systemic breakdowns in ecological and social systems (Buckton et al., 2023). In this context,

[1]Lecturer, Department of Integrated Design, University of Moratuwa, Sri Lanka, chathurangid@uom.lk

regeneration has emerged as a complementary and expanded paradigm; one that seeks not merely to sustain current conditions, yet to restore vitality and support the long-term nurturing of living systems.

Regenerative development extends sustainability by shifting emphasis from minimising negative impact to fostering co-evolution between human and natural systems (Buckton et al., 2023). Rather than focusing solely on efficiency or compliance, regeneration is grounded in an ecological worldview that values mutualism, reflexivity, diversity, and long-term systemic health (Yunibandhu & Hallinger, 2025). Within design discourse, regenerative approaches are increasingly recognised as capable of generating positive environmental and social contributions within the built environment (Kumar et al., 2025). However, while regenerative concepts have matured within architecture and large-scale planning, there remains a recognised methodological gap at the product and material level (Sörensen et al., 2024). Designers lack clear frameworks for translating regenerative thinking into tangible material practices.

Material innovation within the built environment offers a particularly powerful entry point for addressing this gap. Everyday products such as tools, domestic objects, packaging systems etc. mediate human interaction with space and shape patterns of use, care, and disposal. Approaching material innovation through practice-based approaches allows regeneration to move from theory into embodied experience. Making through observation, cutting, joining, testing, refining, creates direct engagement with material behaviour and lifecycle considerations. When such practice is based on local ecological and cultural contexts, it becomes participatory, drawing upon community knowledge and craft traditions.

In Sri Lanka, the coconut palm represents a deeply integrated ecological and cultural material system. Historically regarded as Kapruka, the "tree of life," the coconut has long supported domestic tools, vernacular artefacts, and livelihoods. Its renewable and biodegradable properties also position it as a viable bio-based material resource within contemporary sustainable built environments.

The aim of this research is to examine how a practice-based and participatory design approach can cultivate regeneration within material innovation for sustainable built environments. Using Culture Code 2025 (a design led educational initiative at the Department of Integrated Design, University of Moratuwa, Sri Lanka, centred this year on coconut-based product innovation), this paper investigates how regeneration can emerge through phases of observation, experimentation, prototyping, and collaboration with craftspeople. Rather than treating regeneration as a fixed metric or certification target, the study explores how regenerative capacity can be developed gradually through material literacy, ethical making, and sustained engagement with local ecological systems.

# 2. LITERATURE REVIEW

## 2.1 COCONUT TREE AS A MATERIAL SYSTEM

Natural materials derived from agricultural ecosystems have increasingly gained attention within discussions of sustainable and regenerative design. Among these, the coconut palm occupies a particularly important position in tropical regions due to its ecological abundance and cultural integration into everyday life. Historically described as a "tree of

life," the coconut palm has supported a wide range of domestic, agricultural, and material uses, with nearly every part of the plant serving a functional purpose.

The coconut tree provides multiple material resources that can be utilised for product development. The coconut shell, a dense lignocellulosic material, has traditionally been used for utensils, bowls, decorative artefacts, and charcoal production. The coconut husk contains coir fibre, which is widely used in ropes, brushes, mats, and biodegradable composites (Nissar et al., 2025). Coconut wood, obtained from mature palms, has been used in furniture and structural components, while coconut leaves and midribs have historically supported woven products such as baskets, roofing materials, and domestic tools. These materials are renewable, biodegradable, and often derived as by-products of agricultural processes (Kumar et al., 2024) (refer Figure 1).

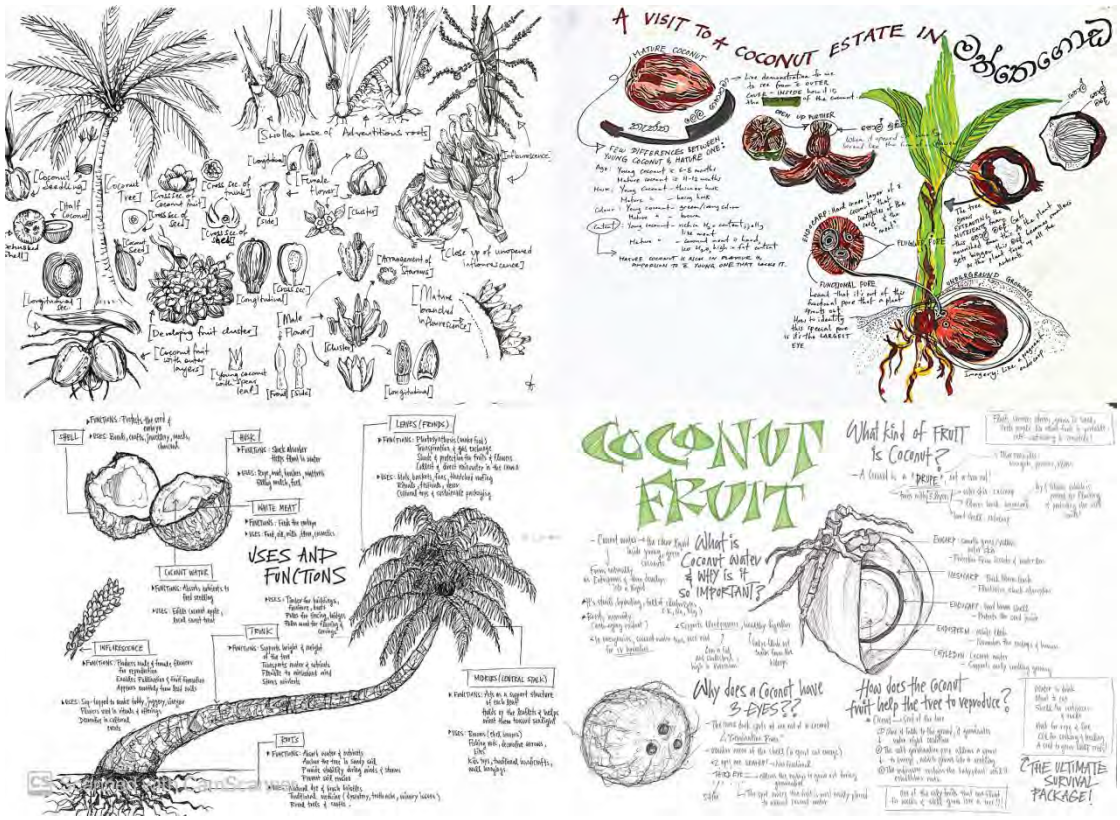



*Figure 1: Studies on coconut tree material system*

Recent discussions on regenerative materials highlight the importance of using bio-based resources and agricultural residues that do not compete with food production and that can circulate within ecological systems (Sörensen et al., 2024). Agricultural by-products such as coconut shell, fibre, and biomass therefore present opportunities for material innovation that aligns with regenerative principles. Rather than relying on resource intensive synthetic materials, locally available plant-based resources can enable design systems that are renewable, repairable, and biodegradable (Yang et al., 2024).

In many parts of South and Southeast Asia, coconut-based craft traditions have demonstrated such material intelligence. Local craft communities have historically developed techniques that utilise the material properties of coconut components efficiently, often producing objects that are durable, multifunctional, and culturally embedded. These traditions illustrate how material use can be closely tied to ecological

cycles and everyday life, suggesting that coconut-derived materials may serve as a valuable foundation for contemporary product innovation within regenerative design contexts.

## 2.2 REGENERATIVE PRACTICES

While sustainability initiatives have focused largely on reducing environmental damage, regenerative approaches seek to actively restore ecological and social systems. Regeneration moves beyond strategies of efficiency or harm reduction and instead aims to renew the vitality of ecosystems and communities through mutually beneficial relationships between human and natural systems (King, 2022).

Regenerative design therefore shifts attention from minimising negative impact to generating positive ecological contributions. Within the built environment, regenerative design frameworks emphasise holistic thinking, systems awareness, and the integration of human activity within ecological processes (Kumar et al., 2025). This perspective views buildings, materials, and products not as isolated technical artefacts yet as components within broader socio ecological systems.

Regenerative material practices often draw upon renewable biological resources, waste streams, and locally available feedstocks. In particular, bio-based materials derived from agricultural residues have been identified as promising resources within regenerative material systems because they can participate in circular biological cycles (Sörensen et al., 2024). When materials are biodegradable, compostable, or capable of re-entering ecological processes at the end of their lifecycle, they can contribute to regenerative systems that restore soil health, reduce waste, and support biodiversity.

Beyond material selection, regenerative practice also involves a shift in worldview that recognises human societies as embedded within living ecosystems (Or, 2021). As a result, regenerative approaches emphasise learning from ecological systems, strengthening local knowledge, and designing in ways that enhance the vitality of both natural and social environments.

## 2.3 PARTICIPATION AND REGENERATIVE PRACTICE

Regenerative approaches are understood not only as technological or environmental interventions but also as social and relational practices. Central to regenerative thinking is the recognition that ecological transformation requires changes in the ways people relate to each other and to the natural world.

Regenerative practice frameworks emphasise reconnection and relationality as essential components of eco-social transformation. Regeneration is therefore seen as a process that involves rebuilding relationships between humans, communities, and more-than-human nature (Or, 2021). Rather than promoting predetermined solutions, regenerative practice frameworks aim to create conditions that allow collective learning and transformation to emerge.

Participation plays a key role in this process. Community participation allows diverse knowledge systems including craft knowledge, indigenous practices, and local ecological understanding to enrich design processes. Participatory approaches therefore help bridge the gap between contemporary design practices and longstanding cultural relationships with materials and landscapes.

Within regenerative practice frameworks, participation can also enable collective action and shared responsibility for environmental change. Instead of waiting for institutional or policy driven solutions, regenerative initiatives often emerge through collaborative local action and experimentation (Or, 2021). Through participatory engagement, communities contribute their knowledge, skills, and lived experiences, enabling design solutions that are contextually relevant and socially meaningful.

In the context of material innovation, participatory approaches allow designers to engage directly with craft communities, material practitioners, and local users. Such collaboration can facilitate knowledge exchange, expand design possibilities, and ensure that material experimentation remains connected to real ecological and social contexts.

Despite the growing recognition of participation within regenerative practice frameworks, existing research has largely engaged community participation at architectural or systems scales. There remains limited scholarly attention to participatory design as a means of cultivating regenerative thinking specifically at the product and material level, and particularly within design education contexts. This study addresses that gap by examining how a participatory, practice-based material exploration process centered on a locally significant biological resource can explore regenerative design outcomes within an educational setting.

The literature highlights three key insights. First, the coconut palm provides a diverse range of renewable material resources that have historically supported craft practices and everyday product systems. Second, regenerative design approaches emphasise the importance of restoring ecological and social relationships through material systems that operate within circular and living processes. Third, participatory approaches play a crucial role in enabling regenerative practices by reconnecting design processes with local knowledge, communities, and ecological contexts.

Despite these insights, there remains limited research exploring how product design using materials derived from the coconut tree (or similar such materials) can contribute to regenerative practices through participatory design processes, particularly within design education.

Therefore, this research investigates how products developed from various components of the coconut tree can contribute to regenerative practices when explored through a participatory and practice-based design approach. Using the Culture Code 2025 project as a case study, the study examines how collaborative material experimentation, craft engagement, and design education can support regenerative thinking and practice within sustainable built environments.

## 3. METHODOLOGY

This research adopts a practice based participatory design methodology to examine how coconut-based material exploration can contribute to regenerative practices within product innovation. The study is based on Culture Code 2025, a design led educational initiative conducted at the Department of Integrated Design, University of Moratuwa.

Culture Code forms part of a long running design research project originally established in 2012 under the name “Adjoining Traditional Crafting”, which aimed to explore sustainable product development through organic materials and local craft traditions.

Over time the initiative evolved into a platform for investigating the relationship between material culture, ecological responsibility, and design practice.

Renamed "Culture Code" in 2017, the initiative expanded its scope to examine a variety of organic materials including cane, talipot, banana fibre, bamboo, cinnamon, and leather. Across these iterations this initiative has operated not merely as a design project but as a reflective system of material exploration, where experimentation, cultural learning, and ethical design thinking are prioritised over rapid solution driven outcomes.

The 2025 edition of the project, titled "RE:NIU – The Coconut in Full Circle," focuses on the coconut palm as a regenerative material system embedded within Sri Lanka's ecological and cultural landscape. The coconut tree has historically supported a wide range of craft traditions and domestic objects, with its shell, husk, fibre, trunk, and fronds contributing to tools, vessels, woven products, and household artefacts.

By revisiting this material system through contemporary design practice, the project seeks to investigate how product innovation using coconut derived materials can contribute to regenerative practices within everyday environments.

## 3.1 REGENERATIVE DESIGN APPROACH

Beyond functioning as a design education project, Culture Code 2025 was structured to explore regenerative thinking through practice-based material engagement. Regenerative approaches within the built environment emphasise restoring relationships between human activity, ecological systems, and cultural knowledge rather than merely reducing environmental harm (Buckton et al., 2023; Kumar et al., 2025). Within this study, regeneration is therefore understood not as a fixed technological outcome but as a design capacity that develops through iterative engagement with materials, communities, and ecological contexts.

The project adopts a regenerative approach in three keyways. First, the use of coconut-derived materials situates design exploration within an existing biological resource system that is renewable, biodegradable, and deeply embedded in local ecological cycles. Second, the project reconnects contemporary design practice with traditional craft knowledge by involving artisans who possess tacit expertise in working with coconut-based materials. Such knowledge exchange supports the continuity of cultural practices while promoting sustainable material innovation (Dhar et al., 2025).

Third, the methodology emphasises participatory learning through observation, experimentation, reflection, and collaboration. Rather than promoting predetermined design outcomes, students were encouraged to develop material understanding through direct interaction with the coconut tree and its various components. This practice led approach reflects regenerative practice frameworks that prioritise relational learning, local knowledge systems, and collective experimentation as pathways toward ecological and social renewal (Or, 2021; King, 2022).

By structuring the design process around these principles, the Culture Code 2025 framework positions material exploration as a means of cultivating regenerative thinking within design education. The following phases describe how this approach was implemented through observation, material experimentation, product development, and craft collaboration.

## 3.2 PARTICIPANTS AND RESEARCH SCOPE

The study involved 84 undergraduate students from the Department of Integrated Design. Participants worked individually or in small collaborative groups within a structured research environment.

This research was conducted taking into consideration the ethical guidelines of University of Moratuwa. All participants including students and artisan collaborators provided consent and were made aware that their work, processes and collaborative activities maybe documented and included in research outputs.

At the start of the project, students were introduced to the central research objective: to explore how products developed from different parts of the coconut tree could contribute to regenerative ecosystems through material innovation and participatory design practice. Participants were expected to:

- Investigate the material properties of coconut derived resources
- Experiment with new product concepts using natural materials
- Consider cultural relevance and everyday usability
- Develop solutions that support sustainable and regenerative ecosystems

Rather than focusing solely on final product outcomes, the research emphasised learning through making, allowing regenerative thinking to emerge through direct engagement with materials, craft practices, and ecological systems.

## 3.3 RESEARCH PHASES

The methodology was structured around three interrelated phases, followed by a stage of prototyping and craft collaboration. These phases formed an iterative learning environment where observation, experimentation, reflection, and collaboration continuously informed the design process.

### 3.3.1 Phase 1: Observation, Immersion, and Cultural Learning

The first phase centred on material observation and cultural research. Students engaged with the coconut palm as a living ecological presence rather than simply as a design resource.

Participants explored different parts of the tree including husk, shell, fibre, fronds, trunk, and pith; documenting their observations through material journals, visual mappings, and sensory narratives. These exercises examined textures, traditional uses, cultural associations, and everyday interactions with the material.

This phase revealed how the coconut palm has historically supported domestic environments, craft traditions, and informal built spaces across Sri Lanka. Known locally as Kapruka, the “tree of life,” the coconut palm represents a system where material use is closely connected to ecological cycles and community knowledge (refer figures 2 and 3).

*Figure 2: Coconut material exploration as student studies*

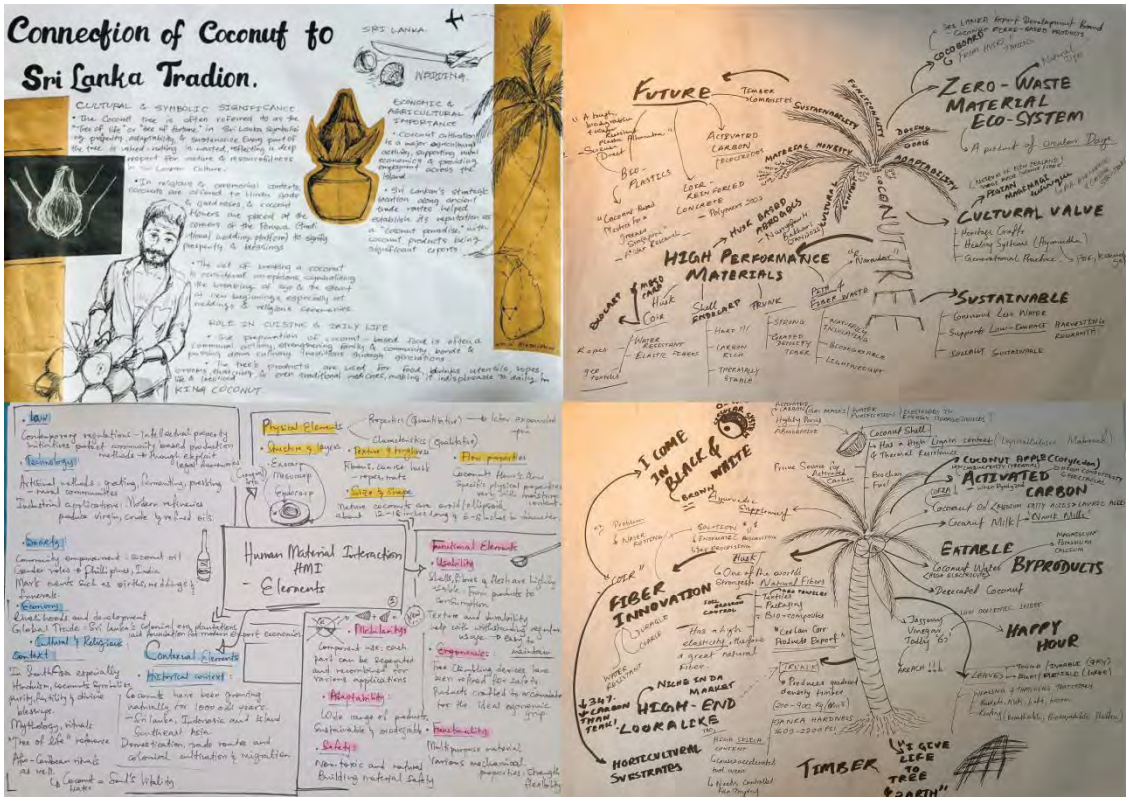



*Figure 3: Student material research journals with focus on cultural associations*

### 3.3.2 Phase 2: Material Exploration as Discovery

The second phase focused on hands on material experimentation, positioning making as the central research activity.

Students worked directly with coconut materials by cutting, charring, grinding, boiling, compressing, sanding, and binding different components of the tree. Through this process they explored properties such as strength, flexibility, acoustic behaviour, texture, and ageing. Material inconsistencies and failures were treated as opportunities for discovery. Repeated experimentation enabled participants to develop knowledge of material

behaviour, allowing design ideas to emerge organically from the material itself systems (refer figures 4 and 5).

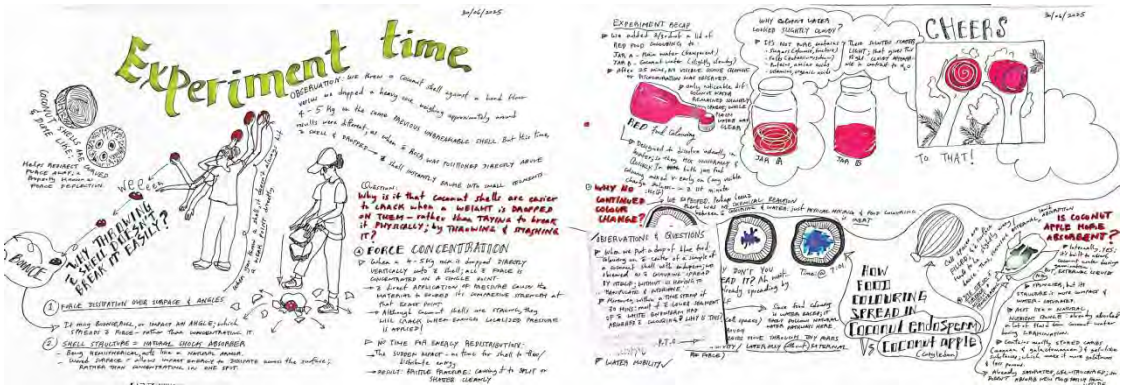



*Figure 4: Material experimentation process*

*Figure 5: Material testing outcomes*

One outcome of this phase was the exploration of experimental composites such as CocoBoard, a cork-like material created using coconut pith and natural starch binders. These explorations contributed to the broader understanding of coconut-based materials and their potential application within sustainable product.

### 3.3.3 Phase 3: Form, Meaning, and Contextual Translation

In the third phase students began translating their material discoveries into product concepts. Design development was guided by a balance between material behaviour, cultural meaning, and user experience. Rather than imposing predetermined aesthetics, students allowed the characteristics of coconut materials to guide form generation (refer Figure 6).

*Figure 6: Product concept developments, initial prototypes and market studies*

Concepts were evaluated based on usability, cultural relevance, and their potential to support everyday sustainable practices. To contextualise these ideas, students conducted market observations and research, visiting retail spaces and exhibitions while analysing contemporary product narratives and consumer behaviours.

### 3.3.4 Prototyping, Refinement, and Craft Collaboration

The final stage focused on prototyping and refinement, where concepts were translated into tangible designs. Students refined proportions, tested joinery techniques, and experimented with finishes to align design intentions with material behaviour. This process emphasised iterative learning and continuous improvement.

A key aspect of this stage was collaboration with local craftspeople who possess specialised knowledge of coconut-based materials. Students worked with artisans to translate design concepts into practical production techniques, gaining insight into the tacit knowledge embedded in traditional craft practices (refer figures 7 and 8).

*Figure 7: Final product prototypes*

*Figure 8: Artisan collaboration process*

Through this collaboration the project reinforced the participatory nature of regenerative design, demonstrating how knowledge exchange between designers and craft communities can contribute to sustainable material innovation.

## 4. RESULTS AND DISCUSSION

The outcomes of the Culture Code 2025 project demonstrate how practice-based design exploration can generate diverse product concepts rooted in regenerative material thinking. Through the participation of 84 students, a wide range of coconut-based products were developed. These products were organised into six thematic categories, each representing different ways in which coconut derived materials could interact with everyday environments. The findings presented in this section illustrate how coconut-based material systems can support regenerative design practices within the built environment in a holistic manner.

### 4.1 RE:CARRY – PORTABLE PRODUCT SYSTEMS

Eleven student projects focused on portable objects designed for everyday mobility and convenience.

These included wearable accessories, earphone cases, portable stands, and small personal objects developed using coconut shell and fibre components. The designs explored lightweight material use while maintaining durability and tactile quality. From a regenerative perspective, these products emphasise material longevity and user attachment, encouraging long term use rather than disposable consumption.

### 4.2 RE:LIVE – DOMESTIC PRODUCT SYSTEMS

18 student projects explored domestic objects that integrate natural materials into interior environments. These included lighting devices, planters, decorative elements, and small

household accessories that incorporate coconut shell and fibre structures. Such objects reintroduce natural materiality into everyday domestic spaces, strengthening sensory connections between people and natural materials.

### 4.3 RE:HEAL – WELLNESS AND CARE OBJECTS

Eleven student projects were developed around products that support physical and emotional wellbeing. Examples include massage tools, baby care products, aroma diffusers, and relaxation devices designed using coconut wood and shell elements. These designs emphasise ergonomics, tactility, and sensory engagement. These objects highlight how regenerative thinking can support human wellbeing while relying on biodegradable natural materials.

### 4.4 RE:NOURISH – FOOD AND KITCHEN PRODUCTS

24 student projects focused on culinary tools and food-related objects. These included spice infusers, juicers, serving utensils, and teapots developed using coconut shell and wood components. The designs encourage mindful cooking and shared food experiences while promoting the use of renewable materials.

### 4.5 RE:PLAY – LEARNING AND INTERACTION

Eight student projects explored playful and educational product systems. These designs include games and interactive objects that use sound, texture, and movement to encourage creative engagement. Coconut shell and fibre elements were used to create tactile and acoustic experiences. Such designs demonstrate how natural materials can support educational and cognitive engagement.

### 4.6 RE:WRAP – SUSTAINABLE PACKAGING SYSTEMS

Twelve student projects investigated sustainable packaging solutions. These projects reimagined packaging for products such as Ceylon arrack, Cinnamon, and Kithul based goods, using coconut-based materials to create biodegradable and culturally meaningful packaging alternatives. These packaging systems illustrate how regenerative design can extend beyond product objects to influence broader material cycles within production and consumption systems.

Taken collectively, the outcomes of the Culture Code 2025 project illustrate how participatory design education can contribute to regenerative material practices. The involvement of 84 student designers created a collaborative research environment where diverse ideas, experiments, and material interpretations emerged simultaneously. Through observation, making, and collaboration with craftspeople, participants developed an expanded understanding of how natural materials can operate within sustainable product systems.

The resulting product concepts demonstrate several regenerative qualities:

- Utilisation of renewable coconut-based materials
- Potential for biodegradable and circular material cycles
- Integration of traditional craft knowledge
- Development of products that encourage long term everyday use

These outcomes suggest that regenerative thinking can emerge not only through technological innovation but also through practice-based exploration and participatory learning environments. By examining the products developed through this process, the study demonstrates that coconut-based material systems can support regenerative design practices within the built environment, offering a culturally rooted pathway for sustainable product innovation.

## 5. CONCLUSIONS

This study set out to examine how regenerative thinking can be approached through material innovation and participatory design practice within the built environment. While sustainability initiatives have traditionally focused on reducing environmental impact, emerging regenerative perspectives emphasise restoring relationships between human activity, ecological systems, and cultural practices. The aim of this research was, therefore, to explore how a practice-based design approach, centred on coconut derived materials and collaborative experimentation, could contribute to regenerative practices.

Using the Culture Code 2025 project as a case study, the research engaged 84 design students in a participatory process of observation, material experimentation, product development, and collaboration with craftspeople. By revisiting the coconut palm as a holistic material system, the project enabled students to investigate the potential of its various components including leaves, shell, husk, fibre, and wood for contemporary product design.

The outcomes of the project demonstrate that coconut-based materials can support diverse product systems across domestic, portable, wellness, educational, and packaging contexts. More importantly, the process itself revealed how regenerative thinking can emerge through practice-based engagement with materials, communities, and ecological systems. Through experimentation, collaboration, and reflection, students developed products that emphasise renewable resources, cultural continuity, material longevity, and everyday usability.

Taken collectively, the findings suggest that regeneration is not solely a technological challenge but also a practice based and relational process. By engaging natural materials through participatory design processes, designers can develop products that contribute to sustainable material cycles while strengthening connections between people, materials, and local ecosystems.

This research is based on a single institutional context and focuses on one material system, which limits the generalisability of findings. Future research should extend this participatory, practice-based approach to other significant material systems and cultural contexts. Further work on how coconut-based product innovations might scale within the built environment industry, bridging the gap between educational prototypes and commercial applications would significantly advance the area of this study.

This research, therefore, demonstrates that product innovation using coconut derived materials, explored through participatory and practice led design education, can contribute to regenerative approaches within the built environment. Such initiatives highlight the importance of design education as a pathway for cultivating regenerative thinking and experimentation. Rather than presenting a universal model, the Culture Code framework illustrates how locally rooted material systems when explored collaboratively can provide meaningful pathways toward regenerative futures.

## 6. ACKNOWLEDGEMENTS

The author acknowledges the Level 2 students of the Department of Integrated Design, University of Moratuwa, and the contributors to the Culture Code 2025 publication, whose work, insights and dedication shaped this work.

## 7. REFERENCES

Asbjörn Sörensen, C., Bursell, A., Nikkola, N., & Musa, E. (2024). Regenerative product design: A literature review in an emerging field. *Proceedings of the International Conference on Engineering and Product Design Education, EPDE 2024*, (pp. 455–460). https://doi.org/10.35199/EPDE.2024.77

Buckton, S. J., Fazey, I., Sharpe, B., Om, E. S., Doherty, B., Ball, P., Denby, K., Bryant, M., Lait, R., Bridle, S., Cain, M., Carmen, E., Collins, L., Nixon, N., Yap, C., Connolly, A., Fletcher, B., Frankowska, A., Gardner, G., … Sinclair, M. (2023). The regenerative lens: A conceptual framework for regenerative social-ecological systems. *One Earth*, *6*(7), 824–842. https://doi.org/10.1016/j.oneear.2023.06.006

Dhar, B. K., Chawla, U., & Mulchandani, D. (2025). Sustainable craft culture: Socio-cultural drivers and economic impact on sustainable development. *Sustainable Development*, *33*(2), 3023–3042. https://doi.org/10.1002/sd.3282

King, J. (2022). Shades of becoming toward regenerative futures: Revelatory purposes and process in sustainability education and public pedagogy. *Journal of Public Pedagogie*s, (6), 39–56. https://doi.org/10.15209/jpp.1244

Kumar, S., Sakagami, K., & Lee, H. P. (2025). Beyond sustainability: The role of regenerative design in optimizing indoor environmental quality. *Sustainability*, *17*(6), 2342. https://doi.org/10.3390/su17062342

Or, Y. (2021). Regenerative practice as transformative design framework. In R. M. Leitão, I. Men, L.-A. Noel, J. Lima, & T. Meninato (Eds.), *Pivot 2021: Dismantling/Reassembling: Proceedings of the Pivot 2021 Conference, July 22–23, 2021*. https://doi.org/10.21606/pluriversal.2021.0024

Yunibandhu, R., & Hallinger, P. (2025). From sustainability to regeneration: Mapping the conceptual foundations and future directions of regenerative development. *Sustainable Development*, *33*(6), 8569–8585. https://doi.org/10.1002/sd.70112

Nimesha, J.S., Kulatunga, U. and Subhasingha, H.D., 2026. Microclimate-aware urban planning in tropical climates: A review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1180-1194. DOI: https://doi.org/10.31705/WCS.2026.86. Available from: https://ciobwcs.com/papers/

# MICROCLIMATE-AWARE URBAN PLANNING IN TROPICAL CLIMATES: A LITERATURE REVIEW

**J.S. Nimesha[1], U. Kulatunga[2] and H.D. Subhasingha[3]**

## *ABSTRACT*

*Rapid urbanization has adversely affected urban microclimates, especially in tropical regions, where high temperatures, humidity, and seasonal monsoon patterns exacerbate environmental degradation. In tropical urban environments, replacing natural landscapes with man-made structures during urbanisation alters microclimatic parameters such as air temperature, relative humidity, and wind speed. These microclimatic changes cause negative impacts on urban areas, such as leading to thermal discomfort and increased energy demand. Despite these risks, economic interests often take precedence because in tropical climates, urban planning lacks the necessary regulatory frameworks and microclimatic awareness to prioritize sustainability by addressing the localised characteristics. Therefore, the present research aims to develop a comprehensive framework that promotes microclimate-aware urban planning in tropical climates. Initially, a background study was conducted to establish a clear research problem, aim, and objectives. This was followed by a comprehensive literature review to identify key relationships between microclimate, urban planning, and urban design strategies. To further refine these concepts, a bibliometric analysis was executed using VOSviewer software. Through the comprehensive literature review, this study identifies the linkage between urban design strategies, their key mitigation mechanisms, the negative impacts of urbanisation, and broader negative consequences for the overall tropical urban environment. By linking urban design strategies such as nature-based solutions, sustainable materials, and building morphology to specific environmental outcomes, the developed framework provides a clear pathway for utilising passive and bioclimatic urban design strategies to improve the quality of life in tropical cities. The developed framework serves as a foundational tool for initiating these essential planning interventions.*

***Keywords:*** *Microclimate; Tropical Climate; Urban Design Strategies; Urbanization.*

## 1. INTRODUCTION

In recent decades, urbanization has experienced significant growth, and as a result, rapid industrialization has taken place (Roy et al., 2025). According to the United Nations Department of Economic and Social Affairs, 2018, by 2050, it is anticipated that two-thirds of the world's population will live in urban regions (Czachura et al., 2022). This significant growth in urbanization has led to a variety of environmental problems (Roy et

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, snimesha501@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Temporary Instructor, Department of Building Economics, University of Moratuwa, Sri Lanka, subhasinghahd.20@uom.lk

al., 2025). Furthermore, the researcher states that, according to NASA/GISS, in 2023, the Earth's temperature increased by approximately 2.45°F compared to the 19th century. These climatic changes globally affect people's health and livelihoods, as well as ecosystem health and biodiversity (Zhu et al., 2023). With rapid urbanization, natural surroundings are replaced by man-made structures. Under a changing climate, the physical properties of these man-made structures directly affect the living environment of the urban microclimate (Yang et al., 2023).

According to Roy et al. (2025) microclimates are the localized climates within small areas that focus on atmospheric conditions near a specific point on Earth's surface, often related to living organisms such as insects or crops. These climates are influenced by factors such as building size and shape, surface albedo, vegetation, and water bodies (Ghiasi et al., 2024). Jia et al. (2024) and Gupta and Haque (2025) stated that an urban local microclimate is reflected by parameters such as local air temperature, relative humidity, wind speed, and direction, which directly affect the health, comfort, and energy consumption of city residents. Due to changes associated with urbanization, such as land use and energy consumption, urban areas can retain and generate more heat than rural regions, leading to higher ground surface and air temperatures near the ground, ultimately resulting in the urban heat island effect, urban pollution island, and urban moisture island (Jia et al., 2024; Yang et al., 2023). In addressing the impact of urbanization on the microclimate, different design strategies can be considered since the amount of energy needed to cool buildings can be reduced as these elements can improve natural cooling and effectively reduce heat loss and heating needs (Roy et al., 2025).

Due to consistent high temperatures with a two-season cycle of wet and dry periods, buildings in tropical regions consume disproportionately more energy to achieve indoor thermal comfort than those in temperate zones (Lee et al., 2021; Pragati et al., 2023). During urban planning, failing to account for these specific characteristics leads to significant microclimatic environmental failure. For instance, while dense urban clusters in four-season temperate climates are designed to trap heat and block cold winter winds as seen in frameworks by Taleghani et al. (2015) for the Netherlands or Jia et al. (2024) for continental zones, this same strategy in a tropical setting blocks the prevailing breezes essential for physiological cooling. Without strategic wind corridors, humidity becomes oppressive, and air pollutants settle at the street level, creating a detrimental stagnant heat effect (Giridharan & Emmanuel, 2018).

Despite these risks, a critical geographical bias exists in urban microclimate literature. While many studies focus on microclimates where seasonal variation dominates, there is a profound lack of evidence-based research specifically for the humid tropics (Roth, 2007). This lack of data has created a situation where current urban design guidelines are often based on temperate-climate evidence and forced to rely on general planning guidelines that are fundamentally incompatible with the high-humidity, high-solar-intensity nature of tropical climates, ultimately leading to unsustainable and thermally uncomfortable urban growth (Emmanuel, 2021; Wong et al., 2021).

Therefore, addressing how to mitigate the negative impacts of urbanisation in tropical climates through integrated urban design strategies is essential for managing microclimatic conditions within a tropical climate. To resolve this geographical mismatch, this study addresses a fundamental question: How can integrated urban design strategies mitigate the negative impacts of urbanization on microclimates within tropical

regions? To address this gap, the present research aims to develop a comprehensive framework that promotes microclimate-aware urban planning in tropical climates. Four key objectives are developed to achieve the aim: to comprehensively review the key concepts related to urban planning and microclimate, to identify the impact of microclimate on the urban environment, to comprehensively review the influence of urban design strategies on microclimatic conditions in tropical climates, and to develop a comprehensive framework that promotes microclimate-aware urban planning in tropical climates. Hereinafter, the paper comprises a methodology, findings, conclusions, and recommendations.

## 2. RESEARCH METHODOLOGY

Research methodology is the science of studying how research is conducted systematically, and here the procedural steps that have been taken to study the research problem are explained (Mishra & Alok, 2017). To address the critical geographical bias in urban microclimate literature, specifically the lack of evidence-based guidelines for humid tropical climates, this study adopted a comprehensive literature review. This methodology establishes a transparent, rigorous process to answer the core research question: How can integrated urban design strategies mitigate the negative impacts of urbanization on microclimates within tropical regions? The overview of the most important findings in the field in which the study will be conducted is described in the first background study. To precisely define the research problem, aim, and objectives of the study, a background study was conducted. Afterwards, a comprehensive literature review was conducted, and the collected literature was analysed to address the identified literature gap. A literature review is a systematic method for collecting and synthesizing previously conducted research (Snyder, 2019). The review progressed through a four-stage process, as illustrated in Figure 1.

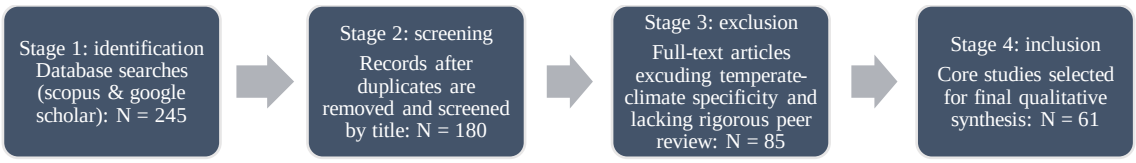



*Figure 1: Review process*

To ensure a comprehensive and reliable academic foundation, literature was systematically gathered from primary electronic databases, including Google Scholar and Scopus. To maintain high methodological rigour, clear boundaries were applied during the screening process. While these procedural frameworks originate from non-tropical academic contexts such as Snyder (2019) in Sweden and Donthu et al. (2021) in the US/India, they provide universal, climate-independent methodological guidelines for structuring rigorous systematic reviews. Furthermore, this review included peer-reviewed journal articles, foundational books, and major conference papers that focus on microclimates and urban design. It excluded grey literature lacking peer review as well as journal articles that were strictly specific and unique to temperate climates. To extract the meaning of microclimate to accomplish objectives 1 and 2, a bibliometric analysis was conducted. Bibliometric analysis is used by researchers for numerous purposes, including investigating the intellectual structure of a specific area within the existing literature and identifying emerging trends in article and journal performance, collaboration patterns, and research elements (Donthu et al., 2021). In this research, the

bibliometric analysis was done using VOSviewer and data sourced from PubMed data source. While Google Scholar and Scopus were utilized to search for and read the core papers used in the literature tables, PubMed was used exclusively for the visual keyword map due to the technical requirements of the mapping software, VOSviewer. VOSviewer is built to natively support files from only a few specific databases, and Google Scholar was excluded because it does not allow users to bulk-download the structured data files required to create the map. Furthermore, while Scopus is a great search tool, it enforces strict download limits per file. PubMed was chosen for this specific task because it integrates perfectly with VOSviewer, is completely free, and easily allows the download of up to 10,000 records at once without breaking the files or losing critical information. When referring to journal articles, books, and conference papers that are related to research and theory, the impact of urbanization on microclimate and the impact of microclimate on various aspects of the urban environment were identified. Furthermore, the literature review discovered methods to reduce the negative impact of microclimatic conditions on various aspects of the urban environment through urban variables. At last, a framework has been developed by analysing gathered data from the literature review.

# 3. RESULTS AND FINDINGS

## 3.1 MICROCLIMATE AND MICROCLIMATIC PARAMETERS

Microclimate is defined as the climatic conditions at a microscale on the Earth's underlying surface, differentiating it from macroscales and mesoscales (Yang et al., 2023). The microscale spans under 1 km horizontally, up to about 2 km at most (Zhu et al., 2023). In meteorology, a microclimate arises within this range, driven mainly by features close to the ground (Fujiwara et al., 2024). Urban local microclimate refers to the local climatic conditions within a micro-scale area (Jia et al., 2024). More broadly, the urban microclimate encompasses the immediate surrounding environment around building clusters inside the urban boundary layer, including any climatic phenomena of urban physics, with a height of two to five times the average building height (Yang et al., 2024). According to Li et al. (2022), the microclimate in small-scale spaces can be significantly influenced by urban planners through various artificial means during city design and construction, helping the city better adapt to larger macro-climatic conditions.

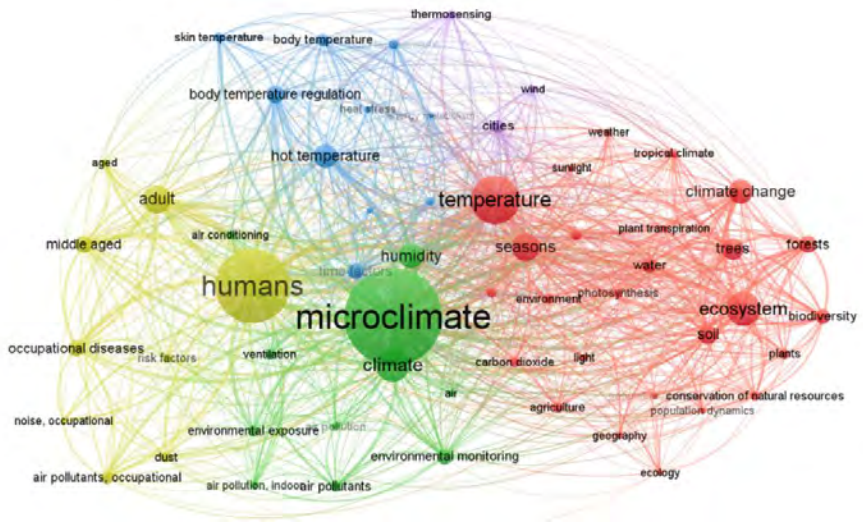



*Figure 1: bibliometric analysis on the concept of microclimate*

The above Figure 2 illustrates a bibliometric network regarding the concept of microclimate. The specific analysis presented here was conducted using data sourced from PubMed. According to the above Figure 2, the green cluster serves as the bridge between the physical environment and the other thematic areas. The red cluster focuses on the broader environmental scale linking climate change, ecosystems, and forests, and the yellow & blue clusters connect the environmental data to the biological reality of urban dwellers. This map serves as a powerful evidence-based justification for the research, showing that urban planning in the tropics is not just about buildings, but about managing a complex relationship between nature and human biology.

Microclimate encompasses factors such as wind aerodynamics, thermal comfort, energy demand, and pollutant dispersion (Yang et al., 2023). The following Table 1 shows the microclimatic parameters that have been identified by researchers.

*Table 1: Microclimatic parameters*

| Item No | Microclimatic Parameter | Source |
|---|---|---|
| 1 | Wind Speed | [2], [3], [4], [5], [6], [7], [11], [14], [18], [20], [21] |
| 2 | Wind Direction | [7], [11], [18], [20] |
| 3 | Wind Aerodynamics. | [1] |
| 4 | Pollution Dispersion | [1], [3], [15], [17] |
| 5 | Wind-Driven Rain | [1] |
| 6 | Air Temperature | [2], [3], [4], [5], [6], [8], [9], [10], [11], [14], [16], [18], [19], [21] |
| 7 | Relative Humidity | [2], [3], [5], [6], [8], [11], [14], [16], [18], [19], [21] |
| 8 | Solar Radiation | [2], [3], [5], [6], [8], [14], [18], [20] |
| 9 | Air Pressure | [3], [10] |
| 10 | Shadow Effect | [11], [12], [13], [14] |

[1] (Yang et al., 2023) [2] (Zhu et al., 2023) [3] (Roy et al., 2025) [4] (Toparlar et al. 2017) [5] (Jia et al., 2024) [6] (Fujiwara et al., 2024) [7] (Yang et al., 2024) [8] (De Groeve et al., 2024) [9] (Antoniou et al., 2024) [10] (Fu et al., 2025) [11] (Ghiasi et al., 2024) [12] (Song et al., 2025) [13] (Liu et al., 2024) [14] (Ni et al., 2025) [15] (Li et al. 2022)[16] (Salmanian & Ujang, 2022) [17] (Leng et al., 2022) [18] (Shafaghat et al., 2016) [19] (Lai et al., 2019) [20] (Toparlar et al., 2017) [21] (Peng et al., 2018)

## 3.2 IMPACTS OF URBANIZATION ON MICROCLIMATE

Rapid urbanization is a key characteristic of modern economic and social development, particularly in highly populated cities (Roy et al., 2025). The researcher further stated that this growth significantly impacts the urban microclimate, leading to a variety of environmental problems. Urban areas, dominated by rigid structures, differ greatly from rural or vegetated settings because land cover and morphology change the surface atmosphere heat exchange (Jia et al., 2024). A primary consequence of this transition is the UHI effect, where urban air temperatures remain consistently higher than those in

surrounding rural areas (Salmanian & Ujang, 2022; Toparlar et al., 2017; Yang et al., 2023). This phenomenon is most pronounced in regions with rapid population surges and urban growth (Meng et al., 2024). UHI occurs because urban surfaces, such as asphalt, brick, and concrete, possess different thermal and radiative properties compared to natural landscapes (Lee et al., 2021). These materials have high heat capacities and low albedo, meaning they absorb more solar radiation during the day and release it as waste heat at night (De Groeve et al., 2024; Lee et al., 2021). The negative implications of UHI are extensive, including increased monthly rainfall, prolonged growing seasons, and the deterioration of air and water quality, all of which compromise human health and ecosystem stability (Lee et al., 2021). To counter these effects, researchers have proposed the Urban Cooling Island (UCI) effect utilising blue and green infrastructure as a natural air conditioning method (Meng et al., 2024).

Beyond materials, the physical arrangement of a city, its morphology, plays a critical role in microclimatic variation (Meng et al., 2024). While dense, high-rise developments provide shading that can improve outdoor comfort by reducing direct sunlight, they simultaneously lower the Sky View Factor (SVF) (Czachura et al., 2022; Yi et al., 2023). A reduced SVF restricts the ability of the ground to cool itself through long-wave radiation to the sky (Giyasova, 2021; Yi et al., 2023). Furthermore, the close proximity of buildings increases solar and infrared inter-reflections between adjacent surfaces, trapping heat within the urban canyon (Lauzet et al., 2019). The loss of vegetation exacerbates these issues. The replacement of green spaces with paved surfaces eliminates evapotranspiration, a vital natural cooling process (Lee et al., 2021). Consequently, the sensible heat flux increases while the latent heat flux decreases, further intensifying localised warming.

Urbanisation also fundamentally reshapes the urban wind environment (Leng et al., 2022). High-rise structures can channel high-altitude, high-speed winds down to the surface, creating hazardous conditions for pedestrians (Tse et al., 2017). Conversely, densely packed building clusters can block natural ventilation, preventing the dissipation of heat and pollutants (Leng et al., 2022; Yim et al., 2009).

### 3.3 IMPACT OF MICROCLIMATE ON VARIOUS ASPECTS OF THE URBAN ENVIRONMENT

The urban microclimate, including phenomena such as urban heat island, influences many aspects of cities, from health to building energy use (Roy et al., 2025). Table 2 presents such impacts according to the conducted studies.

*Table 2: Impact of microclimate on the environment*

| Item No | Impact of microclimate on the environment | Source |
|---|---|---|
| 1 | Thermal discomfort | [1], [4], [5], [6], [7], [11], [12], [14], [16] |
| 2 | Building energy consumption | [1], [3], [4], [5], [6], [8], [12], [13], [17] |
| 3 | Health and wellbeing of residents | [1], [2], [4], [5], [7], [10], [11], [15], [16] |

| Item No | Impact of microclimate on the environment | Source |
|---|---|---|
| 4 | Air quality | [3], [4], [5], [9] |
| 5 | Urban wind environment | [3] |
| 6 | Urban pollution island | [3], [10] |
| 7 | Health of the ecosystem and biodiversity | [2] |

[1] (Czachura et al., 2022) [2] (Zhu et al., 2023) [3] (Yang et al., 2023) [4] (Toparlar et al., 2017) [5] (Roy et al., 2025) [6] (Jia et al., 2024) [7] (Fujiwara et al., 2024) [8] (Yang et al., 2024) [9] (Meng et al., 2024) [10] (De Groeve et al., 2024) [11] (Antoniou et al., 2024) [12] (Fu et al., 2025) [13] (Ghiasi et al., 2024) [14] (Song et al., 2025) [15] (El-Bahrawy, 2024) [16] (Wang et al., 2023) [17] (Pragati et al., 2023)

## 3.4 STRATEGIES TO REDUCE THE NEGATIVE IMPACT OF MICROCLIMATIC CONDITIONS ON VARIOUS ASPECTS OF THE URBAN ENVIRONMENT DURING URBAN PLANNING

The urban design strategies play a significant role in reducing the negative impacts of microclimatic changes caused by urbanization (Semeraro et al., 2024). With the help of the strategic combination of various factors, urban planners and designers can improve thermal comfort, reduce energy usage, and develop more sustainable and liveable cities (Salvati & Kolokotroni, 2023). Urban strategies are particularly relevant, given that the urban microclimate directly impacts the quality of life of the people living in it (Li et al., 2022).

- Trees / Vegetation

Urban vegetation is a primary strategy for mitigating negative microclimate impacts and improving pedestrian thermal comfort (Adıgüzel, 2023; Dissanayake et al., 2023; Liu et al., 2024). Trees provide significant cooling by shading surfaces and regulating radiation, with the effect magnitude determined by species, leaf density, and canopy arrangement (Adıgüzel, 2023; Fu et al., 2025; Fujiwara et al., 2024; Guerri et al., 2023). Complementary infrastructure, such as green walls and roofs, supports Sustainable Development Goal 11 by lowering ambient temperatures through transpiration and shadowing (Adıgüzel, 2023; Pragati et al., 2023; Roy et al., 2025). The performance of these systems depends on plant species, orientation, and local environmental conditions (De Groeve et al., 2024; Pragati et al., 2023).

- Water Bodies

Water bodies significantly mitigate urban overheating by reducing ambient temperatures by 1-2°C (Roy et al., 2025; Shafaghat et al., 2016). This cooling and humidifying effect is most notable within a 9-18 meter radius, enhancing overall human comfort (Lai et al., 2022). Despite these benefits, water bodies can negatively impact nighttime temperatures due to thermal storage (Ampatzidis & Kershaw, 2020). Their cooling potential is particularly vital for tropical cities, though high evaporation rates can limit their effectiveness in coastal areas (Yang et al., 2023).

- Courtyards

Courtyards are also identified as a sustainable approach that enhances thermal comfort and reduces energy use (Taleghani et al., 2015). The geometry of a courtyard, its orientation, openings, wall materials, and landscaping define the microclimate of a

courtyard (Zhu et al., 2023). Wei et al. (2016) observed that the geometry of a courtyard and especially its shape may have an impact on solar radiation and airflow, which are essential parameters of the microclimate.

- Building Morphology (Building Height, Density, Orientation)

Urban morphology, including building height, density, and orientation, critically influences microclimates by regulating sun exposure and shadowing (Liu et al., 2024; Meng et al., 2024; Song et al., 2025). While increased density and lower building heights generally elevate temperatures, building density has a negligible impact on nighttime heat (Lin et al., 2017; Meng et al., 2024). Urban canyons further modify environments by retaining heat and reducing natural ventilation (Salvati & Kolokotroni, 2023). Although dense structures offer beneficial street-level shade, they also act as wind shields. However, high-rise buildings can counteract this by amplifying street-level winds via downwash flow (Fujiwara et al., 2024; Lin et al., 2023; Middel et al., 2014; Ng et al., 2011).

- Material permeability and surface roughness

Reflective surfaces and "cool" materials effectively mitigate the urban heat island effect, though they can occasionally decrease pedestrian comfort due to glare (Elnabawi & Jamei, 2024; Yang et al., 2023). Thermal efficiency is further improved by using lightweight concrete and phase-change materials, which reduce cooling loads, while high-heat materials like stone and petroleum-based flooring should be limited (Adıgüzel, 2023; Lee et al., 2021). Urban surface roughness significantly impacts ventilation, reducing wind speeds by up to 30% generally and 60% in dense areas (Salvati & Kolokotroni, 2023). The researcher further states that these changes increase turbulence and limit the natural cooling potential of free-stream air above buildings.

- Shadow Areas

Building layouts can be strategically designed to create beneficial shadows, improving local thermal conditions and mitigating urban heat island effects (Han et al., 2023; Liu et al., 2023). Artificial structures, such as man-made urban trees, serve as efficient shading tools that can even surpass vegetative cooling in high-rise residential areas (Sun et al., 2024). The extent of daytime shading significantly impacts thermal comfort and is negatively correlated with the sky view factor, a key shading indicator (Ni et al., 2025). Consequently, sky view factor should be integrated into thermal comfort studies alongside vegetation coverage and pavement material types (Liu et al. 2024). These architectural and environmental interventions, summarized in Table 3, represent essential strategies for stabilizing urban ambient conditions.

*Table 3: Urban design strategies*

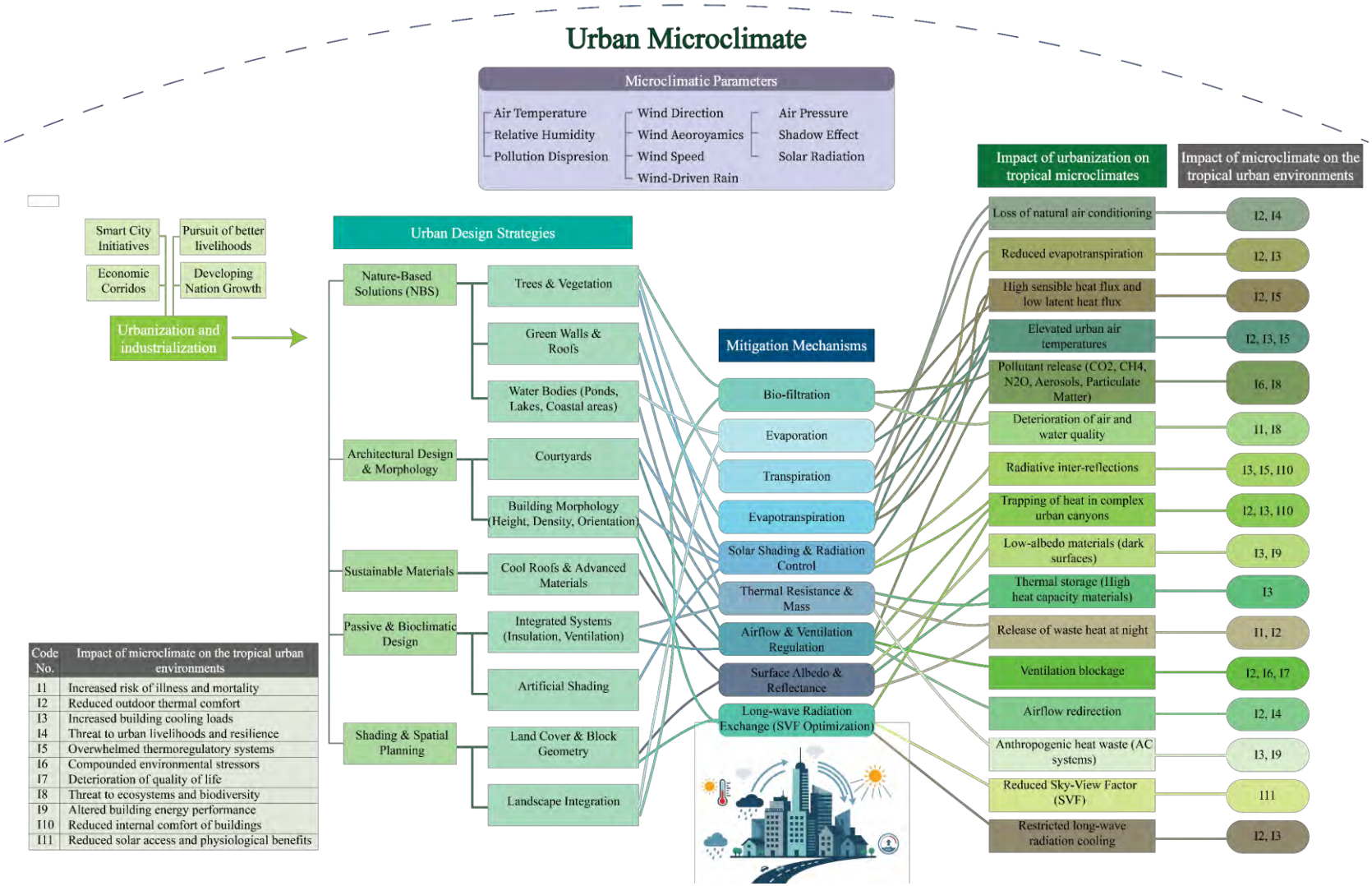
| Item No | Urban design strategies | Source |
|---|---|---|
| 1 | Trees/vegetation | [1], [3], [4], [5], [6], [7], [8], [9], [11], [15], [16], [17], [18], [19] |
| 2 | Water bodies | [1], [3], [6], [13], [17] |
| 3 | Green walls and roofs. | [1], [3], [7], [19] |
| 4 | Street canyons. | [1], [6], [14] |

| Item No | Urban design strategies | Source |
|---|---|---|
| 5 | Courtyards | [2], [11] |
| 6 | Topography | [3] |
| 7 | Block geometry | [4], [11] |
| 8 | Land cover | [4], [11] |
| 9 | Building morphology (building height, density, orientation). | [2], [4], [5], [6], [10], [11], [14] |
| 10 | Landscape | [6], [17] |
| 11 | Nature of building materials | [1], [5], [8], [14], [15], [20] |
| 12 | Canopy covers | [8], [12], [18] |
| 13 | Shadow effect from neighbouring objects | [9], [10], [11], [12] |
| 14 | Passive design strategies such as combined night Ventilation, shading in the building envelope, light-colored coatings, and thermal insulation | [19] |

[1] (Yang et al., 2023) [2] (Zhu et al., 2023) [3] (Roy et al., 2025) [4] (Jia et al., 2024) [5] (Fujiwara et al., 2024) [6] (Meng et al., 2024) [7] (De Groeve et al., 2024) [8] (Fu et al., 2025) [9] (Ghiasi et al., 2024) [10] (Song et al., 2025) [11] (Liu et al., 2024) [12] (Ni et al., 2025) [13] (Shafaghat et al., 2016) [14] (Salvati & Kolokotroni, 2023) [15] (Adıgüzel, 2023) [16] (Dissanayake et al., 2023) [17] (Lai et al., 2022) [18] (Wang et al., 2023) [19] (Pragati et al., 2023) [20] (Lee et al., 2021)

## 3.5 FRAMEWORK

The conceptual framework was logically derived by systematically mapping the findings from the literature synthesis into a causal, step-by-step structural pathway. The process begins with urbanisation and industrialisation, driven by factors such as smart city initiatives, economic corridors, and the pursuit of better livelihoods in developing nations. These urban shifts directly alter the core microclimatic parameters established in Table 1, including air temperature, humidity, wind dynamics, and solar radiation, leading to significant environmental impacts. To address these changes, the framework proposes urban design strategies extracted from Table 3, such as nature-based solutions, architectural morphology, and sustainable materials. Rather than presenting these strategies as isolated concepts, the framework explicitly maps them to the specific functional mechanisms they trigger, such as transpiration (Adıgüzel, 2023; Pragati et al., 2023), evaporation (Roy et al., 2025), biofiltration (Abdo & Huynh, 2021), evapotranspiration (Lee et al., 2021), and solar shading (Adıgüzel, 2023; Han et al., 2023; Wei et al., 2016), which serve as the direct link for counteracting the negative impacts of urbanisation. For instance, the loss of natural air conditioning caused by urbanisation is conceptually mapped to, and neutralized by, the transpiration and evaporation mechanisms provided by integrated greenery. Finally, the framework achieves logical completeness by linking these microclimatic shifts directly back to the broader urban ecosystem consequences categorized in Table 2. For example, the loss of natural air conditioning is mapped directly to its corresponding alphanumeric indicators, showing how it triggers reduced outdoor thermal comfort (I2) and significant threats to urban livelihoods and resilience (I4). By explicitly mapping strategies to active physical mechanisms and mechanisms to final environmental outcomes, this framework provides a clear and logically derived pathway for utilising passive and bioclimatic urban design strategies to improve the quality of life in tropical cities. The following Figure 3 illustrates the conceptual framework derived from this systematic mapping of the literature review.




| Code No. | Impact of microclimate on the tropical urban environments |
|---|---|
| I1 | Increased risk of illness and mortality |
| I2 | Reduced outdoor thermal comfort |
| I3 | Increased building cooling loads |
| I4 | Threat to urban livelihoods and resilience |
| I5 | Overwhelmed thermoregulatory systems |
| I6 | Compounded environmental stressors |
| I7 | Deterioration of quality of life |
| I8 | Threat to ecosystems and biodiversity |
| I9 | Altered building energy performance |
| I10 | Reduced internal comfort of buildings |
| I11 | Reduced solar access and physiological benefits |

*Figure 3: Framework for microclimate-aware urban planning in tropical climates*

## 4. CONCLUSIONS AND RECOMMENDATIONS

Through a rigorous combination of a comprehensive literature review and bibliometric mapping, this research establishes that managing a tropical microclimate requires moving beyond standard physical development to orchestrate a complex relationship between the physical environment and human biology. Ultimately, integrating passive and bioclimatic design variables into urban frameworks is not just a structural choice, but an essential public health and environmental intervention necessary to foster long-term urban liveability.

To achieve the overarching aim of this study, four integrated research objectives were pursued. First, the key concepts of urban planning and microclimate were comprehensively reviewed, establishing that localized parameters such as temperature, wind, and radiation within a 1km microscale can be deliberately modified through urban design. Second, the study identified the direct impacts of altered microclimates on the urban environment, showing how localized warming accelerates building energy consumption, degrades air quality, and causes severe outdoor thermal discomfort. Third, a comprehensive review of urban design strategies in tropical climates revealed that while vegetation, water bodies, and building morphology can mitigate heat, their placement must be carefully balanced to prevent wind obstruction or nighttime heat retention. Finally, these findings were synthesized to develop a comprehensive, microclimate-aware framework for tropical cities, providing a structured pathway that links passive bioclimatic strategies to functional mitigation mechanisms like evapotranspiration and solar shading to enhance urban resilience.

The conceptual framework developed in this study serves as a foundational blueprint to operationalize microclimate-aware urban planning in tropical regions. It explicitly illustrates the structured pathway, and the framework bridges the gap between spatial interventions, including nature-based solutions, altered building morphology, and sustainable materials, and their environmental outcomes. These interventions activate critical mitigation mechanisms, such as evapotranspiration, solar shading, and airflow regulation, which directly counteract the localized heat accumulation, wind blockage, and pollutant stagnation caused by dense man-made structures. Furthermore, the framework maps exactly how these microclimatic shifts translate to broader negative consequences for the overall tropical urban ecosystem. By clearly linking specific design strategies to the mitigation of distinct environmental failures (such as the restricted long-wave radiation cooling caused by low sky-view factors), the framework equips urban planners and policymakers with a clear, predictive tool. This allows decision-makers to shift away from generalized planning methods and prioritize targeted bioclimatic interventions, offering an evidence-based pathway to improve the thermal safety, energy efficiency, and overall quality of life in tropical cities.

## 5. REFERENCES

Abdo, P., & Huynh, B. P. (2021). An experimental investigation of green wall bio-filter towards air temperature and humidity variation. *Journal of Building Engineering*, *39*, 102244. https://doi.org/10.1016/j.jobe.2021.102244

Adıgüzel, F. (2023). Effects of green spaces on microclimate in sustainable urban planning. *International Journal of Environment and Geoinformatics*, *10*(3), 124–131. https://doi.org/10.30897/ijegeo.1342287

Ampatzidis, P., & Kershaw, T. (2020). A review of the impact of blue space on the urban microclimate. *Science of The Total Environment*, *730*, 139068. https://doi.org/10.1016/j.scitotenv.2020.139068

Antoniou, N., Montazeri, H., Blocken, B., & Neophytou, M. (2024). On the impact of climate change on urban microclimate, thermal comfort, and human health: Multiscale numerical simulations. *Building and Environment*, *260*, 111690. https://doi.org/10.1016/j.buildenv.2024.111690

Czachura, A., Gentile, N., Kanters, J., & Wall, M. (2022). Identifying potential indicators of neighbourhood solar access in urban planning. *Buildings*, *12*(10), 1575. https://doi.org/10.3390/buildings12101575

De Groeve, M., Kale, E., Godts, S., Orr, S. A., & De Kock, T. (2024). Impact of vertical greening on urban microclimate and historic building materials: A meta-analysis. *Building and Environment*, *253*, 111365. https://doi.org/10.1016/j.buildenv.2024.111365

Dissanayake, C., Kawshalya, L. W. G., & Weerasinghe, U. G. D. (2023). The influence of planting arrangement on outdoor thermal comfort. *International Review for Spatial Planning and Sustainable Development*, *11*(3), 78–101. https://doi.org/10.14246/irspsd.11.3_78

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, *133*, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

El-Bahrawy, A. M. F. (2024). Investigating ladybug as a tool for measuring outdoor thermal comfort in urban neighborhoods. *Journal of Engineering Sciences*, *52*(1), 33–57. https://pdfs.semanticscholar.org/dc15/2d53c73520133c2ec320bc0d74e226312505.pdf

Elnabawi, M. H., & Jamei, E. (2024). The thermal perception of outdoor urban spaces in a hot arid climate: A structural equation modelling (SEM) approach. *Urban Climate*, *55*, 101969. https://doi.org/10.1016/j.uclim.2024.101969

Emmanuel, R. (2021). Urban microclimate in temperate climates: a summary for practitioners. *Buildings and Cities*, *2*(1), 402–410. https://doi.org/10.5334/bc.109

Fu, H., Jiao, Y., Deng, L., & Wang, W. (2025). Dynamic impacts of vegetation growth and urban development on microclimate and building energy consumption. *Sustainable Cities and Society*, *126*, 106382. https://doi.org/10.1016/j.scs.2025.106382

Fujiwara, K., Khomiakov, M., Yap, W., Ignatius, M., & Biljecki, F. (2024). Microclimate vision: Multimodal prediction of climatic parameters using street-level and satellite imagery. *Sustainable Cities and Society*, *114*, 105733. https://doi.org/10.1016/j.scs.2024.105733

Ghiasi, S., Passe, U., & Thompson, J. R. (2024). Addressing the need for microclimate considerations in doe reference building prototypes for urban energy simulation with a focus on the urban shadow effects. *Proceedings of SimBuild conference 2024* (pp. 511 – 517). International Building Performance Simulation Association. https://publications.ibpsa.org/conference/paper/?id=simbuild2024_2177

Giridharan, R., & Emmanuel, R. (2018). The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: A review. *Sustainable Cities and Society*, *40*, 677–687. https://doi.org/10.1016/j.scs.2018.01.024

Giyasova, I. (2021). Factors affecting microclimatic conditions in urban environment. *E3S Web of Conferences*, *244*, 06010. https://doi.org/10.1051/e3sconf/202124406010

Guerri, G., Crisci, A., & Morabito, M. (2023). Urban microclimate simulations based on GIS data to mitigate thermal hot-spots: Tree design scenarios in an industrial area of Florence. *Building and Environment*, *245*, 110854. https://doi.org/10.1016/j.buildenv.2023.110854

Gupta, K., & Haque, M. (2025). Optimizing microclimatic design in urban environments: Study of methods and strategies for residential clusters. *Civil Engineering and Architecture*, *13*(3), 1858–1874. https://doi.org/10.13189/cea.2025.130330

Han, Y., Jo, Y., & Kim, E. J. (2023). Influence of landscape interventions on thermal comfort under time-varying building shadow; new Gwanghwamun square case, Seoul, South Korea. *Heliyon*, *9*(9), e19436. https://doi.org/10.1016/j.heliyon.2023.e19436

Jia, Q., Zhu, Y., Zhang, T., Li, S., Han, D., Feng, Q., Tan, Y., & Li, B. (2024). Urban microclimate differences in continental zone of China. *Renewable and Sustainable Energy Reviews*, *197*, 114392. https://doi.org/10.1016/j.rser.2024.114392

Lai, D., Liu, W., Gan, T., Liu, K., & Chen, Q. (2019). A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Science of The Total Environment*, *661*, 337–353. https://doi.org/10.1016/j.scitotenv.2019.01.062

Lai, Y., Ning, Q., Ge, X., & Fan, S. (2022). Thermal regulation of coastal urban forest based on ENVI-Met model: A case study in Qinhuangdao, China. *Sustainability*, *14*(12), 7337. https://doi.org/10.3390/su14127337

Lauzet, N., Rodler, A., Musy, M., Azam, M.-H., Guernouti, S., Mauree, D., & Colinart, T. (2019). How building energy models take the local climate into account in an urban context - A review. *Renewable and Sustainable Energy Reviews*, *116*, 109390. https://doi.org/10.1016/j.rser.2019.109390

Lee, Y. H., Amran, M., Lee, Y. Y., Kueh, A. B. H., Kiew, S. F., Fediuk, R., Vatin, N., & Vasilev, Y. (2021). Thermal behavior and energy efficiency of modified concretes in the tropical climate: A systemic review. *Sustainability*, *13*(21), 11957. https://doi.org/10.3390/su132111957

Leng, S., Li, S. W., Hu, Z. Z., Wu, H. Y., & Li, B. Bin. (2022). Development of a micro-in-meso-scale framework for simulating pollutant dispersion and wind environment in building groups. *Journal of Cleaner Production*, *364*, 132661. https://doi.org/10.1016/j.jclepro.2022.132661

Li, J., Mao, Y., Ouyang, J., & Zheng, S. (2022). A Review of urban microclimate research based on CiteSpace and VOSviewer Analysis. *International Journal of Environmental Research and Public Health*, *19*(8), 4741. https://doi.org/10.3390/ijerph19084741

Lin, P., Lau, S. S. Y., Qin, H., & Gou, Z. (2017). Effects of urban planning indicators on urban heat island: a case study of pocket parks in high-rise high-density environment. *Landscape and Urban Planning*, *168*, 48–60. https://doi.org/10.1016/j.landurbplan.2017.09.024

Lin, Q., Ishida, Y., Tanaka, H., Mochida, A., Yang, Q., & Tamura, Y. (2023). Large eddy simulations of strong wind mechanisms at pedestrian level around square-section buildings with same aspect ratios and different sizes. *Building and Environment*, *243*, 110680. https://doi.org/10.1016/j.buildenv.2023.110680

Liu, J., Tang, H., & Zheng, B. (2023). Simulation study of summer microclimate in street space of historic conservation areas in China: A case study in Changsha. *Frontiers in Environmental Science*, *11*, 1146801. https://doi.org/10.3389/fenvs.2023.1146801

Liu, J., Tang, H., & Zheng, B. (2024). Thermal environments of residential areas: Sunlight and building shadow in a Chinese city with hot and humid summers. *Buildings*, *14*(9), 2730. https://doi.org/10.3390/buildings14092730

Meng, Q., Gao, J., Zhang, L., Hu, X., Qian, J., & Jancsó, T. (2024). Coupled cooling effects between urban parks and surrounding building morphologies based on the microclimate evaluation framework integrating remote sensing data. *Sustainable Cities and Society*, *102*, 105235. https://doi.org/10.1016/j.scs.2024.105235

Middel, A., Häb, K., Brazel, A. J., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in phoenix local climate zones. *Landscape and Urban Planning*, *122*, 16–28. https://doi.org/10.1016/j.landurbplan.2013.11.004

Mishra, S. B., & Alok, S. (2017). *Handbook of research methodology* (1st ed.). Educreation. https://www.researchgate.net/publication/319207471

Ng, E., Yuan, C., Chen, L., Ren, C., & Fung, J. C. H. (2011). Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong. *Landscape and Urban Planning*, *101*(1), 59–74. https://doi.org/10.1016/j.landurbplan.2011.01.004

Ni, Y., Lin, L., Xia, H., & Wang, X. (2025). Urban street greening and resident comfort: An integrated approach based on high-precision shadow distribution and facade visual assessment. *Sustainability*, *17*(3), 1026. https://doi.org/10.3390/su17031026

Peng, L., Liu, J.-P., Wang, Y., Chan, P., Lee, T., Peng, F., Wong, M., & Li, Y. (2018). Wind weakening in a dense high-rise city due to over nearly five decades of urbanization. *Building and Environment*, *138*, 207–220. https://doi.org/10.1016/j.buildenv.2018.04.037

Pragati, S., Shanthi Priya, R., Pradeepa, C., & Senthil, R. (2023). Simulation of the energy performance of a building with green roofs and green walls in a tropical climate. *Sustainability*, *15*(3), 2006. https://doi.org/10.3390/su15032006

Roth, M. (2007). Review of urban climate research in (sub)tropical regions. *International Journal of Climatology*, *27*(14), 1859–1873. https://doi.org/10.1002/joc.1591

Roy, T. B., Middey, A., & Krupadam, R. J. (2025). Unveiling the microclimate: A comprehensive review of tools, techniques, and future directions for sustainable cities. *Building and Environment*, *274*, 112726. https://doi.org/10.1016/j.buildenv.2025.112726

Salmanian, M., & Ujang, N. (2022). Emerging need for micro-climatic considerations in urban design process: A review. *Jurnal Teknologi*, *84*(1), 129–148. https://doi.org/10.11113/jurnalteknologi.v84.15111

Salvati, A., & Kolokotroni, M. (2023). Urban microclimate and climate change impact on the thermal performance and ventilation of multi-family residential buildings. *Energy and Buildings*, *294*, 113224. https://doi.org/10.1016/j.enbuild.2023.113224

Semeraro, T., Calisi, A., Hang, J., Emmanuel, R., & Buccolieri, R. (2024). Nature-based solutions planning for urban microclimate improvement and health: An integrated ecological and economic approach. *Land*, *13*(12), 2143. https://doi.org/10.3390/land13122143

Shafaghat, A., Manteghi, G., Keyvanfar, A., Bin Lamit, H., Saito, K., & Ossen, D. R. (2016). Street geometry factors influence urban microclimate in tropical coastal cities: A review. *Environmental and Climate Technologies*, *17*(1), 61–75. https://doi.org/10.1515/rtuect-2016-0006

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Song, J., Liu, Y., Chow, D. H. C., Liu, B., & Cho, S. (2025). Correlation between the insolation shadow ratio and thermal comfort of urban outdoor spaces in residential areas in Xi'an. *Buildings*, *15*(12), 1995. https://doi.org/10.3390/buildings15121995

Sun, T., Chen, L., & Sun, R. (2024). Cooling effects in urban communities: Parsing green spaces and building shadows. *Urban Forestry & Urban Greening*, *94*, 128264. https://doi.org/10.1016/j.ufug.2024.128264

Taleghani, M., Kleerekoper, L., Tenpierik, M., & van den Dobbelsteen, A. (2015). Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and Environment*, *83*, 65–78. https://doi.org/10.1016/j.buildenv.2014.03.014

Toparlar, Y., Blocken, B., Maiheu, B., & van Heijst, G. J. F. (2017). A review on the CFD analysis of urban microclimate. *Renewable and Sustainable Energy Reviews*, *80*, 1613–1640. https://doi.org/10.1016/j.rser.2017.05.248

Tse, K. T., Weerasuriya, A. U., Zhang, X., Li, S., & Kwok, K. C. S. (2017). Pedestrian-level wind environment around isolated buildings under the influence of twisted wind flows. *Journal of Wind Engineering and Industrial Aerodynamics*, *162*, 12–23. https://doi.org/10.1016/j.jweia.2017.01.002

Wang, H., Cai, Y., Deng, W., Li, C., Dong, Y., Zhou, L., Sun, J., Li, C., Song, B., Zhang, F., & Zhou, G. (2023). The effects of tree canopy structure and tree coverage ratios on urban air temperature based on ENVI-Met. *Forests*, *14*(1), 80. https://doi.org/10.3390/f14010080

Wei, R., Song, D., Wong, N. H., & Martin, M. (2016). Impact of urban morphology parameters on microclimate. *Procedia Engineering*, *169*, 142–149. https://doi.org/10.1016/j.proeng.2016.10.017

Wong, N. H., He, Y., Nguyen, N. S., Raghavan, S. V., Martin, M., Hii, D. J. C., Yu, Z., & Deng, J. (2021). An integrated multiscale urban microclimate model for the urban thermal environment. *Urban Climate*, *35*, 100730. https://doi.org/10.1016/j.uclim.2020.100730

Yang, S., Wang, L., Stathopoulos, T., & Marey, A. M. (2023). Urban microclimate and its impact on built environment: A review. *Building and Environment*, *238*, 110334. https://doi.org/10.1016/j.buildenv.2023.110334

Yang, S., Zhan, D., Stathopoulos, T., Zou, J., Shu, C., & Wang, L. L. (2024). Urban microclimate prediction based on weather station data and artificial neural network. *Energy and Buildings*, *314*, 114283. https://doi.org/10.1016/j.enbuild.2024.114283

Yi, P., Liu, L., Huang, Y., Zhang, M., Liu, H., & Bedra, K. B. (2023). Study on the coupling relationship between thermal comfort and urban center spatial morphology in summer. *Sustainability*, *15*(6), 5084. https://doi.org/10.3390/su15065084

Yim, S. H. L., Fung, J. C. H., Lau, A. K. H., & Kot, S. C. (2009). Air ventilation impacts of the "wall effect" resulting from the alignment of high-rise buildings. *Atmospheric Environment*, *43*(32), 4982–4994. https://doi.org/10.1016/j.atmosenv.2009.07.002

Zhu, J., Feng, J., Lu, J., Chen, Y., Li, W., Lian, P., & Zhao, X. (2023). A review of the influence of courtyard geometry and orientation on microclimate. *Building and Environment*, *236*, 110269. https://doi.org/10.1016/j.buildenv.2023.110269

Dheshan, K. and Perera, N., 2026. Microclimate-driven spatial patterns for adaptive urban design: Evidence from Kotahena, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1195 -1207. DOI: https://doi.org/10.31705/WCS.2026.87. Available from: https://ciobwcs.com/papers/

# MICROCLIMATE-DRIVEN SPATIAL PATTERNS FOR ADAPTIVE URBAN DESIGN: EVIDENCE FROM KOTAHENA, SRI LANKA

**Dheshan Kumar[1] and Narein Perera[2]**

## *ABSTRACT*

*Rapid urbanisation and unplanned vertical expansion in tropical cities have intensified environmental pressures within dense informal neighbourhoods where urban form evolves beyond formal planning control. In many global cities, including those in Sri Lanka, everyday urban environments emerge through incremental development driven by economic constraints, with buildings predominantly constructed through labour-intensive and experience-based practices rather than professionally standardized construction processes. This ad-hoc development, combined with a growing population, has produced saturated built environments that intensify microclimate stress at street level. Interventions for such contexts typically rely on conventional sustainability frameworks that prioritise technical or climate-based solutions, while insufficiently engaging with the lived spatial and social dynamics of everyday urban environments. While climate-responsive urban research frequently evaluates environmental performance, fewer studies examine how microclimatic conditions shape spatial behaviour patterns that structure everyday urban life. This paper investigates the relationship between microclimate and spatial behaviour in dense informal contexts using Kotahena, Colombo. The study integrates spatial analysis, behavioural observation and microclimatic simulation to examine how urban morphology influences thermal comfort and patterns of urban activity. Comparative analysis reveals consistent relationships between thermal conditions and spatial behaviour patterns. The research proposes a framework for microclimate-driven spatial patterns capable of informing adaptive urban design strategies for this dense tropical environment. The patterns provide practically applicable guidance for policy and planning, supporting climate-responsive urban environments while remaining compatible with informal and experience-led urban development practices.*

***Keywords:*** *Adaptive Urban design; Informal Urbanism; Spatial patterns; Urban microclimate; Urban Sustainability.*

## 1. INTRODUCTION

Rapid urbanisation in developing cities has intensified environmental and social pressures, particularly within dense urban areas that have expanded beyond formal planning controls (Perera, 2014). Globally, 58% of the population now lives in urban areas, a figure projected to increase significantly by 2050 (World Bank, 2023). In many

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, dheshank.26@uom.lk
[2] Professor, Department of Architecture, University of Moratuwa, Sri Lanka, nareinperera@uom.lk

cities of the Global South, this rapid growth has occurred largely through incremental and unplanned development, producing compact and vertically expanding urban fabrics that challenge both the urban microclimate and the social and spatial dynamics that structure everyday public life. In the Sri Lankan context, urban public spaces rarely take the form of formally planned settings such as plazas or parks. Instead, everyday streets function as the primary spatial environments through which social, cultural, and economic interactions unfold. Consequently, conventional planning approaches derived from formal Western urban models often fail to respond effectively to these conditions. Sustainable urban interventions that focus solely on environmental performance frequently prove impractical in such contexts, as they require communities to adapt to externally imposed spatial frameworks rather than responding to existing patterns of urban life.

Urban environments function through interconnected social and spatial systems (Eisner, 1985), and effective interventions must therefore operate as adaptive spatial wholes rather than isolated design elements (Alexander, 2002). Recent studies on tropical urbanism further demonstrate that microclimatic conditions directly influence patterns of pedestrian movement, occupation, and public-space usage within dense urban environments (Dissanayake et al., 2021; Emmanuel, 2005). In dense and diverse urban populations, planning strategies must therefore respond to the reciprocal relationship between microclimate and spatial behaviour within the lived dynamics of the city (Hashemi et al., 2023).

However, implementing planning policies within such contexts remains challenging due to the ad-hoc and incremental nature of urban development, where much of the built environment evolves through practice-led construction processes with limited professional involvement (Lerociyan et al., 2012). Studies on informal tropical urban environments also suggest that everyday adaptive practices such as shaded occupation, edge-based gathering, and informal commercial spillovers frequently emerge in response to local environmental conditions rather than formal planning intentions (Makevita & Rajapakse, 2013) (refer Figure 1).

*Figure 1: Urban microclimate - Spatial behaviour relationship (Source: Author)*

This study therefore investigates how microclimatic variation influences spatial behaviour in dense informal urban contexts, where microclimatic variation structures spatial occupation patterns in informal urban systems. By translating this relationship into a pattern-based framework, the research contributes an empirically grounded understanding of adaptive urban space in tropical cities.

# 2. LITERATURE REVIEW

## 2.1 MICROCLIMATIC CONDITIONS IN INFORMAL URBAN ENVIRONMENTS

Within dense informal urban environments, microclimate plays a significant role in mediating the relationship between built morphology and human spatial behaviour. In

hot-humid regions such as Sri Lanka, interactions between urban forms and atmospheric processes significantly influence thermal conditions at street level, thereby affecting patterns of movement, occupation, and social interaction. Tropical urban environments are particularly sensitive to even minor variations in built form, land cover, and human activity (Emmanuel, 2005; Jendritzky et al., 2012).

Street orientation further modifies microclimatic performance by influencing solar exposure and airflow conditions. East-west oriented streets typically receive prolonged solar radiation on facades and pavements, increasing surface temperatures and radiant heat loads. In contrast, north-south oriented streets may experience more consistent shading but can also suffer from reduced wind permeability, affecting convective cooling. Vegetation can mitigate these conditions through shading and evapotranspiration, contributing to improved thermal comfort within urban environments.

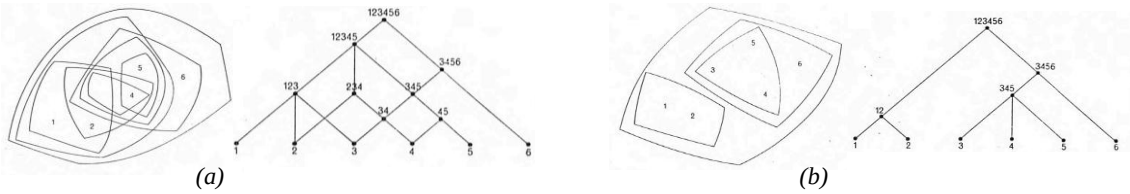



*Figure 2: (a) Tree formation (b) Semi-lattice formation (Source: Alexander, 1965)*

As these processes intensify within compact neighbourhoods, modifications to airflow, solar access, and surface heat storage contribute to the Urban Heat Island (UHI) effect, amplifying thermal stress within dense urban areas (Perera, 2014). The UHI phenomenon describes the tendency of urban environments to remain warmer than surrounding rural areas, particularly during night-time, and is often visualised as a dome of warmer air above built-up regions (Emmanuel, 1993).

Considering these aspects, several environmental variables become critical in defining microclimate-spatial relationships within dense urban fabrics. Key parameters include air temperature, Mean Radiant Temperature (MRT), relative humidity, wind speed and direction, and solar exposure and shading conditions. Understanding how these variables interact with urban morphology is essential for interpreting how thermal environments influence patterns of spatial occupation and behaviour within informal contexts.

## 2.2 MICROCLIMATE INFLUENCES ON SPATIAL PATTERNS

Within dense informal urban environments, microclimate plays a significant role in mediating the relationship between built morphology and human spatial behaviour. In hot-humid regions such as Sri Lanka, interactions between urban forms and atmospheric processes significantly influence thermal conditions at street level, thereby affecting patterns of movement, occupation, and social interaction. Tropical urban environments are particularly sensitive to even minor variations in built form, land cover, and human activity (Emmanuel, 2005).

One of the most influential spatial conditions shaping urban microclimate is the formation of urban canyons, created by closely spaced buildings along narrow streets. High Height-to-Width (H/W) ratios reduce sky view factor, limit nocturnal radiant cooling, and increase the trapping of both short-wave and long-wave radiation within street corridors. These processes generate spatially differentiated thermal environments, where certain

street segments experience significantly higher radiant temperatures than others. Such variations frequently influence spatial occupation patterns, as pedestrians gravitate toward shaded and ventilated areas while avoiding thermally stressful zones. Empirical studies conducted within tropical street canyons further demonstrate that variations in MRT, airflow, and shading conditions significantly affect pedestrian comfort and duration of occupation within public spaces (Ali-Toudert, 2005; Dissanayake et al., 2021). Street orientation further modifies microclimatic performance by influencing solar exposure and airflow conditions. East-west oriented streets typically receive prolonged solar radiation on facades and pavements, increasing surface temperatures and radiant heat loads. In contrast, north-south oriented streets may experience more consistent shading but can also suffer from reduced wind permeability, affecting convective cooling.

Vegetation can mitigate these conditions through shading and evapotranspiration, contributing to improved thermal comfort within urban environments. As these processes intensify within compact neighbourhoods, modifications to airflow, solar access, and surface heat storage contribute to the Urban Heat Island (UHI) effect, amplifying thermal stress within dense urban areas (Perera, 2014). The UHI phenomenon describes the tendency of urban environments to remain warmer than surrounding rural areas, particularly during night-time, and is often visualised as a dome of warmer air above built-up regions (Emmanuel, 1993).

Considering these aspects, several environmental variables become critical in defining microclimate-spatial relationships within dense urban fabrics. Key parameters include air temperature, MRT, relative humidity, wind speed and direction, and solar exposure and shading conditions. Understanding how these variables interact with urban morphology is essential for interpreting how thermal environments influence patterns of spatial occupation and behaviour within informal contexts.

### 2.3 RESEARCH GAP: MICROCLIMATE-SPATIAL RELATIONSHIP IN INFORMAL CONTEXTS

Although studies on urban microclimate and urban spatial behaviour are well established, they are largely examined as separate analytical domains. Limited research investigates how microclimatic conditions influence the emergence of spatial patterns within dense informal urban environments, particularly in tropical cities of the Global South where everyday streets function as primary public spaces. Existing climate-responsive urban research frequently prioritises environmental performance evaluation, while comparatively fewer empirical studies examine how measurable microclimatic variation shapes recurring behavioural occupation patterns within informal urban contexts. In tropical cities where everyday streets function as primary public spaces, understanding this relationship becomes critical for developing climate-responsive and socially adaptive urban design strategies. This study addresses this gap by empirically demonstrating how thermal variation structures spatial occupation patterns in informal urban systems and translating these relationships into a spatial pattern framework.

## 3. METHOD

### 3.1 INTRODUCTION TO CASE STUDY

Kotahena is a dense, mixed-use suburb in the northern quadrant of Colombo that has evolved largely through incremental and spontaneous urban growth. Strategically

positioned between Pettah and Modara, it functions as a transitional urban zone linking the central business district with the northern residential suburbs of Colombo. With approximately 60,000 residents within an area of 2.5 km², Kotahena represents one of the most densely populated urban districts in the city. The area contains active commercial streets embedded within compact residential neighborhoods, supporting a diverse multi-ethnic urban population. Its compact urban morphology, narrow street canyons, and high building density generate distinct microclimatic conditions at pedestrian level, which directly influence patterns of spatial use, movement, and social interaction.

In addition, the area demonstrates highly adaptive informal spatial practices, where commercial spillovers, temporary shading conditions, and edge-based activities continuously reshape the use of public space. These characteristics make Kotahena a representative case for examining the relationship between urban microclimate and spatial behaviour in dense informal urban contexts.

## 3.2 RESEARCH DESIGN FRAMEWORK

Figure 3 illustrates the overall research design framework adopted in the study. The study adopts a mixed-method research approach combining spatial analysis, theoretical pattern comparison, empirical field observation, and microclimate simulation to examine how urban morphology, microclimate, and spatial behaviour interact within dense informal environments.

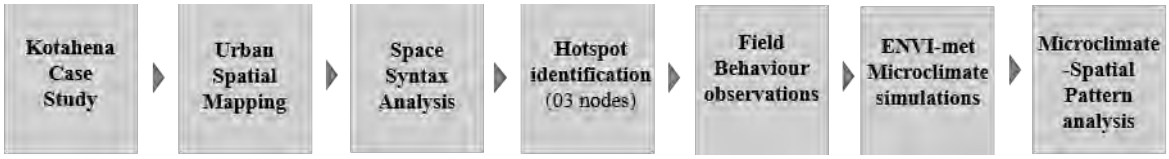



*Figure 3: Research design framework (Source: Author)*

The broader spatial structure of Kotahena was mapped to examine urban morphology, circulation hierarchy, and functional distribution. Spatial mapping identified commercial corridors, pedestrian movement intensities, transitional edges, and concentrations of informal occupation. Space syntax analysis identified movement networks based on spatial accessibility and visibility relationships, while connectivity analyses assessed spatial integration and potential movement concentration. Although space syntax does not directly represent human behaviour, it provided an objective framework for locating areas with a high probability of pedestrian interaction and activity concentration.

Based on spatial integration, land-use intensity, pedestrian concentration, and environmental variation, three urban hotspots were selected for detailed study. These represented distinct spatial and microclimatic conditions, enabling comparative analysis of behavioural responses across varying environments.

To establish a comparative baseline, selected spatial patterns from *A Pattern Language* (Alexander et al., 1977) were mapped against the hotspots. These patterns were chosen for their relevance to pedestrian occupation, edge conditions, activity clustering, transitional space, and climatic responsiveness in dense urban contexts. The comparison was not to validate applicability, but to examine limitations of normative planning assumptions against the spatial realities of informal tropical urbanism, enabling a structured contrast between prescribed spatial logic and emergent adaptive spatial

behaviour in Kotahena. To capture real-world patterns of spatial occupation, systematic behavioural observations were conducted within the identified hotspots at strategically selected periods of the day corresponding to varying thermal conditions and activity intensities. Field observations focused on pedestrian movement patterns, stationary occupation, gathering behaviour, informal commercial spillovers, shaded occupation zones, and edge-based activities. Behavioural mapping and photographic documentation were used to capture recurring spatial occupation patterns and user responses to environmental conditions (refer Figure 4, 5 and 6).

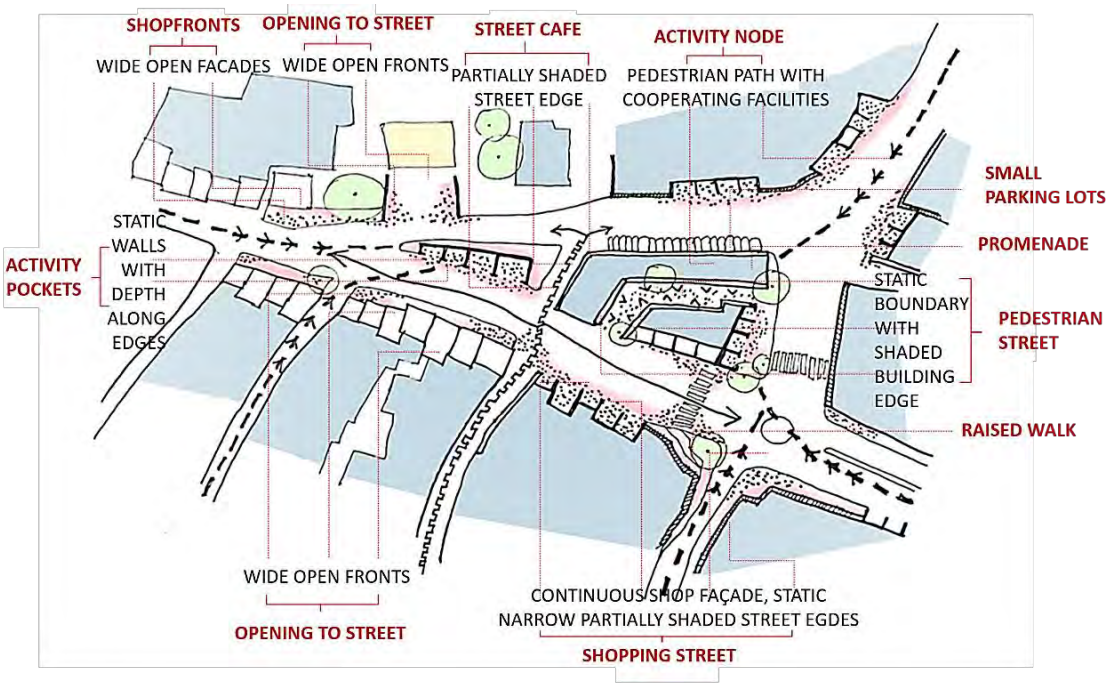



*Figure 4: Theoretical pattern mapping of Hotspot 01 (Source: Author)*

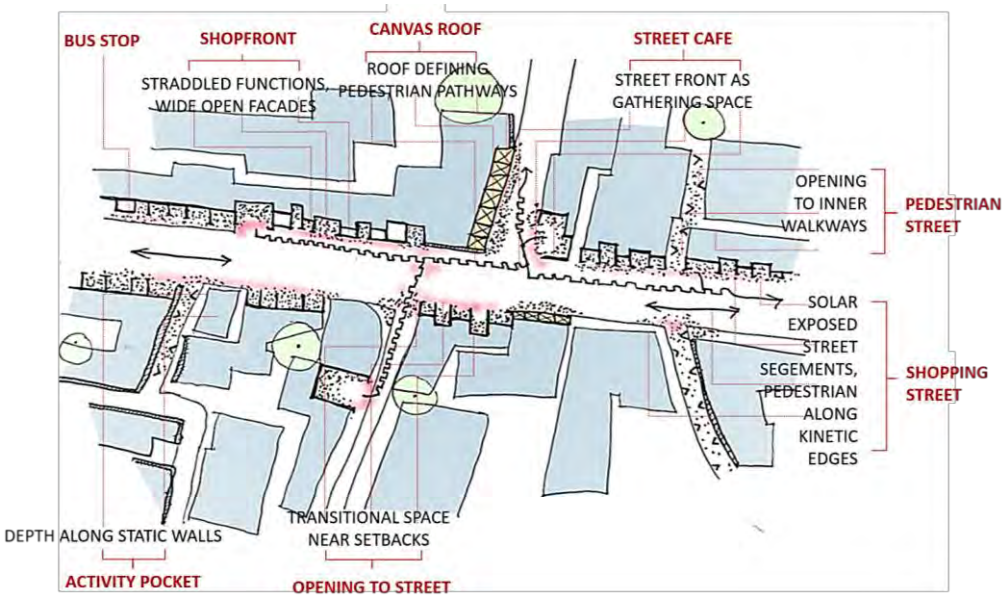



*Figure 5: Theoretical pattern mapping of Hotspot 02 (Source: Author)*

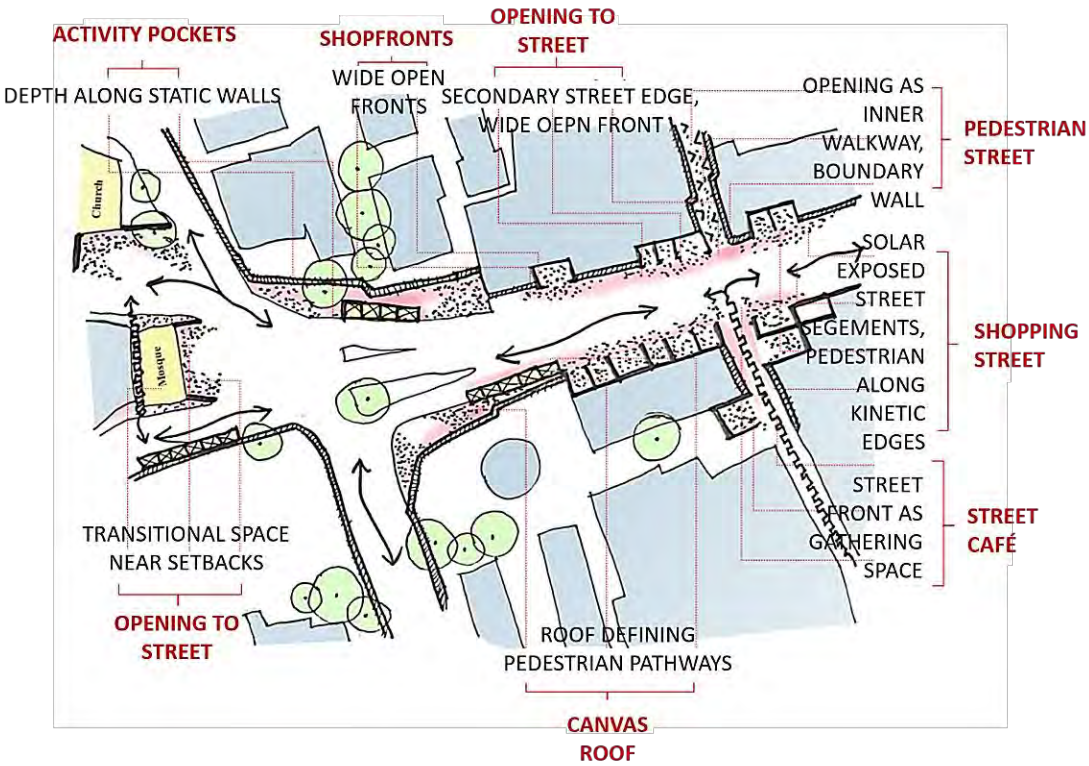



*Figure 6: Theoretical pattern mapping of Hotspot 03 (Source: Author)*

The same locations were subsequently modelled using the ENVI-met simulation platform to analyses key pedestrian-level microclimatic variables including Air Temperature, Relative Humidity, Wind Flow, MRT, and Predicted Mean Vote (PMV).

## 3.3 SIMULATION PROTOCOL

Simulation models were developed to represent the existing urban morphology of the selected hotspot areas. The models incorporated street geometry, built form configuration, surface materials, and vegetation distribution in order to evaluate their influence on local microclimatic performance. Climatic input data were derived from meteorological records and validated through on-site field measurements to ensure contextual accuracy (refer Figure 7).

**Hotspot 01** **Hotspot 02** **Hotspot 03**

*Figure 7: 3D simulation models built for testing (Source: Author)*

Given the focus on commercial streets and associated public activities, the analysis examined thermal conditions between 8:00 a.m. and 6:00 p.m., corresponding to peak activity periods within the study area. This time range enabled identification of changing thermal conditions and associated behavioural responses throughout the day. The simulation models incorporated built forms, street geometry, surface materials, and

vegetation patterns to evaluate how these spatial parameters influence local microclimatic conditions and associated patterns of spatial occupation. The resulting MRT and PMV outputs were comparatively analysed with observed behavioural patterns to identify recurring relationships between thermal comfort conditions and adaptive spatial use within the selected urban hotspots.

# 4. RESULTS AND ANALYSIS

## 4.1 SPATIAL MORPHOLOGY AND MICROCLIMATIC-BEHAVIORAL RESPONSE

Behavioural patterns observed across all hotspots demonstrated consistent adaptive responses to microclimatic variation (refer Table 01).

*Table 01: Microclimate influence on Spatial patterns and Behavioural response*

| Hotspot | Spatial pattern Condition | Microclimatic condition | Behavioural Response |
|---|---|---|---|
| **Hotspot 01** | Narrow street canyon | MRT: 42.71°C<br>PMV: 2.35 (midday peak thermal stress). | Reduced stationary activities and shorter pedestrian dwell times. |
| | Partially shaded street edge | MRT: 23.68°C–36.91°C<br>PMV: moderate range (intermittent exposure conditions). | Short pauses and moderate pedestrian presence. |
| | Shaded building edge | MRT: 20.01°C–25.22°C<br>PMV: 0.67–1.28 (reduced thermal stress). | Higher social interaction and prolonged occupation. |
| **Hotspot 02** | Solar-exposed street segment | MRT: 27.90°C–33.71°C<br>PMV: elevated (daytime exposure conditions). | Lower pedestrian occupation and predominantly transient movement. |
| | Transitional space near setbacks | MRT: reduced relative to exposed segments (moderated conditions)<br>PMV: lower than exposed zones. | Movement corridor with occasional gathering. |
| | Ventilated junctions | MRT: lower relative thermal load<br>PMV: 0.97–1.24 (improved comfort during evening periods). | Higher pedestrian concentration and informal interaction. |
| **Hotspot 03** | Dense canyon corridor | MRT: elevated (restricted sky exposure condition)<br>PMV: up to 2.19 (midday peak stress). | Limited pedestrian activity and reduced stationary occupation. |
| | Moderately shaded street section | MRT: 22.19°C–33.63°C<br>PMV: moderate range | Continuous pedestrian movement and moderate occupation. |
| | Semi-open edge condition | MRT: lower thermal stress condition<br>PMV: reduced during evening periods | Informal social interaction and prolonged spatial use. |

*(Source: Author)*

Spatial environments characterised by elevated MRT and PMV values, particularly within exposed canyon segments, predominantly supported transient pedestrian movement with limited stationary occupation during peak daytime conditions. In contrast, spaces incorporating shading, setbacks, porous edges, and improved airflow consistently exhibited higher pedestrian retention, prolonged occupation, and increased informal social interaction.

### 4.2 MICROCLIMATE-DRIVEN BEHAVIOURAL PATTERNS AND SPATIAL ADAPTATION

Behavioural patterns observed across all hotspots demonstrated consistent adaptive responses to microclimatic variation. Spatial environments characterised by elevated MRT and PMV values, particularly within exposed canyon segments, predominantly supported transient pedestrian movement with limited stationary occupation during peak daytime conditions. In contrast, spaces incorporating shading, setbacks, porous edges, and improved airflow consistently exhibited higher pedestrian retention, prolonged occupation, and increased informal social interaction.

Temporal variation further reinforced these behavioural shifts. During midday periods, exposed street segments demonstrated minimal stationary activity, whereas shaded transitional spaces maintained moderate pedestrian presence. As thermal stress declined during evening periods, pedestrian density and duration of occupation increased across all hotspots, indicating that behavioural occupancy within dense informal urban environments is dynamically adjusted in response to measurable thermal variation.

The integrated analysis of spatial morphology, microclimate, and behavioural mapping demonstrates that microclimate acts as a spatial sorting mechanism for pedestrian behaviour across the study area. Conditions characterised by excessive enclosure, restricted airflow, and high radiant heat accumulation consistently corresponded with reduced spatial usability. Conversely, configurations incorporating ventilation corridors, spatial porosity, and transitional setbacks demonstrated improved microclimatic performance and increased pedestrian activity.

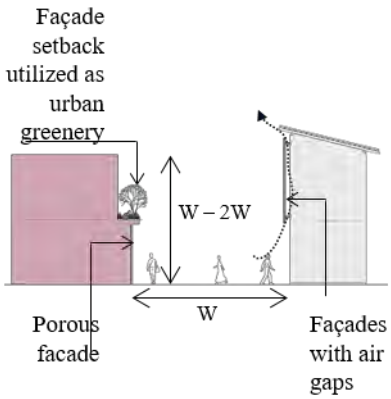
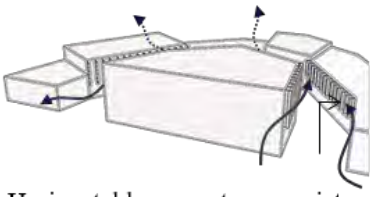
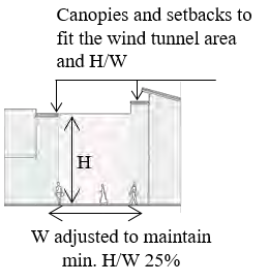
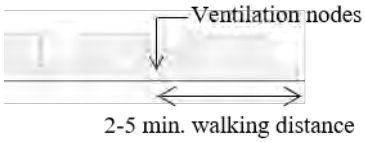
Across all hotspots, these relationships remained consistent, confirming a stable linkage between urban morphology, environmental performance, and everyday spatial use. The findings indicate that street geometry, building form, solar exposure, and ventilation operate as primary determinants of thermal comfort and behavioural distribution within dense informal urban environments. Accordingly, the combined MRT/PMV and behavioural evidence establishes a basis for defining microclimate-responsive spatial configurations capable of supporting pedestrian comfort, prolonged occupation, and adaptive social activity in tropical urban contexts.

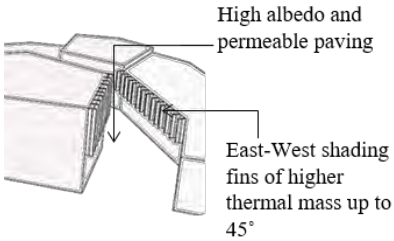
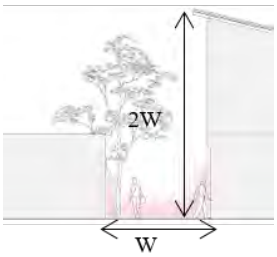
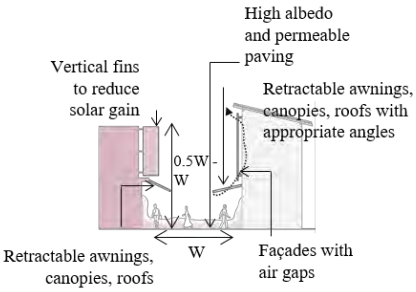
## 5. DISCUSSION AND CONCLUSION

### 5.1 PRACTICAL APPLICATION

The identified spatial patterns emerge from a consistent empirical relationship between microclimatic variation and behavioural adaptation observed across all hotspots (Refer Table 02).

Table 02: Microclimate-driven spatial patterns

| **Spatial Pattern** | **Microclimate Effect** | **Adaptive Spatial Strategy** |
|---|---|---|
| **Activity Nodes in Open Squares**   | Heat accumulation along continuous edges.<br><br>Reduced cross-ventilation.<br>(Higher MRT and PMV peaks observed in exposed segments). | Break façades with stepped/segmented edges maintaining H/W ≈ 0.5–2.0.<br><br>Introduce porous ground edges and shaded transition zones to reduce radiant heat accumulation and increase airflow permeability. |
| **Activity Nodes along Winding Paths**   | Air stagnation and uneven wind acceleration creating localized thermal variability. | Introduce façade breaks and setbacks.<br><br>Use vertical fins or articulated edges.<br><br>Establish ventilation nodes aligned with airflow corridors to moderate microclimatic discontinuities. |
| **Promenades**   | High solar exposure along continuous linear corridors with elevated MRT during midday. | Segment corridors with shaded pockets maintaining H/W ≤ 1.<br>Introduce resting nodes and adjustable shading systems (0–45°) to reduce thermal exposure and support pedestrian retention. |
| **Shopping Streets**   | Urban canyon heat build-up with restricted ventilation and high PMV values in peak hours. | Introduce cross passages.<br><br>Break continuous façades with setbacks.<br><br>Apply ventilated cladding or shading fins. |

| Spatial Pattern | Microclimate Effect | Adaptive Spatial Strategy |
|---|---|---|
| **Shopfront Edges**   | Localised heat accumulation at thresholds due to direct solar exposure. | Use recessed entrances, angled façades to enhance airflow deflection, and combine permeable paving with shading fins to reduce thermal stress at pedestrian interfaces. |
| **Openings to Communal Life**   | Improved ventilation and reduced MRT in cross-connected spatial zones.<br><br>Heat retention along enclosed public edges with limited air exchange. | Introduce courtyard gaps, maintain visual permeability, and orient openings toward prevailing wind directions to enhance cooling efficiency and social activation. |
| **Edges of Activity Pockets**   | Heat retention along enclosed public edges with limited air exchange. | Maintain porous lower edges, introduce stepped façade articulation, and integrate vertical shading systems that facilitate upward heat dissipation. |

*(Source: Author)*

Rather than being abstract design propositions, these patterns represent performance-based spatial responses to thermal stress in dense informal urban environments. Importantly, the identified patterns are not abstract design propositions; they are directly derived from consistent empirical correspondences between measured microclimatic variations (MRT and PMV outputs) and observed behavioural adaptations across the three analysed hotspots.

The identified patterns demonstrate consistent alignment between measured microclimatic performance and observed spatial behaviour across all three hotspots. Across the dataset, zones exhibiting lower MRT and PMV values consistently corresponded with increased pedestrian retention, prolonged occupation, and higher levels of informal social interaction. Conversely, thermally stressed zones with elevated MRT values consistently functioned as transient movement corridors with limited stationary activity.

This systematic correspondence establishes that spatial behaviour in dense informal urban environments is strongly conditioned by measurable microclimatic variation mediated through urban morphology. Accordingly, the proposed spatial patterns are derived through a triangulated evidence framework combining: Spatial morphology analysis, ENVI-met derived microclimatic simulation outputs and Behavioural observation mapping. This triangulation strengthens the validity of the transition from analytical findings to design implications, ensuring that the proposed patterns are evidence-based rather than interpretative constructs.

The practical relevance of these patterns lies in their applicability to sustainable urban design and incremental upgrading strategies in dense tropical cities. They can inform design decisions related to building setbacks, façade articulation, shading strategies, ventilation corridors, and public space configuration. Unlike conventional form-driven design approaches, the proposed framework links urban morphology directly to pedestrian thermal experience and spatial behaviour. This enables a performance-based understanding of informal urban space, where design interventions can be aligned with microclimatic regulation and everyday spatial practices to improve comfort, usability, and social activity in tropical cities.

## 5.2 FURTHER RESEARCH

This study identifies a set of microclimate-driven spatial patterns grounded in the local context of Kotahena, demonstrating how spatial form, movement networks, and everyday urban practices shape thermal comfort and public life. As the findings are based on a limited number of hotspots, future research should extend this approach to larger urban areas, diverse land-use typologies, and multiple climatic zones.

Future studies should incorporate higher-resolution behavioural datasets, extended seasonal monitoring, and multi-temporal simulations to capture long-term variations in microclimate-behaviour relationships. Longitudinal and comparative multi-site studies would strengthen the transferability and predictive capacity of the proposed framework. Further development may also integrate advanced simulation tools, machine learning approaches, and real-time environmental sensing to enhance adaptive urban performance modelling.

## 5.3 CONTRIBUTIONS

This research reframes informal urban environments as sites of adaptive climatic intelligence rather than planning deficiency. By integrating microclimatic analysis with spatial and behavioural dynamics, the study challenges conventional sustainability approaches that prioritise environmental performance in isolation from lived urban experience.

The key contribution of this study lies in establishing a direct empirical linkage between microclimate (MRT/PMV) variation and observable spatial behaviour and translating this relationship into a structured set of adaptive spatial design patterns. It advances a human-centred, pattern-based design framework that aligns climatic responsiveness with everyday spatial practices. In doing so, the study provides urban designers, planners, and policymakers with a transferable evidence-based methodology for developing resilient, inclusive, and climatically adaptive urban environments in rapidly transforming tropical cities.

# 6. REFERENCES


Alexander, C. (1965). *A City is not a Tree* (1st ed). Sustasis Press. https://bp.ntu.edu.tw/001/Upload/1352/ckfile/176357fb-2068-4e40-8c50-593780261ce7.pdf

Alexander, C. (2002). *The Nature of Order An essay on the art of building and the nature of the universe Book 1: The Phenomenon of Life*. New York : Oxford University Press. https://archive.org/details/natureoforderess0000alex_i7q2.

Alexander, C., Ishikawa, S., & Silverstein, M. (1977). *A pattern language: Towns, buildings, construction*. Oxford University Press.

Ali-Toudert, F. (2005). *Dependence of outdoor thermal comfort on street design in hot and dry climate* [PhD Thesis, Albert-Ludwig University of Freiburg]. https://freidok.uni-freiburg.de/files/2078/ucaAy6a75oMbNUVc/Diss_Freidok_Ali_Toudert_Fazia.pdf

Dissanayake, C., Weerasinghe, U. G. D., & Dharmasena, J. (2021). Assessment of thermal comfort and microclimate in urban street canyons. *Proceedings of the IOFAR International Conference on Sustainability, Energy and Environment*. https://papers.iafor.org/wp-content/uploads/papers/iicseehawaii2021/IICSEEHawaii2021_59376.pdf

Eisner, E. (1985). Chapter II: Aesthetic Modes of Knowing. *Teachers College Record the Voice of Scholarship in Education*, 86(6), 23–36. https://doi.org/10.1177/016146818508600602s.

Emmanuel, R. (1993). *Making the commons liveable: Climate conscious urban activity patterns for equatorial tropics* [Master's thesis]. University of Queensland.

Emmanuel, R. (2005). *An urban approach to climate sensitive design* (1st ed.). Taylor & Francis. https://doi.org/10.4324/9780203414644

Hashemi, F., Poerschke, U., Iulo, L. D., & Chi, G. (2023). Urban Microclimate, Outdoor Thermal Comfort, and Socio-Economic Mapping: A case study of Philadelphia, PA. *Buildings*, 13(4), 1040. https://doi.org/10.3390/buildings13041040

Jendritzky, G., De Dear, R., & Havenith, G. (2012). UTCI—Why another thermal index? *International Journal of Biometeorology*, 56(3), 421–428. https://doi.org/10.1007/s00484-011-0513-7

Lerociyan, J J, J., Jeevanarth, T., Thushyanthy, S., & Dissanayake, P. (2012). Informal construction sector and its effects on the construction industry of Sri Lanka. In *ICSBE-2012: International Conference on Sustainable Built Environment*. University of Moratuwa. http://www.civil.mrt.ac.lk/web/conference/ICSBE2012/SBE-12-261.pd.

Makewita, U., & Rajapakse, A. (2013). Ascertaining the kinetic patterns of informal spaces in the commercial streets of Pettah, Sri Lanka. *In Proceedings of the International Urban Design Conference on Cities, People and Places.* https://dl.lib.uom.lk/server/api/core/bitstreams/833e77fc-a4d0-4f42-8440-80e216f84da9/content.

Perera, N., & Samanthilaka, K. (2014). Effect of Street Canyon Materials on the Urban Heat Island Phenomenon in Colombo. In International Conference on 'Cities, People and Places. University of Moratuwa. https://www.academia.edu/9150470/Effect_of_Street_Canyon_Materials_on_the_Urban_Heat_Island_Phenomenon_in_Colomb.

World Bank. (2023). Urban development. World Bank Group. https://www.worldbank.org/ext/en/topic/urban-development

Rahubadda, R.V.A.D., Ingirige, B. and Kulatunga, U., 2026. Nature-based solutions for flood mitigation: A systematic review of evidence, performance mechanisms, and implementation conditions. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1208-1222. DOI: https://doi.org/10.31705/WCS.2026.88. Available from: https://ciobwcs.com/papers/

# NATURE-BASED SOLUTIONS FOR FLOOD MITIGATION: A SYSTEMATIC REVIEW OF EVIDENCE, PERFORMANCE MECHANISMS, AND IMPLEMENTATION CONDITIONS

**R.V.A.D Rahubadda[1], B. Ingirige[2] and U. Kulathunga[3]**

## *ABSTRACT*

*Flooding is one of the most significant natural hazards worldwide, with risks intensifying due to climate change, rapid urbanisation, and land-use transformation. In response to the limitations of conventional grey infrastructure, Nature-Based Solutions (NBS) have gained increasing attention as sustainable strategies for flood risk management. This study presents a systematic literature review examining how NBS are applied and evaluated in flood mitigation research. Peer-reviewed studies published between 2016 and 2026 were identified through structured searches in Scopus and Web of Science, guided by the PRISMA framework and a SPIDER-based review structure. Following duplicate removal and eligibility screening, 136 studies were retained for analysis. Evidence was synthesised using structured coding, descriptive statistics, and thematic synthesis to examine NBS types, flood hazard contexts, performance indicators, hydrological mechanisms, co-benefits, and governance conditions. The findings show that urban green infrastructure and low-impact development measures dominate the literature, particularly for pluvial flooding, while wetland restoration and river restoration approaches are more commonly applied to riverine flood management. Key hydrological mechanisms include increased infiltration, floodwater storage, hydraulic roughness, and hydrograph desynchronisation. However, the evidence base remains dominated by modelling approaches, with limited long-term empirical monitoring of implemented interventions. This review contributes by linking NBS types, flood hazards, performance evaluation metrics, and implementation conditions. The findings highlight the need for stronger empirical evidence, standardised hydrological indicators, and integrated grey–green infrastructure approaches to support the wider adoption of NBS in sustainable flood risk management.*

***Keywords:*** *Flood Risk Management; Green Infrastructure; Nature-Based Solutions; Natural Flood Management; Systematic Literature Review.*

## 1. INTRODUCTION

Flooding is one of the most frequent and destructive natural hazards worldwide, causing significant economic losses, environmental degradation, and social disruption (Kienzler

[1] Research assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, dilrukshaashen@gmail.com
[2] Professor, School of Science, Engineering & Environment, University of Salford, United Kingdom, M.J.B.Ingirige@salford.ac.uk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

et al., 2016). Climate change, rapid urbanisation, and land-use transformation are intensifying flood risks across riverine, pluvial, and coastal environments (Intergovernmental Panel on Climate Change [IPCC], 2022). Conventional flood management strategies have historically relied on engineered or "grey" infrastructure, including levees, floodwalls, drainage networks, and dams (Devi et al., 2025). Although these structural measures can provide effective protection against flood events, they often involve high construction and maintenance costs and may transfer risks downstream while neglecting broader ecological and social dimensions of resilience (Schubert et al., 2017).

In response to these limitations, NBS have emerged as an increasingly prominent approach in climate adaptation and flood risk management (Griffiths et al., 2024). NBS refer to strategies that utilise natural processes and ecosystem functions to address societal challenges while simultaneously generating environmental, social, and economic co-benefits (Griffiths et al., 2024; Schröder et al., 2025). Examples include wetland restoration, floodplain reconnection, urban green infrastructure, mangrove conservation, and ecosystem-based coastal protection (Sabut et al., 2026; Wu et al., 2022). By enhancing water storage capacity, increasing infiltration, and attenuating flow velocities, these interventions can reduce flood hazards while also improving biodiversity, water quality, and urban liveability (Huang et al., 2026; Watson et al., 2016).

Over the past decade, NBS have gained increasing prominence within global climate adaptation and disaster risk reduction policies. International organisations such as the European Commission, the International Union for Conservation of Nature (IUCN), and the United Nations have actively promoted ecosystem-based approaches as complements to conventional flood defence systems (Devi et al., 2025; Lindenberger et al., 2025). As a result, research on NBS for flood mitigation has expanded rapidly, reflecting a broader paradigm shift in flood management from purely structural protection toward more integrated, adaptive, and ecosystem-based strategies.

Despite this growing body of research, several critical gaps remain in the existing literature. First, studies examining NBS for flood mitigation are often fragmented across different flood contexts, including pluvial, riverine, and coastal flooding, making it difficult to identify how NBS are selected and applied across varying hazard types (Iliadis et al., 2024; Inácio et al., 2023). Second, while many studies report positive outcomes associated with NBS, the evidence base remains heterogeneous in terms of evaluation metrics, reported effectiveness, and the underlying mechanisms through which these interventions influence flood dynamics (Caroppi et al., 2024; Marino et al., 2025). Third, the successful implementation of NBS depends not only on technical performance but also on enabling governance structures, financing mechanisms, and institutional coordination, which remain insufficiently synthesised in the current literature (Inácio et al., 2023; Marino et al., 2025).

Addressing these knowledge gaps is important for supporting the wider integration of NBS into flood risk management and infrastructure planning. Therefore, this study conducts a systematic literature review to examine how NBS are applied and evaluated in flood mitigation research. Specifically, the review synthesises peer-reviewed evidence to identify dominant NBS strategies, analyse their reported mechanisms and effectiveness in reducing flood risks, and examine the governance and implementation conditions that influence their adoption.

Accordingly, this study is guided by three research questions.

- **RQ1.** How are Nature-Based Solutions applied and evaluated for flood mitigation across riverine, pluvial, and coastal contexts?
- **RQ2.** What does the literature report regarding the effectiveness, hydrological mechanisms, co-benefits, and potential trade-offs of Nature-Based Solutions in reducing flood risks?
- **RQ3.** What governance, financing, and implementation conditions enable the successful integration and mainstreaming of Nature-Based Solutions in flood risk management?

## 2. METHODOLOGY

This study employed a systematic literature review (SLR) to identify, screen, and synthesise peer-reviewed research on the application of NBS for flood mitigation. The SLR approach was selected because it provides a transparent, structured, and reproducible method for reviewing a large interdisciplinary body of literature while reducing selection bias through explicit search, screening, and eligibility procedures. The review followed established systematic review guidance (Petticrew & Roberts, 2006) and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020.

This study used a SPIDER framework to structure the review and guide the search strategy. The framework was suitable because the review synthesises interdisciplinary evidence on diverse NBS interventions across riverine, pluvial, and coastal flood contexts. The SPIDER elements were defined as follows: Sample: flood-prone urban, riverine, coastal, and catchment systems; Phenomenon of Interest: NBS and related ecosystem-based flood management interventions; Design: empirical studies, modelling studies, evaluation frameworks, and systematic assessments; Evaluation: flood mitigation outcomes, hydrological mechanisms, performance indicators, co-benefits, and governance conditions; and Research type: quantitative, qualitative, and mixed-method studies.

The literature search was conducted in Scopus and Web of Science because these databases provide broad coverage of peer-reviewed research in environmental science, hydrology, climate adaptation, infrastructure, and urban planning. The search strategy was developed around three conceptual domains: flood hazard, NBS, and flood risk reduction outcomes. Search terms were selected to capture both explicit NBS terminology and related concepts, including green infrastructure, blue-green infrastructure, natural flood management, ecosystem-based adaptation, wetland restoration, floodplain restoration, permeable pavements, bioswales, and low-impact development. Boolean operators and wildcard characters were used to improve search sensitivity, and searches were applied to title, abstract, and keyword fields. The final search string was: *TITLE-ABS-KEY (flood* OR flooding OR "river flood*" OR "coastal flood*" OR "pluvial flood*")AND TITLE-ABS-KEY ("nature-based solutions" OR NBS OR "natural flood management" OR "green infrastructure" OR "blue-green infrastructure" OR "ecosystem-based adaptation" OR "ecosystem services" OR "wetland restoration" OR "floodplain restoration" OR "green roof" OR bioswale OR "permeable pavement" OR "stormwater management" OR "low impact development") AND TITLE-ABS-KEY (mitigation OR prevention OR "flood risk reduction" OR "disaster risk reduction")*

The review included peer-reviewed journal articles published in English between 2016 and 2026. Studies were included if they examined the application, performance, modelling, evaluation, or governance of NBS for flood mitigation. Eligible interventions included green infrastructure, wetlands, floodplain reconnection, river restoration, mangroves, coastal ecosystems, and ecosystem-based adaptation. Studies were excluded if they focused on non-flood hazards, discussed ecosystem concepts without direct relevance to flood mitigation, were not peer-reviewed journal articles, were conference abstracts, reports, grey literature, or were not written in English.

The database search identified 924 records from Scopus and Web of Science. After duplicate removal, 548 unique records remained. Title and abstract screening were conducted to assess relevance to NBS and flood mitigation. Records were excluded if they did not focus on flooding, did not examine NBS or related ecosystem-based interventions, or did not address flood mitigation, flood risk reduction, or flood management outcomes. Full-text eligibility assessment was then conducted for potentially relevant studies. At this stage, records were excluded if they were outside the review period, lacked direct relevance to NBS-based flood mitigation, did not provide sufficient methodological or analytical detail, or failed to meet the publication and language criteria. Following all eligibility checks, 136 studies were retained for detailed analysis. The screening process is summarized in the PRISMA flow diagram presented in Figure 1.

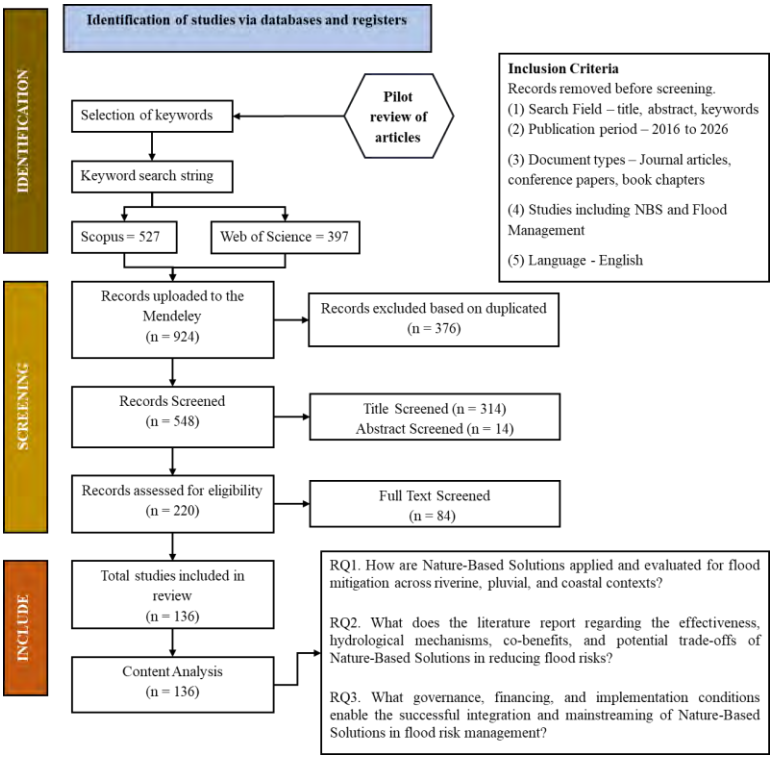



*Figure 1: Overview of research methodology.*

Data were extracted using a structured coding sheet developed from the research questions and SPIDER framework. Extracted information included publication year, country or region, flood hazard type, NBS category, research method, performance indicators, hydrological mechanisms, co-benefits, and governance or implementation conditions. Coding combined deductive and inductive approaches. Deductive codes were

developed from the review objectives, including flood hazard types, NBS categories, research methods, and evaluation metrics. Inductive coding was used to capture recurring themes emerging from the studies, including institutional barriers, financing constraints, monitoring limitations, and hybrid grey–green infrastructure approaches.

The selected studies were analyzed using descriptive statistics and thematic synthesis. Descriptive analysis identified publication trends, geographic distribution, dominant NBS types, flood contexts, and evaluation metrics. Thematic synthesis was used to interpret how NBS influence flood dynamics and how institutional, financial, and governance conditions affect implementation. A quality appraisal was also conducted based on methodological clarity, relevance to flood mitigation, transparency of data or modelling assumptions, appropriateness of evaluation methods, and clarity of reported outcomes. Studies were not excluded solely on quality; instead, appraisal informed the interpretation of evidence strength.

# 3. RESULTS AND DISCUSSION

## 3.1 PUBLISHED ARTICLES, ANNUAL AND WORLDWIDE DISTRIBUTIONS

The systematic review identified a rapidly expanding body of literature on the application of NBS for flood risk reduction between 2016 and 2026. As shown in Figure 2, publication activity remained relatively limited during the early years of the review period, with only one to four studies published annually between 2016 and 2019. This suggests that the application of NBS to flood management was still an emerging research field during this period, despite broader international interest in ecosystem-based adaptation, green infrastructure, and sustainable urban drainage. A clear increase in research activity began in 2020, when the number of publications rose to nine, followed by fourteen in 2021 and sixteen in 2022. Although a slight decline was observed in 2023, with eleven publications, the field expanded substantially thereafter, reaching twenty-six publications in 2024 and peaking at forty-three in 2025. The lower number of publications recorded in 2026 is most likely attributable to the incomplete coverage of the year at the time of data collection rather than a decline in research interest.

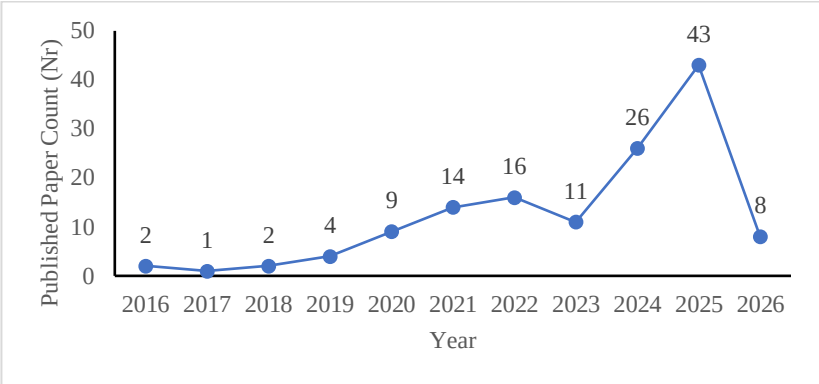



*Figure 2: Annual publication trend*

This upward trend reflects the increasing recognition of NBS as a complementary approach to conventional flood management. The growing number of studies also corresponds with wider policy interest in climate adaptation, urban resilience, biodiversity restoration, and sustainable infrastructure. Flooding is increasingly understood not only as a hydraulic or engineering problem but also as a socio-ecological

challenge shaped by land-use change, catchment degradation, urbanisation, and climate variability. Consequently, the rapid growth of NBS research indicates a broader transition in flood management thinking, moving away from reliance on purely structural defences and towards more adaptive, multifunctional, and ecosystem-based strategies.

However, the geographical distribution of the reviewed studies reveals a pronounced imbalance in the evidence base. As illustrated in Figure 3, the United States accounts for the largest share of publications, with 35 studies. This reflects the country's strong research and policy engagement with sustainable drainage systems, natural flood management, catchment-based planning, and green infrastructure. In comparison, fewer studies were identified from other countries, with China contributing eight publications and Australia contributing seven, while many countries were represented by only one study. Although Europe has played a leading role in climate policy and environmental governance (Oberthür & Kelly, 2008), the number of studies specifically addressing NBS for flood reduction remains unevenly distributed even within Europe and comparatively limited across many flood-prone regions.

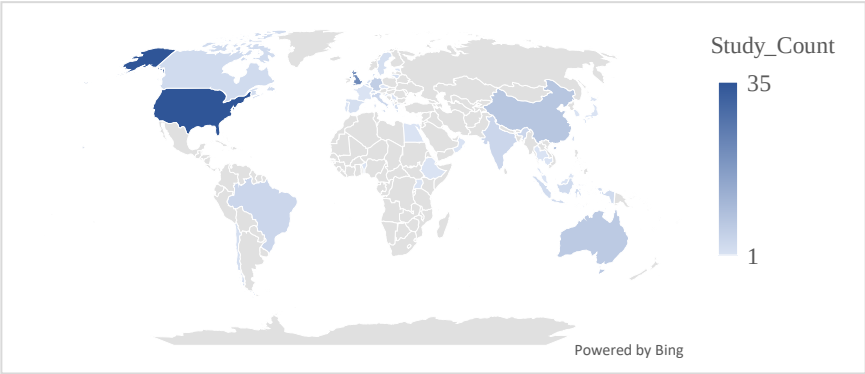



*Figure 3: Worldwide distribution map of publications*

This geographical imbalance is especially important because many countries in the Global South are highly exposed to flooding due to rapid urbanisation, inadequate drainage infrastructure, informal settlement growth, land-use pressures, and increasing climate-related rainfall extremes. The limited representation of Global South contexts reduces the transferability of current findings, particularly because the performance and feasibility of NBS are strongly shaped by governance capacity, land availability, maintenance systems, hydrological conditions, and socio-economic constraints. This highlights the need for more empirical studies from the Global South that document locally adapted practices, assess hydrological performance, and examine governance and maintenance requirements.

## 3.2 TYPES OF NATURE-BASED SOLUTION

The reviewed literature demonstrates that NBS for flood management are highly diverse and should not be treated as a single homogeneous category. To improve analytical clarity, this review classified the identified interventions according to three dimensions: intervention type, spatial scale, and dominant flood-mitigation function. This classification enables a clearer distinction between site-level stormwater measures, connected green–blue infrastructure networks, floodplain and wetland storage systems, river restoration and natural flood management, coastal ecosystem-based protection, and catchment-scale interventions.

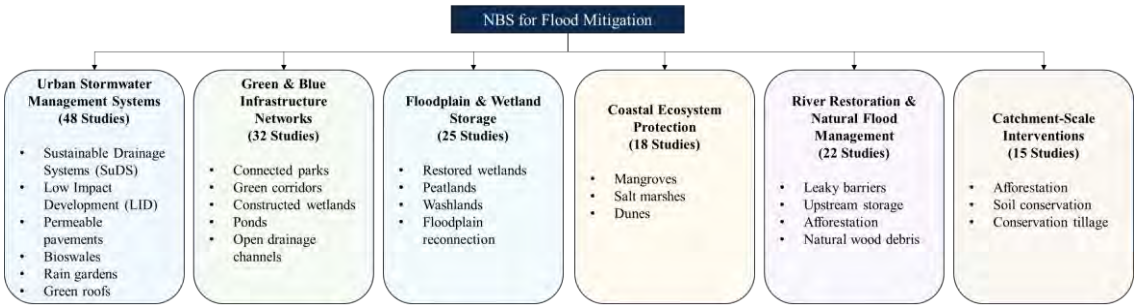



*Figure 4: Types of NBS solutions*

As shown in Figure 4, urban stormwater management systems represent the most frequently examined category, appearing in 48 studies. This group includes Sustainable Drainage Systems, Low Impact Development measures, permeable pavements, bioswales, rain gardens, green roofs, detention basins, retention systems, and sponge city measures. These interventions are primarily designed to address pluvial flooding by increasing infiltration, reducing runoff volume, enhancing temporary storage, and delaying peak discharge. Their prominence reflects the growing importance of urban flood management under rapid urban expansion and increasing impervious surface cover. However, their effectiveness is usually strongest at the site or neighborhood scale and may be limited during high-intensity or long-duration rainfall events if storage capacity is exceeded or drainage systems are already overloaded.

Green and blue infrastructure networks appeared in 32 studies. These systems include connected parks, green corridors, constructed wetlands, ponds, open drainage channels, and multifunctional urban landscapes. Unlike isolated stormwater measures, green–blue infrastructure networks depend on spatial connectivity and cumulative hydrological effects. Their performance is influenced not only by the capacity of individual components but also by their arrangement within urban drainage networks, catchments, and runoff pathways. Fragmented green spaces may provide local benefits, but their contribution to wider flood mitigation may remain limited unless they are strategically connected to drainage systems, rivers, or receiving water bodies.

Floodplain and wetland storage systems were examined in 25 studies. These include restored wetlands, peatlands, washlands, and floodplain reconnection schemes. Their primary function is to store excess water, attenuate riverine flood peaks, and reduce downstream flood intensity. In contrast to urban stormwater systems, these interventions usually operate at larger spatial scales and are closely linked to river basin hydrology. Their effectiveness depends on available storage volume, floodplain connectivity, vegetation structure, soil conditions, antecedent moisture, and the timing of flood wave propagation. Therefore, their performance can vary considerably between catchments and flood events.

River restoration and natural flood management were identified in 22 studies. These interventions include leaky barriers, upstream storage, afforestation, riparian vegetation restoration, re-meandering, and natural wood debris. They aim to slow runoff, increase channel roughness, enhance temporary storage, and reconnect rivers with floodplains. However, their effectiveness is context-specific and may depend on catchment size, slope, land use, soil permeability, intervention density, and maintenance. Small-scale measures may reduce local flood peaks but may not substantially influence downstream flooding unless implemented at sufficient scale and in hydrologically suitable locations.

Coastal ecosystem-based protection appeared in 18 studies and includes mangroves, salt marshes, dunes, coastal wetlands, and hybrid coastal defense systems. These interventions reduce coastal flood hazards by attenuating wave energy, limiting storm-surge impacts, stabilizing shorelines, and creating buffer zones between the sea and exposed settlements. Their effectiveness depends on ecosystem width, vegetation density, elevation, tidal range, sediment supply, and storm intensity. Catchment-scale interventions, including afforestation, soil conservation, conservation tillage, upland storage, and distributed retention measures, appeared in 15 studies, indicating that watershed-level NBS remain less represented than urban and floodplain-focused approaches.

Therefore, the dominance of urban stormwater systems suggests that NBS research has been strongly shaped by urban flood concerns and the policy visibility of green infrastructure. However, this emphasis may create a narrow understanding of NBS effectiveness if broader and interacting flood mechanisms are underrepresented. Flooding often results from multiple interacting drivers, including intense rainfall, high river levels, storm surge, drainage exceedance, and rising groundwater. Yet groundwater flooding and compound flooding remain insufficiently addressed in the reviewed studies. This is a major limitation because NBS performance under compound conditions may differ from performance under single-source flood events.

### 3.3 RELATIONSHIP BETWEEN THE PRIMARY NATURE-BASED SOLUTION (NBS) TYPES AND THE FLOOD HAZARDS

Figure 5 illustrates how the primary NBS categories identified in the review are distributed across different flood hazard contexts. The results show that NBS are not applied uniformly across flood types; rather, their use reflects the dominant hydrological and hydraulic processes associated with each hazard. Urban stormwater systems are most strongly associated with pluvial and urban flooding because they address rainfall-runoff generation, surface-water accumulation, and drainage exceedance close to where rainfall occurs. In contrast, floodplain storage, wetland restoration, river restoration, and natural flood management are more commonly linked to riverine flooding, where the main objective is to attenuate flood peaks, increase temporary storage, slow flow conveyance, and reconnect rivers with their floodplains.

Green and blue-green infrastructure networks occupy an intermediate position because they can contribute to both pluvial and riverine flood management. Their effectiveness depends on how well individual green and blue spaces are connected to runoff pathways, drainage systems, river corridors, and receiving water bodies. Similarly, catchment-scale interventions, such as afforestation, upland storage, soil conservation, and distributed retention, operate across broader hydrological systems by influencing runoff generation, flow pathways, and downstream flood peaks. These interventions are therefore less tied to a single flood type and more relevant to multi-scale flood management.

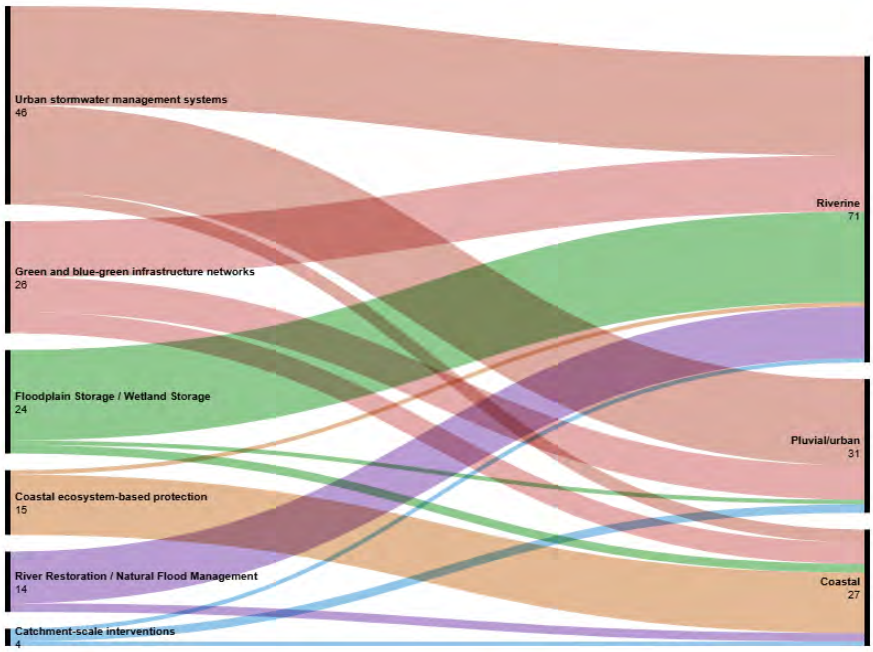



*Figure 5: Relationship between the primary NBS types and the flood hazards addressed in the selected studies*

Coastal ecosystem-based protection is primarily associated with coastal flooding, where mangroves, salt marshes, dunes, reefs, and coastal wetlands reduce hazards by dissipating wave energy, moderating storm-surge impacts, trapping sediment, and stabilising shorelines. However, the limited number of studies addressing groundwater and compound flooding indicates an important gap in the evidence base. Many real flood events involve interacting drivers, such as intense rainfall, high river levels, storm surge, drainage exceedance, and rising groundwater. Therefore, Figure 5 highlights not only the dominant pairing between NBS types and flood hazards, but also the need for future studies to assess how NBS perform under overlapping and multi-source flood conditions.

## 3.4 OUTCOME METRICS USED TO EVALUATE NBS EFFECTIVENESS

Figure 6 summarises the outcome metrics used to evaluate the effectiveness of NBS in the reviewed literature. The findings show that most studies rely on broad flood risk or flood hazard indices, reported in 73.5% of the reviewed studies. These indices commonly combine hazard intensity, exposure, and vulnerability to estimate overall flood risk reduction. Although useful for communicating wider risk implications, such composite indicators can obscure the specific hydrological processes through which NBS influence flood behaviour. This is important because different NBS types operate through different mechanisms and are therefore expected to affect different flood variables.

Urban stormwater interventions, such as green roofs, permeable pavements, rain gardens, bioswales, and detention systems, are mainly assessed in relation to pluvial flooding. Their effectiveness is commonly measured using runoff reduction, drainage performance, flood depth, surface water accumulation, and stormwater load indicators (Hankin et al., 2021). In contrast, floodplain restoration, wetland rehabilitation, river re-meandering, and riparian buffer interventions are more frequently evaluated in fluvial flood contexts using peak discharge, inundation extent, flood storage, flow attenuation, and water-level indicators (Schröder et al., 2025). Coastal ecosystem-based protection, including

mangroves, salt marshes, dunes, and coastal wetlands, is usually assessed through wave attenuation, storm-surge reduction, shoreline stability, erosion control, and avoided damage (Inácio et al., 2023). These patterns indicate that performance assessment is shaped by both the NBS intervention type and the dominant flood mechanism being addressed.

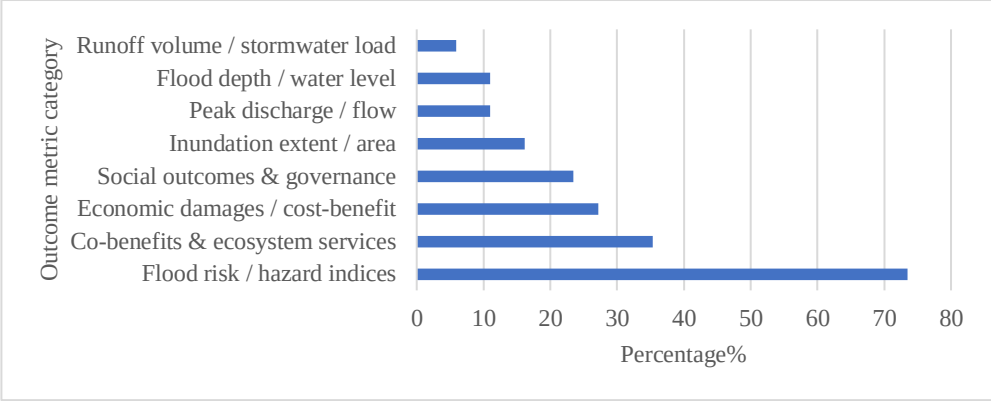



*Figure 6: Outcome metrics reported in the reviewed studies*

However, direct hydrological performance indicators are reported less consistently than broader risk-reduction and co-benefit outcomes. Co-benefits and ecosystem services are reported in 35.3% of studies, including biodiversity enhancement, water quality improvement, urban cooling, carbon storage, recreation, and landscape amenity. Economic damage reduction and cost–benefit assessments appear in 27.2% of studies, while social and governance outcomes are reported in 23.5%. By comparison, inundation extent appears in only 16.2% of studies, while peak discharge and flood depth or water level is each reported in 11.0%. Runoff volume or stormwater load is reported in only 5.9% of studies. This imbalance suggests that the literature gives greater attention to broad risk-reduction narratives and ecosystem-service benefits than to measurable hydrological performance. As a result, it remains difficult to compare NBS effectiveness across studies, flood types, spatial scales, and intervention designs.

A further limitation concerns temporal performance and uncertainty. Approximately 61% of the reviewed studies rely on hydrological or hydraulic modelling frameworks, including SWMM, HEC-RAS, and MIKE FLOOD, to estimate NBS performance under different rainfall, climate, land-use, and urbanisation scenarios(Ahiablame et al., 2012; Eckart et al., 2017). These approaches are valuable for testing design alternatives and future conditions, and previous studies have shown that NBS performance can vary with rainfall intensity, spatial configuration, and intervention scale (Ruangpan et al., 2024; Schubert et al., 2017). However, modelled results remain sensitive to assumptions, parameterisation, rainfall inputs, spatial resolution, and the representation of vegetation and soil processes. Moreover, relatively few studies evaluate how NBS performance changes over time as vegetation matures, soils become compacted, sediment accumulates, maintenance regimes vary, and flood extremes intensify. The limited availability of long-term empirical monitoring therefore remains a major weakness, as also highlighted by Chausson et al. (2020) and Elmqvist et al. (2013).This creates a trade-off in performance assessment: while co-benefits are widely reported, they are not always evaluated alongside direct hydrological indicators.

### 3.5 MECHANISMS THROUGH WHICH NBS INFLUENCE FLOOD RISK

The reviewed studies consistently identify several hydrological and ecological mechanisms through which NBS influence flood hazards. One of the most widely documented mechanisms is increased infiltration and soil water storage. Urban green infrastructure interventions such as permeable pavements, bioswales, rain gardens, and vegetated surfaces enhance infiltration rates and reduce surface runoff volumes during rainfall events (Ahiablame et al., 2012; Bush et al., 2021). These processes delay runoff generation, reduce peak discharge, and lower pressure on conventional drainage systems.

Wetlands and floodplain restoration provide floodwater storage and attenuation benefits

(Lindenberger et al., 2025; Watson et al., 2016). By reconnecting rivers with floodplains or restoring wetland storage capacity, these systems can temporarily retain high flows and reduce downstream flood peaks. Vegetation-based systems also increase hydraulic roughness, slowing water movement across landscapes. Riparian vegetation, floodplain forests, and mangroves can reduce flow velocity and modify the propagation of flood waves (Dadson et al., 2017). In coastal settings, dense vegetation and complex root structures can attenuate wave energy and reduce storm-surge impacts, supporting findings from coastal wetland studies (Inácio et al., 2023).

Another important mechanism is hydrograph desynchronisation through distributed interventions. When NBS measures are implemented across multiple locations in a catchment, they can delay runoff generation from different sub-catchments and reduce the synchronisation of peak flows. This distributed effect can lower downstream flood peaks, particularly in urban drainage networks where runoff convergence is rapid (Dadson et al., 2017). This finding reinforces the importance of evaluating NBS not only as isolated interventions but also as components of wider catchment and infrastructure systems. Nevertheless, the effectiveness of NBS is highly context specific. Performance varies according to rainfall intensity, catchment size, soil permeability, antecedent moisture conditions, land availability, vegetation maturity, maintenance quality, storage capacity, and integration with grey infrastructure (Giordano et al., 2020). NBS may perform well during frequent low-to-moderate events but become less effective when storage capacity is exceeded or systems become saturated. Therefore, NBS should not be presented as universal replacements for conventional flood defences. Instead, they should be understood as adaptive components within multi-layered flood risk management systems.

Governance and institutional conditions also strongly influence NBS implementation. Fragmented responsibilities remain a major barrier, operating both horizontally and vertically (Griffiths et al., 2024). Horizontally, weak coordination between water management authorities, planning departments, environmental agencies, infrastructure providers, and landowners can make responsibilities for planning, funding, maintenance, and monitoring unclear (Schröder et al., 2025). Vertically, misalignment between national adaptation policies, regional catchment strategies, local planning controls, and site-level delivery capacity can limit the translation of broad NBS commitments into implemented projects. Land availability is another constraint, especially in dense urban areas where space for green infrastructure or floodplain reconnection is limited (Hankin et al., 2021). Financial barriers further reinforce these challenges because conventional funding mechanisms often favour grey infrastructure with easily defined costs and outputs, whereas NBS benefits are distributed across multiple sectors, beneficiaries, and

timeframes. This can undervalue ecosystem-service benefits in cost–benefit assessment and weaken provision for long-term maintenance, despite evidence that NBS can generate resilience and wider environmental benefits (Ruangpan et al., 2024; Seddon et al., 2020).

A central implication of the reviewed evidence is that hybrid grey–green infrastructure systems may offer a practical pathway for integrating NBS into flood management, particularly where ecological measures alone are unlikely to provide sufficient protection during extreme events (Kim, 2024). Hybrid systems combine engineered structures with ecological processes, allowing NBS to manage frequent or moderate flood events while conventional infrastructure provides additional protection during larger or more hazardous events. However, this should be interpreted cautiously, as much of the evidence remains conceptual, model-based, or derived from case-specific applications. Differing perspectives exist regarding the scalability, reliability, cost-effectiveness, and maintenance requirements of hybrid systems. While some studies present grey–green integration as a means of improving flexibility, redundancy, and multifunctionality, others highlight trade-offs related to land availability, institutional coordination, long-term maintenance, uncertain performance under extreme or compound flooding, and the difficulty of balancing hydrological objectives with co-benefits such as biodiversity, recreation, and urban amenity. Therefore, hybrid systems should not be presented as universally superior solutions, but as context-dependent strategies whose effectiveness depends on design, scale, governance capacity, and local hydrological conditions.

### 3.6 POLICY IMPLICATIONS FOR MAINSTREAMING NBS IN FLOOD RISK MANAGEMENT

The synthesis of evidence indicates several policy-relevant implications for mainstreaming NBS in flood risk management. These should be interpreted as evidence-informed directions rather than universal prescriptions, as the strength of evidence varies across intervention types and flood contexts. First, relatively strong evidence suggests that NBS should be considered early in spatial planning, since land availability, landscape connectivity, and hydrological pathways strongly influence their feasibility and performance. Second, the literature provides moderate support for using broader appraisal methods, including ecosystem service valuation and multi-criteria decision analysis, because conventional cost–benefit approaches may overlook co-benefits such as biodiversity, carbon sequestration, water quality, and recreation. Third, strong evidence highlights the need for long-term monitoring to validate modelled outcomes and reduce uncertainty regarding real-world performance and maintenance. Finally, cross-sector governance coordination emerges as an important but more context-dependent implication, requiring further evidence across different institutional settings.

## 4. CONCLUSIONS

This systematic literature review examined the role of NBS in flood mitigation, focusing on their application across pluvial, riverine, and coastal flood contexts, their underlying hydrological mechanisms, and the governance conditions influencing implementation. Based on 136 peer-reviewed studies, the findings confirm a rapidly growing interest in NBS as sustainable and multifunctional approaches to flood risk management. The review shows that urban green infrastructure and low-impact development measures dominate the literature, particularly for pluvial flooding in urban areas. Wetland restoration, floodplain reconnection, and river restoration are more commonly associated

with riverine flood management, while mangroves and other coastal ecosystems are frequently examined for coastal flood protection. Across these contexts, NBS reduce flood hazards through enhanced infiltration, increased water storage, vegetation-induced hydraulic roughness, and delayed runoff at catchment scale. However, the evidence base remains uneven. Current research is geographically biased, with limited representation from the Global South, despite these regions facing increasing flood exposure. The literature also relies heavily on modelling, composite indices, and pilot-scale assessments, while long-term empirical monitoring and direct hydrological validation remain limited. These gaps constrain confidence in the transferability and real-world performance of NBS. Thus, this review demonstrates that NBS can play a significant role in future flood mitigation when integrated into spatial planning, supported by multi-criteria evaluation, and coordinated through cross-sector governance. Advancing hybrid gray–green infrastructure and strengthening empirical evidence will be essential for mainstreaming NBS as credible, scalable, and context-sensitive flood mitigation strategies.

## 5. REFERENCES

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of low impact development practices: literature review and suggestions for future research. *Water, Air, & Soil Pollution*, *223*(7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

Bush, J., Ashley, G., Foster, B., & Hall, G. (2021). Integrating green infrastructure into urban planning: Developing Melbourne's green factor tool. *Urban Planning*, *6*(1), 20–31. https://doi.org/10.17645/up.v6i1.3515

Caroppi, G., Pugliese, F., Gerundo, C., De Paola, F., Stanganelli, M., Urciuoli, G., Nadim, F., Oen, A., Andrés, P., & Giugni, M. (2024). A comprehensive framework tool for performance assessment of NBS for hydro-meteorological risk management. *Journal of Environmental Planning and Management*, *67*(6), 1231–1257. https://doi.org/10.1080/09640568.2023.2166818

Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., Key, I., Roe, D., Smith, A., Woroniecki, S., & Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, *26*(11), 6134–6155. https://doi.org/10.1111/gcb.15310

Dadson, S. J., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P., Lane, S. N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C., & Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *473*(2199), 20160706. https://doi.org/10.1098/rspa.2016.0706

Devi, N., Ganapathy, A., Silva, A. F. R., Vorogushyn, S., Apel, H., Kreibich, H., Oostwegel, L. J. N., Kuiry, S. N., & Sairam, N. (2025). Lost water bodies and a flooded city – Counterfactual scenarios of the extreme Chennai flood highlight the potential of nature-based solutions. *Urban Climate*, *61*, 102454. https://doi.org/10.1016/j.uclim.2025.102454

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment*, *607–608*, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Elmqvist, T., Goodness, J., Marcotullio, P. J., Parnell, S., Sendstad, M., Wilkinson, C., Fragkias, M., Güneralp, B., McDonald, R. I., Schewenius, M., & Seto, K. C. (2013). Urbanization, biodiversity and ecosystem services: Challenges and opportunities: A global assessment. In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*. Springer Netherlands. https://doi.org/10.1007/978-94-007-7088-1

Giordano, R., Pluchinotta, I., Pagano, A., Scrieciu, A., & Nanu, F. (2020). Enhancing nature-based solutions acceptance through stakeholders' engagement in co-benefits identification and trade-offs analysis. *Science of The Total Environment*, *713*, 136552. https://doi.org/10.1016/j.scitotenv.2020.136552

Griffiths, J., Borne, K. E., Semadeni-Davies, A., & Tanner, C. C. (2024). Selection, Planning, and Modelling of Nature-Based Solutions for Flood Mitigation. *Water*, *16*(19), 2802. https://doi.org/10.3390/w16192802

Hankin, B., Page, T., McShane, G., Chappell, N., Spray, C., Black, A., & Comins, L. (2021). How can we plan resilient systems of nature-based mitigation measures in larger catchments for flood risk reduction now and in the future? *Water Security*, *13*, 100091. https://doi.org/10.1016/j.wasec.2021.100091

Huang, R., Tian, Z., Fan, D., Ye, Q., Liu, Q., Kong, M., Wang, Y., Lyu, J., & Sun, L. (2026). Nature's double defense: How mangroves and intertidal topography shape coastal flood mitigation. *Ocean & Coastal Management*, *272*, 108004. https://doi.org/10.1016/j.ocecoaman.2025.108004

Iliadis, C., Glenis, V., & Kilsby, C. (2024). A cost-benefit 'source-receptor' framework for implementation of Blue-Green flood risk management. *Journal of Hydrology*, *634*, 131113. https://doi.org/10.1016/j.jhydrol.2024.131113

Inácio, M., Barboza, F. R., & Villoslada, M. (2023). The protection of coastal lagoons as a nature-based solution to mitigate coastal floods. *Current Opinion in Environmental Science & Health*, *34*, 100491. https://doi.org/10.1016/j.coesh.2023.100491

Intergovernmental Panel on Climate Change [IPCC]. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_FullReport.pdf

Kienzler, S., Kreibich, H., Müller, M., Pech, I., & Thieken, A. H. (2016). Assessment of flood loss model transferability considering changes in precaution of flood-affected residents in Germany . *3rd European Conference on Flood Risk Management (FLOODRISK 2016)*, 1–11. https://doi.org/10.1051/e3sconf/20160713002

Kim, K.-G. (2024). *Overview and Exploration of Nature-Based Flooding Solutions: The Green Transition* (pp. 59–75). https://doi.org/10.1007/978-3-031-50365-8_6

Lindenberger, A., Rauch, H. P., Kasak, K., Stelzhammer, M., & von der Thannen, M. (2025). Impact of various flood conditions on the CO2 ecosystem exchange as a component of floodplain grassland restoration. *Ecological Engineering*, *212*, 107489. https://doi.org/10.1016/j.ecoleng.2024.107489

Marino, M., Baptist, M. J., Alkharoubi, A. I. K., Nasca, S., Cavallaro, L., Foti, E., & Musumeci, R. E. (2025). Nature-based Solutions as Building Blocks for coastal flood risk reduction: a model-based ecosystem service assessment. *Scientific Reports*, *15*(1), 12070. https://doi.org/10.1038/s41598-025-95230-4

Oberthür, S., & Kelly, C. (2008). EU leadership in international climate policy: Achievements and challenges. *The International Spectator*, *43*(3), 35–50. https://doi.org/10.1080/03932720802280594

Petticrew, M., & Roberts, H. (2006). *Systematic Reviews in the Social Sciences*. Wiley. https://doi.org/10.1002/9780470754887

Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., & Brdjanovic, D. (2024). Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. *Journal of Environmental Management*, *352*, 119985. https://doi.org/10.1016/j.jenvman.2023.119985

Sabut, A., Bhat, A. M., Tripathi, I. M., & Mohapatra, P. K. (2026). Optimizing Green Infrastructure for Urban Flood Mitigation Using the SWMM: A Case Study in Kozhikode, India. *Journal of Hydrologic Engineering*, *31*(2). https://doi.org/10.1061/JHYEFF.HEENG-6677

Schröder, P. T., Wübbelmann, T., & Kabisch, N. (2025). A scenario-based modelling approach to implementing nature-based solutions for flood risk mitigation in Hannover. *NPJ Urban Sustainability*, *6*(1), 21. https://doi.org/10.1038/s42949-025-00326-5

Schubert, J. E., Burns, M. J., Fletcher, T. D., & Sanders, B. F. (2017). A framework for the case-specific assessment of Green Infrastructure in mitigating urban flood hazards. *Advances in Water Resources*, *108*, 55–68. https://doi.org/10.1016/j.advwatres.2017.07.009

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Watson, K. B., Ricketts, T., Galford, G., Polasky, S., & O'Niel-Dunne, J. (2016). Quantifying flood mitigation services: The economic value of Otter Creek wetlands and floodplains to Middlebury, VT. *Ecological Economics*, *130*, 16–24. https://doi.org/10.1016/j.ecolecon.2016.05.015

Wu, Y., Sun, J., Jun Xu, Y., Zhang, G., & Liu, T. (2022). Projection of future hydrometeorological extremes and wetland flood mitigation services with different global warming levels: A case study in the Nenjiang river basin. *Ecological Indicators*, *140*, 108987. https://doi.org/10.1016/j.ecolind.2022.108987

Peiris, S.D.N.B., Gunatilake, S. and Ilangakoon, I.W.M.A.D., 2026. Occupational stressors among Sri Lankan construction professionals. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Wimalaratne, P.L.I. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1223-1235. DOI: https://doi.org/10.31705/WCS.2026.89. Available from: https://ciobwcs.com/papers/

# OCCUPATIONAL STRESSORS AMONG SRI LANKAN CONSTRUCTION PROFESSIONALS

**S.D.N.B. Peiris[1], S. Gunatilake[2] and I.W.M.A.D. Ilangakoon[3]**

## *ABSTRACT*

*The construction industry is widely recognized as a high-pressure work environment due to demanding workloads, strict deadlines, and challenging work conditions. Occupational stress is a significant concern among construction professionals. Despite growing attention to mental health in construction, limited empirical evidence exists on the relative significance of occupational stressors affecting construction professionals, particularly in the Sri Lankan context. Therefore, this study aims to identify and rank the most significant occupational stressors among Sri Lankan construction professionals and highlight their implications for psychological resilience. A quantitative research approach was adopted using a structured questionnaire survey. Data were collected from 41 construction professionals across engineering, quantity surveying, architecture, and site supervision/management through snowball sampling. A five-point Likert scale was used to assess the significance of identified stressors, and Weighted Mean Rating (WMR) was employed to rank them. The findings indicate that task-related stressors are the most dominant. High workload and strict deadlines jointly emerged as the highest-ranked stressors, followed by long working hours, lack of resources and task complexity. Among organisational stressors, workplace injustice recorded was identified as the most significant factor. Poor work environment and exposure to dangerous working conditions were the most prominent physical stressors, while poor work–life balance was identified as the leading personal stressor. The study concludes that occupational stress among Sri Lankan construction professionals is systemic and multidimensional. By identifying the most critical stressors, the research provides a context-specific basis for targeted stress management interventions and resilience-building strategies within the construction industry.*

***Keywords:*** *Construction Professionals; Occupational Stress; Sri Lanka; Stressors.*

## 1. INTRODUCTION

The construction industry is widely recognized as one of the riskiest sectors for poor mental health in the world due to high job demands, tight deadlines, the dynamic nature of construction projects, poor interpersonal relationships, and work-life imbalance

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, peirisnawodi@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sachieg@uom.lk
[3] PhD Candidate, Department of Civil and Environmental Engineering, Monash University, Australia, Ashinsana.IlangakoonWMudiyanselage@monash.edu

(Campbell & Gunning, 2020; Chan et al., 2020; Duckworth et al., 2022; Rahman et al., 2025).

Moreover, there was a significant impact from the COVID-19 pandemic, which introduced additional stressors such as uncertainty, increased workloads, and isolation (Pamidimukkala & Kermanshachi, 2021). These conditions generate significant stress among construction professionals (CPs), including Project Managers, Architects, Engineers, and Quantity Surveyors (Pamidimukkala & Kermanshachi, 2021). In addition, CPs also bear the responsibility of supporting subordinates and maintaining a psychologically healthy work environment. Research demonstrates that such stress significantly affects both workers and their organizations (Campbell & Gunning, 2020). Therefore, the mental well-being of professionals in the construction industry should be seriously considered as a strategic priority rather than an afterthought.

Empirical evidence highlights the seriousness of this issue. A survey conducted by (Lawani et al., 2023), in the UK reported that sixty-eight percent (68%) of CPs experience stress-related disorders, with many suffering from anxiety, depression, and suicidal ideation. A 2020 global survey consisting of 2,081 construction industry professionals indicates high rates of stress (97%), anxiety (87%), depression (70%), fatigue (96%), poor concentration (95%), feeling overwhelmed (91%), and low self-confidence (86%), experienced at least once within the past twelve months (Van Heerden et al., 2024). Furthermore, one in four construction workers has considered taking their own life underscoring the severity of mental health challenges within the sector (Campbell & Gunning, 2020).

The consequences extend beyond individual well-being. Poor mental health among CPs is associated with low performance, high turnover and absenteeism, poor internal communication, rising conflicts (Duckworth et al., 2022). For instance, Chan et al. (2020), highlight that there is a direct correlation between psychological distress and the likelihood of occupational injury. Supporting this, a study by Carnide et al. (2015), revealed that workers with depressive symptoms are three times more likely to experience workplace injuries and fatalities.

Although occupational stress and mental health issues in the construction industry have been widely researched all around the world, most research on this topic have been conducted in developed countries such as the United Kingdom (Sarhan et al., 2024), Australia (Hon et al., 2023), and New Zealand (Kaur, 2024). The construction sector functions in an environment that is different economically, socially, and culturally and has its own impacts on the types and levels of stress experienced by professionals (Liu et al., 2022). Sri Lanka has recently faced with economic instability, shortage of resources, labour issues, and uncertainty in delivering projects (Firose et al., 2025). Therefore, findings from international studies cannot be directly generalised to the Sri Lankan construction context.

Furthermore, current studies are mostly centered on either general construction workers, specific professions, or occupational stressors in isolation (Fagbenro et al., 2023). Limited research has undertaken comprehensive analysis to understand and rank the importance of occupational stressors among varied categories of construction professionals in Sri Lanka. Since psychological resilience and stress coping mechanisms depend on knowledge of the major stressors in a particular setting (O'Dowd et al., 2018), this knowledge gap is quite critical. Therefore, the aim of this study was to identify and rank

the most significant occupational stressors affecting Sri Lankan construction professionals, thereby providing a context-specific foundation for future stress management and resilience-building initiatives.

# 2. LITERATURE REVIEW

## 2.1 OCCUPATIONAL STRESS IN THE CONSTRUCTION INDUSTRY

Pich (2018) defines occupational stress as the "harmful physical and emotional responses that occur when the requirements of the job do not match the capabilities, resources, or needs of the worker". In the construction industry, stress is not episodic but structurally embedded within its operational characteristics (Sarhan et al., 2024). This stems from its project-based nature, tight deadlines, cost pressures, reliance on temporary teams, strict contractual obligations, all of which create a highly stressful environment (Bayhan et al., 2022). Unlike routine industries, construction projects are inherently dynamic and uncertain, often requiring rapid decision-making under conditions of incomplete information (Love et al., 2023; Wang et al., 2023).

From a theoretical perspective, the Job Demands–Resources (JD-R) model provides a useful lens for examining this dynamic. JD-R theory shows that job demands can be classified as the stressors faced by the CPs and job resources are the physical, mental, social aspects that are functional in achieving work goals, reduce job demands (Bakker & Demerouti, 2007). The model posits that high job demands contribute to strain when not balanced by sufficient resources, while personal resources such as resilience, buffer the negative impact of job demands and promote well-being. In the construction industry, where many stressors are structural and unavoidable, enhancing personal and organizational resources becomes essential. Psychological resilience therefore operates as a mediating factor that strengthens the effectiveness of coping strategies and mitigates adverse outcomes.

Although stress has been widely acknowledged as prevalent in construction, much of the literature treats it as a general industry phenomenon rather than examining its structured sources or differentiating between occupational roles. Consequently, there remains limited clarity regarding the relative significance of specific stressors affecting CPs.

## 2.2 STRESSORS AFFECTING CONSTRUCTION PROFESSIONALS

Stressors are stimuli or events that disrupt an individual's balance triggering a stress response (Alla et al., 2022). They are essential components of stress and have the potential to cause physiological and psychological reactions (Enshassi & Al.Swaity, 2015). In the context of occupational settings, stressors can generally be divided into four major categories: task-related, personal, physical, and organizational (Senaratne & Rasagopalasingam, 2016).

- Task-related stressors, such as work overload, poor role congruence, long working hours, lack of resources,
- Organizational stressors, such as poor organizational structure, workplace injustice, insufficient remuneration, job insecurity,
- Physical stressors, such as exposure to dangerous working conditions, non-ergonomic situation, poor work environment,

- Personal stressors, such as work group cooperation, poor work-life balance, lack of social support, gender-based impacts, language barriers, age.

Haynes and Love (2004) revealed that workload was the highest-ranking stressor in the UK construction industry followed by working long hours and conflict between family and work. In addition, Leung et al. (2005) surveyed on stressors of construction cost estimators in Hong Kong which showed work overload, role conflict, job ambiguity, and the working environment were the most significant stressors. Overall, the literature reviewed in this study identified 22 specific stressors, which were categorized into task-related (5), organizational (6), physical (3), and personal (8) stressors. Given the wide range of stressors identified in the construction industry, many of them are difficult to remove entirely (Lingard & Francis, 2006). Hence it is critical to search how CPs can adapt to these stressful environments and maintain their wellbeing.

## 2.3 ROLE OF PSYCHOLOGICAL RESILIENCE IN STRESS ADAPTATION

Psychological resilience refers to the capacity to adapt positively and maintain functional stability in the face of adversity and prolonged stress (Wu et al., 2020). It is an important protective factor against stress which acts as an internal resource (Kocjan et al., 2020) that mobilizes positive emotions to deal with stressful events (Su et al., 2023). High levels of psychological resilience can reduce the risk of various mental disorders such as anxiety, depression, post-traumatic stress disorder (Ren et al., 2017).

Empirical research supports these findings in construction settings. Nwaogu et al. (2021) found that tradesmen who were more resilient were less prone to suffer from depressive and anxiety symptoms as well as suicide ideation. Similarly, in the Canadian construction industry, psychological resilience was identified as a secondary preventer of job stress for trade workers due to its significant negative impact on stress (Li et al., 2017). In addition to mitigating stress, it has been discovered that high psychological resilience enhances job satisfaction across various professions, including healthcare and construction (Matos et al., 2010). Therefore, building resilience is essential in developing employee satisfied work environment (Ren et al., 2017).

During adverse events, resilience influences the way stressors are appraised, while the behavioral and emotional responses that follow are known as coping strategies (Thompson et al., 2017). Resilience develops through repeated engagement in effective coping strategies (Booth & Neill, 2017). Mainly high levels of resilience are associated with the use of positive coping strategies (Li et al., 2017). Furthermore, resilience has the ability to mediate and moderate the relationship between coping strategies and psychological outcomes (Smith et al., 2015; Wu et al., 2020). This correlation can be illustrated in Figure 1.

Despite its importance, research on psychological resilience as a protective factor within the construction industry remains relatively scarce (Nwaogu et al., 2022) highlighting the need for further empirical investigation. Effective coping strategies contribute to resilience over time; however, these strategies must be aligned with the dominant stressors faced by professionals. Therefore, a clear understanding of the most significant occupational stressors is essential to enhance one's psychological resilience.

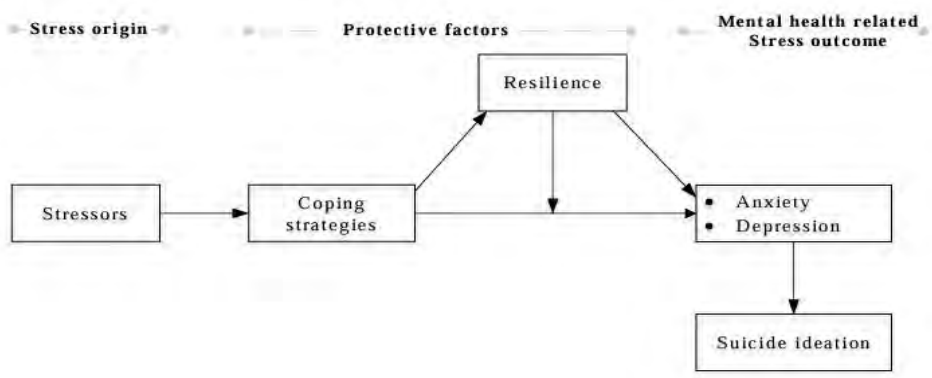



*Figure 1: The stress-coping-resilience framework*

## 3. METHODOLOGY

A structured questionnaire survey was selected as the primary data collection method, as it enables systematic measurement and comparative ranking of stressors comparison of perceived stressors across respondents (Zurlo et al., 2020). The quantitative approach was considered appropriate because the study aimed to quantify the relative significance of occupational stressors and establish their prioritisation.

The sampling technique adopted in this research was snowball sampling. Snowball sampling was selected because construction professionals are distributed across numerous organisations, projects, and geographical locations (Kirchherr & Charles, 2018). This makes it difficult to obtain a comprehensive sampling frame of eligible participants. Furthermore, access to experienced professionals often relies on professional networks and referrals. Therefore, snowball sampling was considered appropriate for identifying and recruiting participants with relevant industry experience while improving response rates within the limited time available for data collection.

In this study, the term 'construction professional' can be defined as a person who performs a technical, management, and professional function related to the planning, designing, coordination, supervision, and management of construction projects (Hoxley, 2000). Consequently, architects, engineers, quantity surveyors, were selected as they represent main construction professionals in Sri Lankan context.

The questionnaire survey has adopted a five-point Likert Scale, which allows easy quantification. A total of 41 valid responses were obtained among professionals in the field of engineering, quantity surveying, architecture and site supervising and managing. Initially, respondents were asked to rank the stressors and strategies which were collected through the literature review on a Likert Scale of 1-5 where 1 refers to ‘Strongly Disagree’, 2 - ‘Disagree’, 3 - ‘Neutral’, 4 - ‘Agree’ and 5 - ‘Strongly Agree’.

Profiles of the questionnaire survey respondents are illustrated in the Figure 2. Throughout the questionnaire survey, most of the responses were gathered from Quantity Surveyors and who has Bachelor of Science (B.Sc.) degree as the highest educational qualification. Most of them had 1-5 years of construction experience.

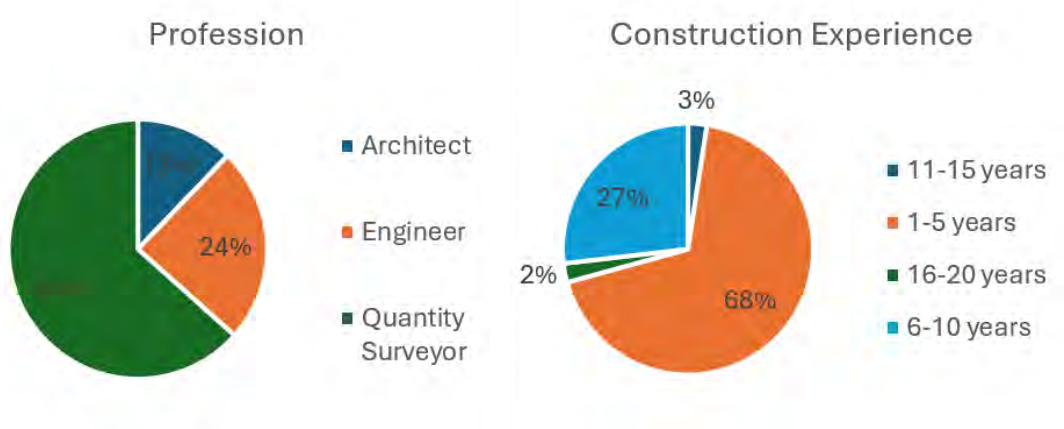



*Figure 2: Professions and construction experience of respondents*

**Weighted Mean Rating (WMR)**

The data collected via questionnaires was analysed based on the Weighted Mean Rating (WMR) given in following formula, which reflected the importance given to each of the selection of stressor and strategy by the respondents.

(1)

Where: WMR= Weighted Mean Rating for an attribute; $fi$ = Frequency of responses for an attribute, $X_i$= Likert scale for an attribute (ranging 1 to 5), n= Total number of respondents.

According to Miller et al. (2018) 3 is considered to be the neutral point in the statistical arena and >3 is considered to be influential in a study. This was further emphasized in a study done by Nelumdeniya et al. (2023). Thus, in this study the cut-off level for significant stressors and for the strategies is considered as 3. Stressors were ranked in descending order based on their WMR values to identify priority areas requiring attention.

# 4. ANALYSIS AND FINDINGS

## 4.1 MOST SIGNIFICANT STRESSORS IN THE CONSTRUCTION INDUSTRY

Twenty-seven stressors were identified from the literature as stressors for CPs. Professionals were asked to rank them through their observations and experience. Significant stressors were ranked based on the WMR.

### 4.1.1 Task- Related Stressors

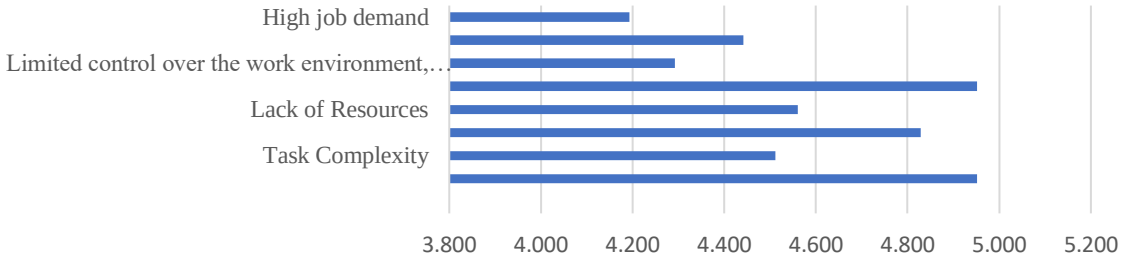



*Figure 3: Task stressors in the construction industry*

All task-related stressors recorded WMR values above the cut-off value of 3.0, indicating agreement among respondents regarding their significance. As illustrated in Figure 3 "High Workload and "Strict Deadlines" were marked as the most significant task stressors in the current construction industry gaining a weighted mean rating of 4.95. This indicates that excessive job demands are a central source of stress within the construction industry.

Further Long Working Hours" followed with a high WMR of 4.829. In addition, Lack of Resources" (WMR=4.561) and "Task Complexity" (WMR=4.512**)** were also highlighted as significant stressors. These findings suggest that stress is not only driven by workload intensity but also by insufficient support and increasing task demands.

"High Job Demand" (4.194) was also perceived as substantial but relatively less critical compared to the others. Overall, the results highlight that task-related stressors are the most dominant category, reflecting structurally embedded pressures in project delivery environments.

### 4.1.2 Organizational Stressors

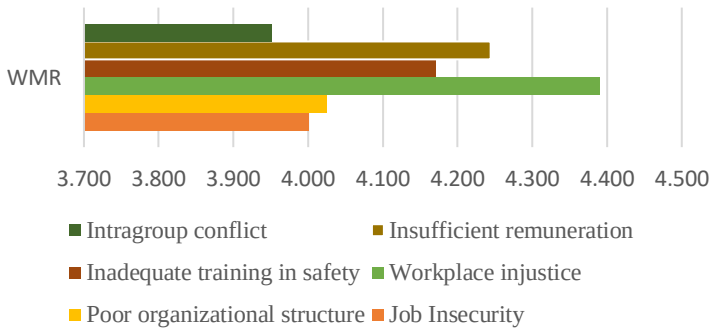



*Figure 4: Organizational stressors in the construction industry*

According to the data presented in Figure 4 reveal that among the six organizational stressors evaluated, "Workplace injustice" was rated as the most critical, with the highest WMR of approximately 4.39**.** Moreover, 20 respondents strongly agreed that workplace injustice is a significant organizational stressor which also has affected to get a higher WMR value. Considering the WMR of all the six stressors, they all fall under the most significant category which poses values of more than 3.

### 4.1.3 Physical Stressors

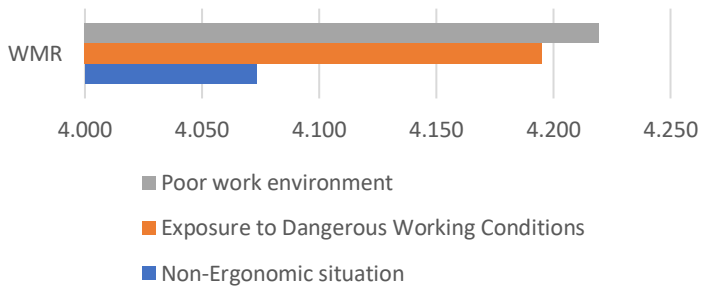



*Figure 5: Physical stressors in construction industry*

Regarding physical stressors, as illustrated in Figure 5**Error! Reference source not found.** WMR of three key physical stressors indicate significant levels of concern among respondents. Among them, "Poor Work Environment" was rated the highest, with a WMR above 4.220. The second most significant physical stressor was "Exposure to Dangerous Working Conditions"**,** which received a slightly lower WMR but still ranked prominently. "Non-Ergonomic Situations" scored the lowest among the three but still had a WMR exceeding 4.0. Therefore, these physical stressors also come under most significant category.

### 4.1.4 Personal Stressors

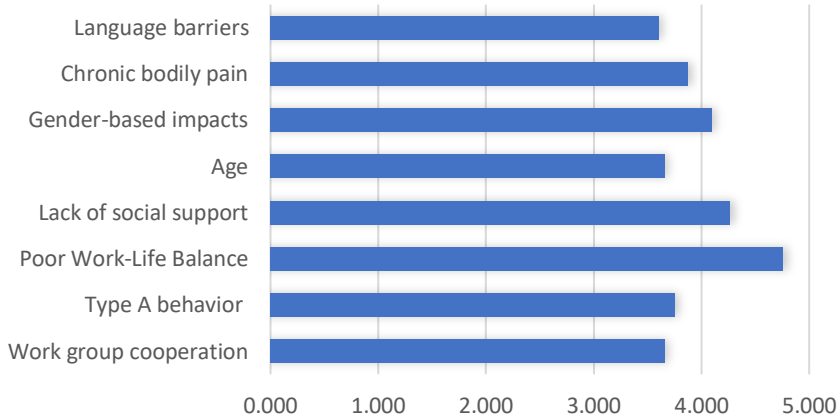



*Figure 6: Personal stressors of construction industry*

According to multiple personal stressors were identified with nearly equal significance. All these stressors recorded WMR values above 3, indicating its significant. They highlight the multifaceted nature of personal burdens experienced by CPs. Among the listed factors, Poor Work-Life Balance emerged as the most significant personal stressor among the other 7 personal stressors which accounts for 15% of the total. In addition, "Gender based impacts and "lack of social support" were marked with same percentages (13%), showing their second most significance after the poor work life balance stressor. Likewise, "work group cooperation", "chronic bodily pain" and "Type A behaviour" got the same percentages (12%) representing the third most significant stressors. the least most significant stressor is "language barrier" with a percentage of 11%.

Across all categories, task-related stressors were identified as the most dominant, followed by organisational, physical, and personal stressors. This indicates that occupational stress among construction professionals is primarily driven by work demands, but is further intensified by organisational practices, physical conditions, and personal constraints. The results demonstrate that stress in the construction industry is multidimensional, requiring integrated management approaches rather than isolated interventions.

## 4.2 DISCUSSION OF FINDINGS

The findings indicate that High Workload and Strict Deadlines (WMR = 4.95) represent the dominant task-related stressors affecting construction professionals. The prominence of workload and deadline pressures suggests that stress in the construction industry is not episodic but systemic. This sustained demand increases the likelihood of chronic stress

accumulation. Long Working Hours (WMR = 4.829) further reinforces this demand overload. Within JD-R theory, prolonged exposure to high demands without sufficient recovery periods accelerates energy depletion, thereby increasing burnout risk. Importantly, the high ranking of Lack of Resources (WMR = 4.561) suggests a simultaneous deficiency in job resources. This creates a compounded effect where high demands paired with inadequate resource support. JD-R theory predicts that such imbalance magnifies psychological strain.

These findings are consistent with to Gunasekara and Perera (2022), who identified "high workload" as the most prevalent task stressor in Sri Lanka. In contrast, Enshassi and Al.Swaity (2015), emphasized "long working hours" as the most critical stressor in Palestine construction industry, which ranked only third in this study with a WMR of 4.829. Additionally, the stressor "lack of resources" was found to be significant which aligns with previous findings by Oladinrin et al. (2014) which highlighted about the Nigerian construction industry. This shows that resource constraints are a key stressor in construction project delivery.

Furthermore, regarding organizational stressors, “Workplace injustice” was rated as the most critical, with the highest WMR of approximately 4.39**.** This finding supports previous assertions by Leung et al. (2005), who highlighted the impact of perceived injustice and inequality on professional stress. Unlike other studies that prioritized job insecurity or organizational culture as top contributors, this research underscores the role of fairness and transparency in reducing occupational stress among CPs.

Regarding physical stressors "Poor work environment" and "exposure to dangerous working conditions" were revealed as the most significant physical stressors. These align with findings by Bowen et al. (2013) psychological health. "Poor work-life balance" was the most significant personal stressor identified. This corroborates the observations by Lingard and Francis (2006), who found that CPs often face difficulties balancing professional and personal responsibilities. Interestingly, stressors such as "gender-based impacts" and "lack of social support" also emerged prominently. These stressors were not commonly prioritized in earlier Sri Lankan studies, suggesting a shifting awareness toward diversity and support systems in the workplace.

Overall, the findings demonstrate that occupational stress among construction professionals is multidimensional and influenced by the interaction of task, organisational, physical, and personal factors. This highlights the need for integrated stress management approaches that address both structural work conditions and individual coping capacities. In this context, psychological resilience plays an important role, as it enables individuals to adapt to high-demand environments. However, resilience alone is insufficient if organisational and task-related stressors remain unaddressed, indicating the importance of combined individual and organisational intervention.

## 5. CONCLUSIONS

The aim of this study to identify and rank the most significant occupational stressors affecting Sri Lankan construction professionals. Four main stressor groups were identified: task, organizational, physical and personal. The results of this study indicated that task-related factors were the most influential. High workload and strict deadlines emerged as the dominant stressors, followed by long working hours, lack of resources,

and task complexity. This indicates that CPs operate within a highly demanding work environment where sustained pressure has become embedded in normal practice.

Regarding organizational stressors, the current study showed that workplace injustice was the most critical stressor which highlights the importance of fairness and transparency in the work environment. Physical stressors such as poor work environment and exposure to dangerous working conditions also remained significant, while poor work-life balance emerged as the most prominent personal stressor.

Since resilience depends on the ability to respond to specific occupational pressures, identifying the dominant stressors is a necessary first step toward developing effective resilience-building strategies. In this sense, the study contributes not only by ranking stressors, but also by providing a practical basis for targeted interventions to strengthen adaptive capacity among professionals.

Overall, this research offers context-specific evidence on occupational stressors affecting Sri Lankan construction professionals. The findings offer a practical foundation for developing targeted stress management strategies and improving working conditions within the construction industry. The study provides valuable empirical evidence to support future efforts aimed at creating healthier, more sustainable, and psychologically supportive construction workplaces in Sri Lanka.

## 6. CONTRIBUTION TO KNOWLEDGE

This study contributes to the existing body of knowledge in three important ways. First, it provides a contemporary and context-specific assessment of occupational stressors affecting construction professionals in Sri Lanka. Second, it systematically ranks stressors across task-related, organisational, physical, and personal dimensions. This enables practitioners and researchers to identify priority areas requiring intervention. Third, the findings establish an empirical foundation for future studies examining psychological resilience, coping strategies, and mental health interventions within the Sri Lankan construction industry.

## 7. PRACTICAL AND RESEARCH IMPLICATIONS

The findings have important implications for construction organisations, project managers, and professional bodies. As high workload, strict deadlines, and long working hours emerged as the most significant stressors, organisations should adopt realistic project planning, effective workload management, and adequate resource allocation practices. Additionally, the prominence of workplace injustice highlights the need for transparent management and fair work environments. From a research perspective, the findings provide a basis for future studies on psychological resilience among construction professionals. Future research may examine the relationships among stressors, coping strategies, resilience, mental health outcomes, and organisational performance using larger samples and advanced analytical techniques.

## 8. FURTHER RESEARCH

The research presented in this paper is considered an initial step to identify the key stressors that lead to stress among construction professionals in Sri Lanka, using a questionnaire survey. Therefore, additional qualitative approaches, such as semi-

structured interviews, case studies and focus groups, are required to further explore in detail the causes, contributing factors and the effects of the stressors identified in this study. In addition, further research is needed to investigate the coping strategies and organisational interventions most suitable for addressing these stressors within construction project environments. Examining how such strategies contribute to stress reduction, psychological resilience, and professional productivity would provide more practical guidance for the industry.

# 9. REFERENCES


Alla, A. M. A., Hussein, R. A. E., Sehlo, M. G., Metwally, E. T. A., & El-Saied, E. A. (2022). Important Notes and Influences of Stress. *The Egyptian Journal of Hospital Medicine*, *87*(1), 2224–2227. https://doi.org/10.21608/ejhm.2022.234287

Bakker, A. B., & Demerouti, E. (2007). The Job Demands-Resources model: state of the art. *Journal of Managerial Psychology*, *22*(3), 309–328. https://doi.org/10.1108/02683940710733115

Bayhan, H. G., Mollaoglu, S., Zhang, H., & Frank, K. A. (2022). Project team collaborations during time of disruptions: Transaction costs, knowledge flows, and social network theory perspective. In *Construction Research Congress 2022: Project Management and Delivery, Controls, and Design and Materials* (pp. 1012–1023). American Society of Civil Engineers. https://doi.org/10.1061/9780784483978.103

Booth, J. W., & Neill, J. T. (2017). Coping strategies and the development of psychological resilience. *Journal of Outdoor and Environmental Education*, *20*(1), 47–54. https://doi.org/10.1007/bf03401002

Bowen, P., Edwards, P., Lingard, H., & Cattell, K. (2013). Workplace stress, stress effects, and coping mechanisms in the construction industry. *Journal of Construction Engineering and Management*, *140*(3). https://doi.org/10.1061/(asce)co.1943-7862.0000807

Campbell, M. A., & Gunning, J. G. (2020). Strategies to improve mental health and well-being within the UK construction industry. *Proceedings of the Institution of Civil Engineers - Management Procurement and Law*, *173*(2), 64–74. https://doi.org/10.1680/jmapl.19.00020

Carnide, N., Franche, R., Hogg-Johnson, S., Côté, P., Breslin, F. C., Severin, C. N., Bültmann, U., & Krause, N. (2015). Course of Depressive symptoms following a workplace injury: A 12-Month Follow-Up Update. *Journal of Occupational Rehabilitation*, *26*(2), 204–215. https://doi.org/10.1007/s10926-015-9604-3

Chan, A. P. C., Nwaogu, J. M., & Naslund, J. A. (2020). Mental Ill-Health Risk Factors in the Construction Industry: Systematic review. *Journal of Construction Engineering and Management*, *146*(3). https://doi.org/10.1061/(asce)co.1943-7862.0001771

Duckworth, J., Hasan, A., & Kamardeen, I. (2022). Mental health challenges of manual and trade workers in the construction industry: a systematic review of causes, effects and interventions. *Engineering Construction & Architectural Management*, *31*(4), 1497–1516. https://doi.org/10.1108/ecam-11-2021-1022

Enshassi, A., & Swaity, E. A. (2015). Key stressors leading to construction professionals' stress in the Gaza Strip, Palestine. *Universiti Sains Malaysia Institutional Repository (Universiti Sains Malaysia)*. http://eprints.usm.my/41468/1/JCDC_20(2)_2015%2DArt._4(53%2D79).pdf

Fagbenro, R. K., Sunindijo, R. Y., Illankoon, C., & Frimpong, S. (2023). Influence of prefabricated construction on the mental health of workers: Systematic review. *European Journal of Investigation in Health Psychology and Education*, *13*(2), 345–363. https://doi.org/10.3390/ejihpe13020026

Firose, M. M., Chathurangi, B. N. M., & Kamardeen, I. (2025). Work stress among construction professionals during an economic crisis: a case study of Sri Lanka. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/sasbe-10-2024-0411

Gunasekara, K. A., & Perera, B. A. K. S. (2022). Stressors of Quantity Surveyors Working On-Site: Female vs Male. In Sandanayake, Y.G., Gunatilake, S., & Waidyasekara, K.G.A.S. (Eds.), *Proceedings of the 10th World Construction Symposium* (pp. 769–781). https://ciobwcs.com/downloads/papers22/WCS2022_Proceedings_62.pdf

Haynes, N. S., & Love, P. E. D. (2004). Psychological adjustment and coping among construction project managers. *Construction Management and Economics*, *22*(2), 129–140. https://doi.org/10.1080/0144619042000201330

Hon, C. K., Sun, C., Way, K. A., Jimmieson, N. L., Xia, B., & Biggs, H. C. (2023). Psychosocial hazards affecting mental health in the construction industry: a qualitative study in Australia. *Engineering Construction & Architectural Management*, *31*(8), 3165–3192. https://doi.org/10.1108/ecam-07-2022-0617

Hoxley, M. (2000). Measuring UK construction professional service quality: the what, how, when and who. *International Journal of Quality & Reliability Management*, *17*(4/5), 511–526. https://doi.org/10.1108/02656710010298553

Kaur, J. (2024). *Exploring construction workers' experiences of stress in the work environment in Aotearoa/New Zealand*. [Masters Thesis, Victoria University of Wellington]. https://doi.org/10.26686/wgtn.25593507

Kirchherr, J., & Charles, K. (2018). Enhancing the sample diversity of snowball samples: Recommendations from a research project on anti-dam movements in Southeast Asia. *PLoS ONE*, *13*(8), e0201710. https://doi.org/10.1371/journal.pone.0201710

Kocjan, G. Z., Kavčič, T., & Avsec, A. (2020). Resilience matters: Explaining the association between personality and psychological functioning during the COVID-19 pandemic. *International Journal of Clinical and Health Psychology*, *21*(1), 100198. https://doi.org/10.1016/j.ijchp.2020.08.002

Lawani, K., Hare, B., Tong, M., & Cameron, I. (2023). Exploring mental health challenges and implications for construction safety. *Journal of Engineering Design and Technology*, *23*(4), 1062–1086. https://doi.org/10.1108/jedt-07-2023-0327

Leung, M., Ng, S. T., Skitmore, M., & Cheung, S. (2005). Critical stressors influencing construction estimators in Hong Kong. *Construction Management and Economics*, *23*(1), 33–44. https://doi.org/10.1080/01446190410001678099

Li, Y. H., Yu, C. Y., Li, X. X., Zhang, P., Tang, J., Yang, Q., Fu, T., Zhang, X., Cui, X., Tu, G., Zhang, Y., Li, S., Yang, F., Sun, Q., Qin, C., Zeng, X., Chen, Z., Chen, Y. Z., & Zhu, F. (2017). Therapeutic target database update 2018: enriched resource for facilitating bench-to-clinic research of targeted therapeutics. *Nucleic Acids Research*, *46*(D1), D1121–D1127. https://doi.org/10.1093/nar/gkx1076

Lingard, H., & Francis, V. (2006). Does a supportive work environment moderate the relationship between work-family conflict and burnout among construction professionals? *Construction Management and Economics*, *24*(2), 185–196. https://doi.org/10.1080/14697010500226913

Liu, Q., Feng, Y., London, K., & Zhang, P. (2022). Influence of personal characteristics and environmental stressors on mental health for multicultural construction workplaces in Australia. *Construction Management and Economics*, *41*(2), 116–137. https://doi.org/10.1080/01446193.2022.2127154

Love, P. E., Ika, L. A., & Pinto, J. K. (2023). Fast-and-frugal heuristics for decision-making in uncertain and complex settings in construction. *Developments in the Built Environment*, *14*, 100129. https://doi.org/10.1016/j.dibe.2023.100129

Matos, P. S., Neushotz, L. A., Griffin, M. T. Q., & Fitzpatrick, J. J. (2010). An exploratory study of resilience and job satisfaction among psychiatric nurses working in inpatient units. *International Journal of Mental Health Nursing*, *19*(5), 307–312. https://doi.org/10.1111/j.1447-0349.2010.00690.x

Miller, J. E. D., Damschen, E. I., & Ives, A. R. (2018). Functional traits and community composition: A comparison among community-weighted means, weighted correlations, and multilevel models. *Methods in Ecology and Evolution*, *10*(3), 415–425. https://doi.org/10.1111/2041-210x.13119

Nelumdeniya, A. U., Perera, B., & Gimhani, K. (2023). Usage of digital technology in improving the mental health of workers on construction sites. *Construction Innovation*, *25*(3), 931–971. https://doi.org/10.1108/ci-08-2022-0214

Nwaogu, J. M., Chan, A. P. C., Sunindijo, R. Y., Darko, A., Yang, J. Y., & Salihu, D. (2022). Prevalence and risk factors for poor mental health and suicidal ideation in the Nigerian construction industry. *Journal of Construction Engineering and Management*, *149*(3). https://doi.org/10.1061/jcemd4.coeng-12253

Nwaogu, J. M., Chan, A. P., & Tetteh, M. O. (2021). Staff resilience and coping behavior as protective factors for mental health among construction tradesmen. *Journal of Engineering Design and Technology*, *20*(3), 671–695. https://doi.org/10.1108/jedt-11-2020-0464

O'Dowd, E., O'Connor, P., Lydon, S., Mongan, O., Connolly, F., Diskin, C., McLoughlin, A., Rabbitt, L., McVicker, L., Reid-McDermott, B., & Byrne, D. (2018). Stress, coping, and psychological resilience among physicians. *BMC Health Services Research*, *18*(1), 730. https://doi.org/10.1186/s12913-018-3541-8

Oladinrin, T. O., Adeniyi, O. & Udi, M. O. (2014). Analysis of Stress Management among Professionals in the Nigerian Construction Industry [Research Article]. *International Journal of Multidisciplinary and Current Research*, *2*(Jan/Feb 2014). http://ijmcr.com

Pamidimukkala, A., & Kermanshachi, S. (2021). Impact of Covid-19 on field and office workforce in construction industry. *Project Leadership and Society*, *2*, 100018. https://doi.org/10.1016/j.plas.2021.100018

Pich, J. (2018). Preventing occupational stress in healthcare workers. *Research in Nursing & Health*, *41*(4), 408–409. https://doi.org/10.1002/nur.21899

Rahman, A., Leifels, K., & Adakporia, K. O. (2025). Risk and causative factors of psychological harm among construction workers: a systematic review. *Workplace Health & Safety*, *73*(6), 266–285. https://doi.org/10.1177/21650799241303529

Ren, Y., Zhou, Y., Wang, S., Luo, T., Huang, M., & Zeng, Y. (2017). Exploratory study on resilience and its influencing factors among hospital nurses in Guangzhou, China. *International Journal of Nursing Sciences*, *5*(1), 57–62. https://doi.org/10.1016/j.ijnss.2017.11.001

Sarhan, S., Pretlove, S., Elghaish, F., Matarneh, S., & Mossman, A. (2024). Sources of occupational stress in UK construction projects: an empirical investigation and agenda for future research. *Smart and Sustainable Built Environment*, *14*(6), 1701–1728. https://doi.org/10.1108/sasbe-11-2023-0356

Senaratne, S., & Rasagopalasingam, V. (2016). The causes and effects of work stress in construction project managers: the case in Sri Lanka. *International Journal of Construction Management*, *17*(1), 65–75. https://doi.org/10.1080/15623599.2016.1167358

Smith, M. M., Saklofske, D. H., Keefer, K. V., & Tremblay, P. F. (2015). Coping Strategies and Psychological Outcomes: The Moderating Effects of Personal Resiliency. *The Journal of Psychology*, *150*(3), 318–332. https://doi.org/10.1080/00223980.2015.1036828

Su, P., Yi, J., Chen, X., & Xiao, Y. (2023). Visual Analysis of Psychological Resilience Research based on Web of Science database. *Psychology Research and Behavior Management*, *16*, 465–481. https://doi.org/10.2147/prbm.s394693

Thompson, N. J., Fiorillo, D., Rothbaum, B. O., Ressler, K. J., & Michopoulos, V. (2017). Coping strategies as mediators in relation to resilience and posttraumatic stress disorder. *Journal of Affective Disorders*, *225*, 153–159. https://doi.org/10.1016/j.jad.2017.08.049

Tugade, M. M., Fredrickson, B. L., & Barrett, L. F. (2004). Psychological Resilience and positive emotional granularity: Examining the benefits of positive emotions on coping and health. *Journal of Personality*, *72*(6), 1161–1190. https://doi.org/10.1111/j.1467-6494.2004.00294.x

Van Heerden, A., Boulic, M., McDonald, B., & Chawynski, G. (2024). Gender-perceived workplace stressors by New Zealand construction professionals. *International Journal of Construction Management*, *25*(3), 289–300. https://doi.org/10.1080/15623599.2024.2317039

Wang, S., Feng, K., & Wang, Y. (2023). Modeling Performance and Uncertainty of Construction Planning under Deep Uncertainty: A Prediction Interval Approach. *Buildings*, *13*(1), 254. https://doi.org/10.3390/buildings13010254

Wu, Y., Yu, W., Wu, X., Wan, H., Wang, Y., & Lu, G. (2020). Psychological resilience and positive coping styles among Chinese undergraduate students: a cross-sectional study. *BMC Psychology*, *8*(1), 79. https://doi.org/10.1186/s40359-020-00444-y

Zurlo, M. C., Della Volta, M. F. C., & Vallone, F. (2020). COVID-19 Student Stress Questionnaire: Development and validation of a questionnaire to evaluate students' stressors related to the coronavirus pandemic lockdown. *Frontiers in Psychology*, *11*, 576758. https://doi.org/10.3389/fpsyg.2020.576758

Perera, W.S.D., Kulatunga, U., Ranasinghe, D., Mahamood, R., Kangana, N. and De Silva, C.K., 2026. Operationalising community-based research through photovoice. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1236-1250. DOI: https://doi.org/10.31705/WCS.2026.90. Available from: https://ciobwcs.com/papers/

# OPERATIONALISING COMMUNITY-BASED RESEARCH THROUGH PHOTOVOICE

**W.S.D. Perera[1], U. Kulatunga[2], Daneesha Ranasinghe[3], Rifat Mahamood[4], Nuwani Kangana[5] and Chathura De Silva[6]**

## *ABSTRACT*

*Community-Based Research (CBR) requires methods that are participatory, contextually grounded, and capable of recognising community members as legitimate knowledge holders. This paper critically evaluates the appropriateness of Photovoice as a participatory visual method within the CBR principles in a study examining how public spaces influence community social cohesion. A qualitative reflective design was adopted, drawing on three sources of evidence: semi-structured interviews with five research team members, selected participant narratives generated during the Photovoice process, and a post-implementation evaluation with 30 community participants focus group discussions. The findings indicate that Photovoice effectively captured lived experience, local meanings of public spaces, and changing patterns of social interaction. It also supported empowerment, co-learning, capacity building, and recognition of the community as a unit of identity by enabling participants to represent and interpret their own spatial realities. The method generated rich insights into how everyday public spaces foster interaction, care, intergenerational relationships, and collective wellbeing. However, some CBR principles were only partially achieved, particularly sustainability, long-term engagement, and equitable shared decision-making. it was highlighted that participant and researcher biases, ethical considerations, and resource constraints need to be appropriately managed to ensure that Photovoice generates meaningful outcomes. The study makes an original contribution to the body of knowledge by integrating Photovoice with CBR principles to demonstrate how participatory visual methods can operationalise CBR in practice while generating community-driven insights into the social value and transformation of public spaces.*

***Keywords:*** *Community-based participatory research; Photovoice; Public space.*

[1] PhD Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, pererawsd.24@uom.lk
[2] Professor in Building Economics, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Consultant-Research at Office of Research, University of Moratuwa, Sri Lanka, madumadhirad.23@uom.lk
[4] Lecturer, Department of Town and Country Planning, University of Moratuwa, Sri Lanka, mahamoodmr@uom.lk
[5] Doctoral Researcher, Department of Civil and Environmental Engineering, Monash University, Australia, Nuwani.Kangana@monash.edu
[6] Senior lecturer, Department of Town and Country Planning, University of Moratuwa, Sri Lanka, chathurads@uom.lk

# 1. INTRODUCTION

CBR has emerged as a critical approach for addressing complex social and spatial challenges by actively involving community members in the knowledge production process (Israel et al., 1998; Minkler & Wallerstein, 2008; Banks et al., 2013). Rooted in participatory action research traditions (McFarlane et al., 2022), the CBR approach recognises communities not merely as subjects of study but as co-researchers who possess valuable experiential knowledge of their own environments (Cornwall, 2008). In CBR, empowering community members to take an active role in shaping and leading research activities is fundamental to ensuring that the research is both contextually relevant and ethically grounded (Banks et al., 2013). Such empowerment moves participants beyond the role of passive subjects to that of co-researchers, recognising their experiential knowledge as a legitimate and valuable form of evidence (Freire, 1970; Zhang et al., 2024). Ensuring that community voices are genuinely heard enables the research to capture locally embedded priorities, meanings, and concerns that may otherwise be overlooked by externally driven approaches (Cornwall, 2008). Hence, CBR not only enhances the credibility and validity of research findings yet fosters ownership (Boston et al., 2023), trust (Tariq et al., 2023), and sustained engagement within communities (McFarlane et al., 2022). By centring community perspectives, community-led research contributes to more inclusive knowledge production and supports outcomes that are responsive to local needs, capacities, and aspirations (Banks et al., 2013).

In this regard, the careful selection of research method(s) for CBR is critical, as they should uphold its core principles while remaining accessible, instinctive, and manageable for community members with diverse levels of knowledge and experience (Minkler & Wallerstein, 2008). Such research methods further need to facilitate ease of engagement, encourage active participation, and reduce barriers to meaningful involvement of the community to strengthen the authenticity of the data generated (Tariq et al., 2023). At the same time, maintaining methodological rigour, ethical standards and relevance of CBR remain essential to ensure the credibility and reliability of the outcomes (Lincoln & Guba, 1985; Creswell & Poth, 2018).

There are numerous research methods available for CBR, including interviews, focus group discussions, surveys, participant observation, community mapping, transect walks, storytelling, participatory rural appraisal techniques, diaries and journals, and participatory workshops (Newell et al., 2023; Creswell & Poth, 2018). While these methods provide valuable insights into community experiences, many rely heavily on verbal articulation and researcher-led interpretation, which may limit the ability of participants to express complex spatial, emotional, and everyday lived experiences, particularly among communities with diverse communication abilities, literacy levels, or socio-cultural backgrounds (Newell et al., 2023).

Among these methods, Photovoice is a participatory technique that integrates ‘photography’ with ‘narratives’ to enable participants to document, reflect on, and communicate their lived experiences (Wang & Burris, 1997; Li et al., 2025). Unlike conventional qualitative methods that primarily depend on verbal accounts, Photovoice enables participants to visually represent their realities, identify locally significant issues, and actively shape the research agenda through image production and collective reflection (Musoke et al., 2025). The visual nature of Photovoice is particularly valuable in the built environment and community studies, as it facilitates the exploration of spatial

experiences, social interactions, meanings attached to place, and everyday practices that may otherwise remain difficult to articulate through interviews or surveys alone (Wang & Burris, 1997). Furthermore, Photovoice demonstrates strong alignment with the participatory principles of CBR by encouraging shared knowledge production, participant empowerment, critical dialogue, and collaborative reflection (Gabrielsson et al., 2022).

Despite its growing application across participatory research contexts, limited research has critically examined the extent to which Photovoice operationalises and sustains the core principles of CBR in practice. Accordingly, this paper critically evaluates the appropriateness of Photovoice as a research technique for community-based research by using an exemplary, real-life project titled Improving Resilience and Social Cohesion Through Transformed Community and Built Spaces' (hereafter referred as ENSEMBLE project). The ENSEMBLE project investigated the influence of both formal and informal public spaces on the social cohesion of communities. The project adopted a CBR approach, with Photovoice serving as the primary data collection method. Participants in the ENSEMBLE project were asked to capture photographs of public spaces (refer Section 3.4) they perceived as influencing social cohesion within their communities and to provide accompanying narratives explaining the significance of these spaces and their lived experiences.

## 2. LITERATURE REVIEW

CBR has emerged as a response to traditional research paradigms that often-positioned communities as passive subjects rather than active knowledge holders (Israel et al., 1998; Zhang et al., 2024). At its core, CBR seeks to rebalance relationships between researchers and communities by foregrounding collaboration, mutual learning, and shared responsibility throughout the research process (Scott, 2024). Central to this reorientation is the prioritisation of lived experience as legitimate and authoritative knowledge. Capturing lived experience is therefore not merely a methodological preference but one that grounds research in contextual realities and resists externally imposed framings (Antunes et al., 2022).

Co-creation of knowledge, shared decision-making, and co-learning are often cited as core principles of CBR, yet their transformative potential depends on how deeply they are enacted (Francis et al., 2018; Suarez-Balcazar et al., 2023). Recognising communities as units of identity (Israel et al., 2012) shifts the analytical focus from individual participants to collective histories, relationships, and shared meanings. Co-learning, as described by Israel et al. (1998) and Wallerstein et al. (2017), disrupts the unidirectional flow of expertise by valuing academic and community knowledge equally. However, as Ryan and Squires (2019) caution, conducting research *with* communities introduces tensions related to representation, expectations, and resource constraints.

Capacity building further distinguishes CBR from conventional research approaches. Rather than treating community involvement as instrumental, CBR frames skill development, confidence building, and institutional strengthening as both process and outcome (Ziervogel et al., 2021; Suarez-Balcazar et al., 2023). Empowerment, another CBR principle extends beyond individual skill acquisition to include collective agency and sustained ownership of research agendas (Munck, 2014). Nevertheless, genuine empowerment demands more than short-term engagement; it requires long-term

commitment, shared accountability, and structural responsiveness (Chandanabhumma et al., 2023).

An ecological and contextual perspective of CBR deepens the analytical contribution. By recognising that community experiences are shaped by intersecting social, cultural, economic, political, and environmental forces, CBR embeds multidimensional analysis into research design and implementation (Wallerstein et al., 2017; Oetzel et al., 2022). This approach enhances local relevance and ethical responsiveness, particularly when addressing structural inequities through cultural humility and reflexive practice (Caine & Mill, 2016). Ultimately, CBR is action-oriented, combining research, dialogue, and intervention to produce tangible community benefit (Kleiner et al., 2012; Özçelik, 2025). Its iterative and reflective nature allows adaptation over time, promoting sustainability and inclusive engagement across generations (Antunes et al., 2022; Miller et al., 2022).

# 3. RESEARCH METHODOLOGY

## 3.1 DATA COLLECTION

The study investigated the appropriateness of the Photovoice technique within the context of CBR drawing on the community-based project ENSEMBLE. Qualitative research approach was considered most suitable, as it facilitates an in-depth understanding of the subjective, experiential, and context-dependent information (Lincoln & Guba, 1985) related to Photovoice as a participatory research method. The reflective design used within the study further enabled a critical examination of the practical application of Photovoice, including its methodological strengths, limitations, potential biases, ethical considerations, and gaps encountered throughout the research process. This investigation consisted with three components and drew on experiential accounts from both the research team and participating community members as detailed below.

**Component 1** - The reflections of the research team (coded as RT01-RT05) who were involved in the field work of the ENSEMBLE project were captured through semi-structured interviews. The research team had been directly involved in the design, facilitation, and implementation of the ENSEMBLE project, hence considered as the most suitable informants to critically reflect on the appropriateness of Photovoice technique in relation to CBR principles. Semi-structured interviews were considered appropriate as they enabled to capture detailed reflections, experiences, and critical insights of the research team while also providing the flexibility to further probe issues emerging during the discussions. The research team consisted with four research assistants and two co-investigators. The co-investigator, who oversaw the overall project coordination and implementation activities, conducted the interviews with the remaining members of the research team.

**Component 2** - Following the completion of the Photovoice activities, a post-implementation evaluation through a focus group discussion was conducted with all the community members (30 members - coded M01-M30) engaged in the ENSEMBLE project. Focus group discussions were used as they enabled collective reflection and interactive dialogue among participants, allowing them to share, compare, and deepen their experiences of engaging in Photovoice activities within the ENSEMBLE project.

**Component 3** - Narratives produced by the community members during the Photovoice process of the ENSEMBLE project also incorporated to investigate the appropriateness

of Photovoice technique in relation to CBR principles. As participant narratives capture authentic community voices, this method was considered appropriate.

## 3.2 DATA ANALYSIS

Data obtained from the semi-structured interviews, focus group discussions, and narratives were analysed using content analysis, a systematic technique for coding, categorising, and interpreting qualitative data to identify patterns and themes (Krippendorff, 2013). The study primarily adopted a deductive coding approach, whereby data were analysed using a set of predefined codes derived from the key principles of CBR identified through the literature review. In line with Hsieh and Shannon (2005), these preliminary codes were developed prior to analysis to guide the initial codes deriving from the primary data. The reflections of the research team, focus group discussions and participant narratives were coded and organised under the predefined codes from the literature review. In addition, an inductive coding approach was incorporated to capture emerging concepts not anticipated within the predefined codes, thereby enabling the identification of new insights grounded in the data. This combined deductive–inductive approach facilitated both theory-driven analysis and openness to unanticipated findings, thereby enhancing the depth, rigor, and interpretive robustness of the analysis of the Photovoice process within the CBR context.

## 3.3 MAINTAINING THE QUALITY OF RESEARCH

By combining interviews, focus groups, and participant narratives, the study achieved methodological triangulation (Donkoh, 2023), enhancing credibility and enabling critical reflection on Photovoice's alignment with CBR principles. Incorporating the perspectives of both the research team and community members ensured the assessment reflected shared knowledge, not just researcher interpretation, consistent with CBR's emphasis on reflexivity and collaborative knowledge production. Further, careful consideration was given to potential sources of bias arising from interpretation of community narratives in relation to CBR principles and the research team's own reflections on the appropriateness of the Photovoice technique within the CBR context. Accordingly, team-based discussions and peer debriefing within the research team enabled multiple perspectives to be considered, thereby reducing the influence of individual interpretations when analysing community responses. To minimise bias in the research team's reflective accounts, reflections were developed based on their lived experience of the process, supported by recall of events and documented field experiences. However, it is acknowledged that the use of a more structured reflexive practice guided by specific prompts could have further reduced the bias from the study. In addition, the inclusion of direct quotations from both community participants and the research team has been done in the paper to ensure that interpretations remained closely grounded in authentic accounts.

## 3.4 IMPLEMENTATION OF PHOTOVOICE TECHNIQUE WITHIN ENSEMBLE PROJECT

As Photovoice technique was relatively new to both the research team and within the Sri Lankan context, the data collection process was carefully structured into five stages to ensure methodological rigor, community engagement, and ethical compliance. They

include (1) Site selection (2) Participant identification (3) Community training (4) Photovoice implementation and filtering and (5) post-activity evaluation.

### 3.4.1 Stage 1: Site Selection and Criteria

When selecting a suitable location for the ENSEMBLE project, following factors were considered; availability of formal and/or informal public gathering spaces, socio-economic and ethnic diversity, accessibility, presence of an active community organization that meet at least once a month and a community that could meaningfully support a participatory Photovoice process. Eight communities were initially shortlisted based on these criteria and having considered the existing social structure that would facilitate coordination, trust-building, and communication between researchers and residents, the final location for the study was selected within the Colombo district.

### 3.4.2 Stage 2: Identification and Recruitment of Participants

Participant recruitment for the ENSEMBLE project was carried out using a combination of physical and digital outreach strategies to ensure broad community representation. This included displaying printed posters at key public locations within the community and sharing recruitment announcement through community-based Facebook pages and local social media groups, enabling the research team to reach both digitally active residents and those who primarily engage through physical community spaces.

*Figure 1: Displaying of posters*

A purposive sampling strategy was adopted to recruit participants who were capable of meaningfully engaging with the Photovoice process and contributing diverse community perspectives. As the Photovoice methodology required capturing photographs, recording voice narratives, and sharing geographic location data, participants needed to own a mobile phone and possess basic digital literacy skills. They were also required to commit to engaging with the research team over four to six months, including attending training sessions and workshops. Efforts were made to ensure inclusivity and representation by selecting participants from diverse socio-economic backgrounds, including several differently abled individuals. Of the 74 individuals who initially registered, 30 participants were selected following screening based on eligibility, diversity considerations, and commitment to long-term engagement.

### 3.4.3 Stage 3: Community Training

To support the effective implementation of the Photovoice methodology, two training sessions (refer Figure 2) were conducted for the selected participants. As the approach was relatively new to the community, capacity building was considered essential prior to data collection. Participants were provided with a printed step-by-step handbook outlining the study objectives, submission procedures, and technical instructions (refer

Figure 3). A live demonstration was also conducted, and participants were guided on recording voice narratives to explain the context and significance of each photograph.

*Figure 2: Training workshop and demonstration of photovoice steps with participants*

*Figure 3: Handbook shared with participants in Sinhalese*

Further, ethical considerations were discussed in detail to promote responsible participation such as not to include identifiable images of individuals in their photographs, refraining from taking content that could be interpreted as discriminatory toward any religion or ethnicity. Participants were then given specific requirements for the Photovoice task. Each participant was instructed to capture between eight and ten photographs representing locations they considered significant within the community. For every photograph, they were required to provide a short voice-recorded narrative, limited to four to five sentences, explaining the relevance of the image. Location information had to be submitted along with each entry. This structured training phase ensured methodological consistency, ethical compliance, and improved the overall quality and reliability of the data collected during the Photovoice implementation stage.

### 3.4.4 Stage 4: Implementation of Photovoice and Data Filtering

During this phase, the research team-maintained communication with participants to provide technical support and clarification where necessary, while ensuring that the documentation process remained participant-driven. From the 30 selected participants, a total of 239 Photovoice entries were received. Each entry consisted of a photograph, an accompanying voice-recorded narrative, and geographic location data. Given the exploratory and participatory nature of the ENSEMBLE project, a systematic multi-stage filtering process was undertaken to ensure data quality, ethical compliance, and analytical relevance to short list 150 Photovoice. In the subsequent stage, a more refined thematic review was conducted, resulting in the selection of 50 photographs that most clearly represented key spatial and social themes emerging from the dataset. These shortlisted photographs were then grouped according to thematic relevance to support deeper qualitative interpretations related to the ENSEMBLE project.

# 4. ANALYSIS AND DISCUSSION

The following section illustrates the appropriateness of Photovoice for CBR through the systematic integration, analysis, and presentation of data collected from multiple sources, including photographs, participant narratives, semi-structured interviews, and focus group discussions.

## 4.1 CAPTURING THE LIVED EXPERIENCE AND SOCIAL CHANGE

Capturing lived experience is a foundational principle of CBR, as it ensures that knowledge production is grounded in how community members experience, interpret, and give meaning to their everyday realities (Oetzel et al., 2022; Lindawati & Marniati, 2024). As evident from the Photovoice (photos and narratives) of the community members, participants foregrounded spaces that were meaningful in their daily lives, such as community wells, clinics, playgrounds, religious sites, cemeteries, and informal gathering areas, thereby capturing routine practices, emotional attachments, and social relationships that are often overlooked in conventional expert-led research. Narratives captured indicated that participants did not merely describe physical spaces; they explained how these spaces were used, how they felt within them, and how their meanings evolved over time. For example, community wells were described as sites of social exchange and mutual support (M02), clinics as places of both physical and emotional healing (M07) and play areas as locations where people interact and build relationships (M08, M12). As M02 narrated, "When we come to fetch water at the well, we meet and discuss the hardships of our families and issues in the village. It is also where we share news and help each other." Such accounts demonstrate how Photovoice captured lived experience, aligning with CBR's emphasis on understanding wellbeing and social cohesion within everyday contexts (Israel et al., 1998; Rosa, Santos, et al., 2025). Importantly, Photovoice enabled reflection on change and collective meaning-making, further deepening the capture of lived experience. The narratives given by M20, M25, M15 compared past and present uses of public spaces. For an example, M25 stated how crises such as the COVID-19 pandemic reshaped social interaction and collective practices.

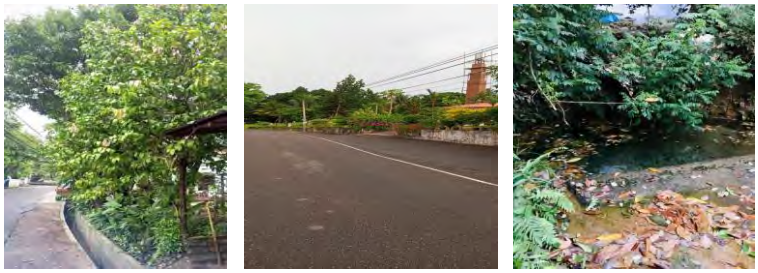


*Figure 4: Photovoice images of the ENSEMBLE project: Lovi tree, cemetery, and community well*

Accordingly, by positioning community members as active knowledge producers rather than research subjects, the photos and narratives given by the community members clearly indicate how Photovoice helped address power asymmetries and legitimised lived experience as valid evidence (Gabrielsson et al., 2022).

## 4.2 EMPOWERMENT AND REDISTRIBUTION OF RESEARCH AUTHORITY

According to Wallerstein et al. (2018), shared power, voice, and community leadership are central to empowerment within CBR. In this study, Photovoice contributed to

participant empowerment by positioning community members as active contributors and co-researchers rather than passive respondents. Participants transformed their lived experiences into analytical knowledge, drawing on their observational skills, storytelling capacities, reflective insights, and local expertise. As reflected by RT03 "by allowing participants to choose what to photograph, how to interpret their images, and which issues mattered most, the study redistributed authority to community members and amplified voices often marginalised in externally driven research." The research team members RT01 and RT 04 further noted that, through the Photovoice technique, community members exercised greater control over how their everyday spaces and experiences were represented, contributing to a sense of ownership over the knowledge produced. These reflections demonstrate how Photovoice supported empowerment as a process, consistent with CBR that emphasises control over representation and meaning as central to participatory research (Phillip et al., 2025).

## 4.3 ECOLOGICAL AND CONTEXTUAL PERSPECTIVE

The narratives given by M11 and M16 reflected on the loss of once-vibrant gathering spaces and changes in social interaction patterns. As M16 noted, "earlier, this was a meeting place for many youth societies. But now we cannot reach that place because of the highway… it has become deserted." Beyond physical accessibility, many participants highlighted the cultural and symbolic meanings of place, identifying temples, cathedrals, medical centres, and community banks as significant public spaces due to their social and spiritual functions. M20 explained, "this picture is of the village Primary Medical Center. We attend clinics here once a month. A friendly meeting is held among the patients who come here." These accounts illustrate how Photovoice captured the ecological embeddedness of community life, showing how wellbeing emerges from interactions between built environments, social relationships, cultural practices, and institutional structures (Collins et al., 2018). Through the Photovoice technique the study documented how public spaces evolved in response to disruptions such as the COVID-19 pandemic. M09 and M18 described how spaces were socially reconfigured to meet emerging needs. As M18 reflected, "Before the pandemic, the cemetery was rarely visited. But during COVID, it became a place where people gathered to stay out of the house. Food distribution happened there; we took food to houses with COVID patients from here." This narrative demonstrates how Photovoice effectively captured the ways in which community dynamics are shaped by context-specific norms, including collective responsibility and informal coordination, rather than by formal institutional directives.

## 4.4 COMMUNITY AS A UNIT OF IDENTITY

In addition to demonstrating an ecological and contextual perspective, the Photovoice given by the community members strongly reflected the CBR principle of recognising the community as a unit of identity (Suarez-Balcazar et al., 2023; Wallerstein et al., 2018). Participants' accounts revealed shared values of care, mutuality, and collective responsibility, particularly during periods of hardship. Photovoice enabled these collective identities to emerge organically through community storytelling, rather than being inferred solely by the research team. The narrative of M19 stated "this is the Lovi tree where people gather to enjoy fruits. We put a ladder to pick them and distribute to the whole village... Children loved it. This tree has been producing fruits for many years and still central to community gatherings." Such narratives highlight how Photovoice has captured public spaces that function as sites of collective belonging and social continuity.

## 4.5 CO-LEARNING

Co-learning is a core principle of CBR, emphasising reciprocal knowledge exchange within and between communities (Rosa, Santos, et al., 2025; Wallerstein et al., 2018). By centring community narratives and visual evidence, Photovoice facilitated co-learning among participants through peer-to-peer sharing of skills and experiences, strengthening collective capacity and mutual understanding. This was evident in intergenerational digital skill transfer during the project. During the focus group discussions M20 noted, "I did not know how to upload the photographs to the online platform at first. A young person in the village showed me step by step how to do it." The reflections captured through the interviews revealed how the overall Photovoice process fostered co-learning within the research team, particularly in navigating challenges related to managing community expectations, engaging local leaders, and building trust within the community.

## 4.6 BUILDING ON COMMUNITY STRENGTHS AND RESOURCES

Consistent with the CBR principle of building on community strengths rather than focusing on deficits (Minkler & Wallerstein, 2008), the research team intentionally leveraged existing social networks and community groups for the project. The reflection of RT01 and RT03 showed how Buddhist groups, women's groups, and youth groups were engaged as entry points when recruiting community members to the project, ensuring broad participation and grounding the research in established community capacities.

## 4.7 INCLUSIVITY, INTERGENERATIONAL ENGAGEMENT, AND CAPACITY BUILDING

The inclusion of participants across different age groups, genders, and social roles within the Photovoice activities enhanced the inclusivity and intergenerational engagement of the study, aligning with participatory equity principles in CBR (Wallerstein et al., 2018). The narratives given by the senior participants provided historical perspectives on changing spaces, while the narratives of the younger participants documented contemporary uses and digital practices. According to Minkler et al. (2012), capacity building is a fundamental principle of CBR, aimed at strengthening community skills and competencies through the research process. In this study, to prepare the participants for the Photovoice activities, training workshops on photography and data sharing were conducted. As M21 noted, "The practical session encouraged participants from different age groups to understand the technique and actively engage in the Photovoice activity… this improved community involvement and cohesion."

## 4.8 LIMITATIONS OF THE PHOTOVOICE RESEARCH TECHNIQUE

Although the study successfully engaged community members in documenting and interpreting public spaces through Photovoice, certain CBR principles were only partially realized. CBR principles sustainability and long-term engagement were limited, as the study was conducted over a defined period and did not include mechanisms for ongoing community involvement or follow-up activities beyond data collection. Similarly, another CBR principle equitable partnerships and shared decision-making were constrained, with most methodological and analytic decisions guided primarily by the research team, rather than being fully co-designed or jointly managed with community participants throughout

the study. Further, although the final Photovoice outputs were selected by the research team following discussion and deliberation, this process may have introduced a degree of researcher bias into the study.

Moreover, during the ENSEMBLE project it was noted that while photographs can powerfully communicate lived experiences, visual representations may oversimplify complex social realities and exclude less visible dimensions such as emotions, histories, or structural inequalities. Similarly, during the Photovoice participants may have chosen places that held personal importance to them, thereby introducing a degree of participant bias. Furthermore, participants may have preferred locations that were easier to access or photograph, which could have affected the genuine representation of places that were most significant to the study context.

Further, in some instances, the visual nature of Photovoice raises complex ethical concerns related to consent, anonymity, representation, and ownership of images, particularly when documenting sensitive community experiences. For example, despite providing clear instructions on ethical considerations (refer Section 3.4.3), there were instances where community members captured photographs that included other individuals without obtaining their consent. Furthermore, it was also noted that the implementation of Photovoice technique was resource-intensive, requiring substantial time, facilitation skills, and ongoing participant engagement.

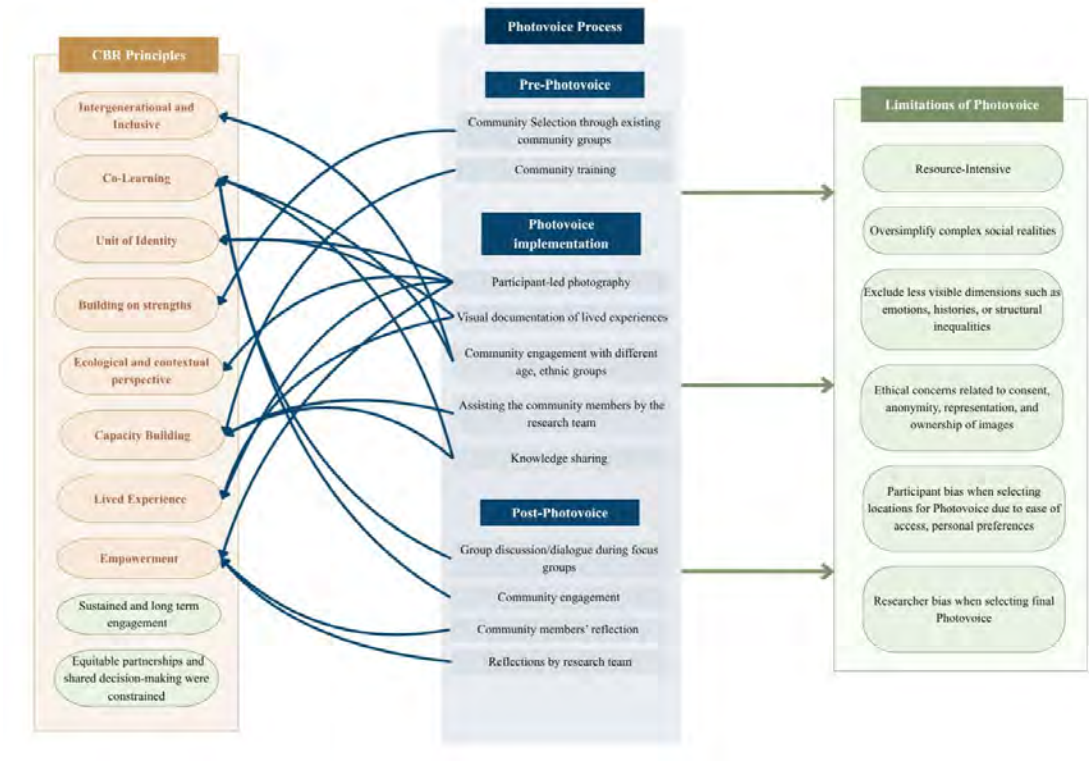



*Figure 5: Appropriateness of photovoice as a research technique for community-based research*

The overall evaluation in Figure 5 suggests that Photovoice is an appropriate method to operationalise key CBR principles. Figure 5 further indicates that pre-Photovoice phase was instrumental in establishing the key CBR principles and promoted capacity building and co-learning by equipping community members with the skills and confidence to engage meaningfully in the research process. During the implementation phase,

Photovoice enabled participants to visually capture and communicate their everyday experiences of public spaces, facilitating the recognition of local knowledge and lived experiences as legitimate forms of evidence beyond conventional verbal expressions. The post-Photovoice phase reinforced the participatory principles of CBR through collective reflection, dialogue, and knowledge sharing among participants and researchers.

While Photovoice fostered meaningful engagement during the study period, the synthesis in Figure 5 shows the time-bound nature of the project limiting opportunities for ongoing collaboration and long-term community involvement beyond the completion of the research. As such, although Photovoice can facilitate participation, empowerment, and co-learning, achieving deeper forms of shared decision-making and sustained engagement may require complementary strategies and longer-term partnerships that extend beyond the application of the Photovoice itself. Further, Figure 5 highlights several limitations affecting the extent to which Photovoice can fully realise its application within CBR context, including its resource-intensive nature, which may challenge sustainability in resource-limited settings; potential oversimplification of complex social realities leading to underrepresentation of certain experiences; ethical concerns and participant and researcher biases that may potentially limit the extent to which the resulting narratives accurately reflect the diversity of broader community perspectives. Hence, it can be argued that Photovoice can be considered an appropriate method for CBR when implemented reflexively and supported by strategies that address potential biases, ethical concerns, and resource constraints.

## 5. CONCLUSION

This paper critically evaluated the appropriateness of Photovoice as a technique for CBR through an in-depth examination of the ENSEMBLE project, providing empirical insights into how the method operationalised key CBR principles in a real-world research context. By positioning participants as co-researchers, Photovoice captured lived experience, revealing how everyday routines, hardships, social, cultural, economic, and political factors foster social connection, collective care, and intergenerational engagement.

The outcomes of the study suggest that the appropriateness of Photovoice for CBR should not be understood solely in terms of its capacity to generate rich visual data. Rather, its value lies in its ability to facilitate participatory processes that operationalise key CBR principles, including inclusivity, co-learning, empowerment, recognition of local knowledge, capacity building, and contextual understanding. However, achieving these benefits requires careful attention to the methodological, ethical, practical limitations and potential biases inherent in the technique.

From a theoretical perspective, the study contributes to the literature on CBR by illustrating how CBR principles can be operationalised through participatory visual methods to foreground community knowledge and lived spatial experiences. By recognising the community as a unit of identity and building on existing local strengths, the research highlights how participatory approaches can facilitate the co-production of knowledge between researchers and community members. Hence, the study advances participatory research by showing how Photovoice can simultaneously capture lived experiences, facilitate community reflection, and critically evaluate the application of CBR principles in practice, while paying close attention to potential biases and ethical considerations. Further research could explore how structured reflexivity frameworks and

participatory ethics protocols can be developed and applied within Photovoice and other CBR approaches to systematically identify, monitor, and mitigate potential biases while ensuring ethically robust practice across diverse community contexts.

## 6. ACKNOWLEDGEMENT

Authors would like to acknowledge financial support provided by the project titled 'Improving Resilience and Social Cohesion Through Transformed Community and Built Spaces' (ENSEMBLE), funded by the New Frontiers in Research Fund, Canada.

## 7. REFERENCES

Antunes, A. L. M. de P., Cachelin, A., Fitisemanu, L., Folau, M., Hart, S., Kuttner, P. J., & Salcedo, A. (2022). Establishing principles for community-based research. *Metropolitan Universities, 33*(3), 52–68. https://doi.org/10.18060/25819

Banks, S., Armstrong, A., Carter, K., Graham, H., Hayward, P., Henry, A., Holland, T., Holmes, C., Lee, A., McNulty, A., Moore, N., Nayling, N., Stokoe, A., & Strachan, A. (2013). Everyday ethics in community-based participatory research. *Contemporary Social Science, 8*(3), 263–277. https://doi.org/10.1080/21582041.2013.769618

Boston, P. Q., Strouble, B., Balogun, A., Lugo-Martinez, B., McClain, M., Mitchell, M. M., Wasserman, K., Rahn, D., Greenberg, M., & Garibay, C. (2023). Community voices on the experiences of community-based participatory research in the environmental justice movement. *Social Sciences, 12*(6), 358. https://doi.org/10.3390/socsci12060358

Caine, V., & Mill, J. (2016). *Essentials of community-based research*. Routledge. https://doi.org/10.4324/9781315545004

Chandanabhumma, P. P., Gabrysiak, A., Brush, B. L., Coombe, C. M., Eng, E., Jensen, M., Lachance, L., Shepard, P., Wallerstein, N. B., & Israel, B. A. (2023). Cultivating an ecosystem: A qualitative exploration of sustainability in long-standing community-based participatory research partnerships. *Progress in Community Health Partnerships: Research, Education, and Action, 17*(3), 393–404. https://doi.org/10.1353/cpr.2023.a907963

Collins, S. E., Clifasefi, S. L., Stanton, J., The LEAP Advisory Board, Straits, K. J. E., Gil-Kashiwabara, E., Rodriguez Espinosa, P., Nicasio, A. V., Andrasik, M. P., Hawes, S. M., Miller, K. A., Nelson, L. A., Orfaly, V. E., Duran, B. M., & Wallerstein, N. (2018). Community-based participatory research (CBPR): Towards equitable involvement of community in psychology research. *American Psychologist, 73*(7), 884–898. https://doi.org/10.1037/amp0000167

Cornwall, A. (2008). Unpacking "participation": Models, meanings and practices. *Community Development Journal, 43*(3), 269–283. https://doi.org/10.1093/cdj/bsn010

Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). SAGE Publications.

Freire, P. (1970). *Pedagogy of the oppressed*. Continuum.

Gabrielsson, H., Cronqvist, A., & Asaba, E. (2022). Photovoice revisited: Dialogue and action as pivotal. *Qualitative Health Research, 32*(5), 814–822. https://doi.org/10.1177/10497323221077300

Israel, B. A., Schulz, A. J., Parker, E. A., & Becker, A. B. (1998). Review of community-based research: assessing partnership approaches to improve public health. *Annual review of public health, 19*, 173–202. https://doi.org/10.1146/annurev.publhealth.19.1.173

Israel, B. A. (2013). *Methods for community-based participatory research for health* (2nd ed.). Jossey-Bass.

Julian McFarlane, S., Occa, A., Peng, W., Awonuga, O., & Morgan, S. E. (2022). Community-based participatory research (CBPR) to enhance participation of racial/ethnic minorities in clinical trials: A 10-year systematic review. *Health Communication, 37*(9), 1075–1092. https://doi.org/10.1080/10410236.2021.1943978

Kleiner, A., Kerstetter, K., & Green, J. (2012). Community-based research: Analysis of outcomes for learning and social change: An introduction. *Journal of Rural Social Sciences, 27*(2), Article 1.https://egrove.olemiss.edu/jrss/vol27/iss2/1

Li, S., Gulley, J., Booty, M., Firchow, B., & McGladrey, M. L. (2025). Using photovoice to improve engagement in community health assessments addressing behavioral health. *Journal of Behavioral Health Services & Research, 52*(2), 213–230. https://doi.org/10.1007/s11414-024-09885-4

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage Publications.

Lindawati, L., & Marniati, M. (2024). Implementation of digital health service policies based on community-based research (CBR) to improve patient accessibility in remote areas. *Health Journal of Community Services, 1*(3), 217–225. https://doi.org/10.62569/hjcs.v1i3.100

Miller, A. K., Alejano-Steele, A., Finger, A., & Napolitano, K. (2022). The Colorado project to comprehensively combat human trafficking: Community-based participatory research in action. *Journal of Human Trafficking, 8*(1), 59–81. https://doi.org/10.1080/23322705.2021.2019532

Minkler, M., & Wallerstein, N. (2008). *Community-based participatory research for health: From process to outcomes* (2nd ed.). Jossey-Bass.

Munck, R. (2014). Community-based research: Genealogy and prospects. In R. Munck & L. McIlrath (Eds.), *Higher education and civic engagement: Comparative perspectives* (pp. 11–26). Palgrave Macmillan. https://doi.org/10.1057/9781137385284_2

Musoke, D., Nalinya, S., Namata, C., Ssemugabo, C., & Ndejjo, R. (2025). Use of photovoice in health systems research: Methodological considerations and experiences from Uganda. *Health Research Policy and Systems, 23*, 156. https://doi.org/10.1186/s12961-025-01420-x

Newell, R., Dring, C., & Newman, L. (2023). Participatory research methods for examining lessons from COVID-19 about local food systems vulnerabilities to exogenous shocks. *Collaborations: A Journal of Community-Based Research and Practice, 6*(1), 12. https://doi.org/10.33596/coll.116

Oetzel, J. G., Villegas, M., Zenone, H., Boursaw, B., Magarati, M., Dickson, E., Sanchez-Youngman, S., Morales, L., Kastelic, S., Eder, M., & Wallerstein, N. (2022). Establishing the benefits of CBPR: An empirical study of CBPR partnership outcomes. *American Journal of Public Health, 112*(6), 906–916. https://doi.org/10.2105/AJPH.2022.306883

Özçelik, M. (2025). Promoting healthy eating habits: The role of community-based research in nutrition. *Journal of Neonatal Surgery, 14*(10S), 900–905. https://doi.org/10.63682/jns.v14i10s.3168

Phillip, E., Walsh, A., Jewitt, S., Conroy, R. M., & Stanistreet, D. (2025). Impact of community-based participatory research on capacity building: Findings from a household and ambient air project. *Sustainable Futures, 10*, 101139. https://doi.org/10.1016/j.sftr.2025.101139

Tariq, S., Grewal, E. K., Booth, R., Nat, B., Ka-Caleni, T., Larsen, M., Lawson, J., Whaley, A., Walsh, C. A., & Campbell, D. J. T. (2023). Lessons learned from a virtual community-based participatory research project: Prioritizing needs of people with diabetes and experiences of homelessness to co-design a participatory action project. *Research Involvement and Engagement, 9*, 46. https://doi.org/10.1186/s40900-023-00456-z

Scott, M. L. (2024). Participatory community-based research. https://doi.org/10.1093/obo/9780195389678-0340

Suarez-Balcazar, Y., Balcazar, F., Miranda, D. E., Velazquez, T., Arcidiacono, C., & Garcia-Ramirez, M. (2022). Promoting justice through community-based research: International case studies. *American Journal of Community Psychology, 69*(3–4), 318–330. https://doi.org/10.1002/ajcp.12584

Wallerstein, N., Duran, B., Oetzel, J. G., & Minkler, M. (Eds.). (2017). *Community-based participatory research for health: Advancing social and health equity*. John Wiley & Sons.

Wang, C., & Burris, M. A. (1997). Photovoice: Concept, methodology, and use for participatory needs assessment. *Health Education & Behavior, 24*(3), 369–387. https://doi.org/10.1177/109019819702400309

Wang, C. C., Yi, W. K., Tao, Z. W., & Carovano, K. (1998). Photovoice as a participatory health promotion strategy. *Health Promotion International, 13*(1), 75–86. https://doi.org/10.1093/heapro/13.1.75

Wojciechowski, L., & Kramer, J. (2025). Assessing partnership: Utilizing community-based participatory research to evaluate participatory design. *IEEE Global Humanitarian Technology Conference (GHTC)*, 219–225. https://doi.org/10.1109/ghtc66843.2025.11266611

Zhang, Y., Xie, Y. J., Yang, L., Li, X., Chen, H., & Wang, P. (2024). Community-based participatory research (CBPR) approaches in vaccination promotion: A scoping review. *International Journal for Equity in Health*, *23*, 227. https://doi.org/10.1186/s12939-024-02278-1

Maneesha, P., Loganathan, S. and Mouli, D. 2026. Operationalising circular economy in mega infrastructure projects: A data-driven analysis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1251-1264. DOI: https://doi.org/10.31705/WCS.2026.91. Available from: https://ciobwcs.com/papers/

# OPERATIONALISING CIRCULAR ECONOMY IN MEGA INFRASTRUCTURE PROJECTS: A DATA-DRIVEN ANALYSIS

**Paidi Maneesha[1], Santhosh Loganathan[2] and Durai Mouli[3]**

## *ABSTRACT*

*The construction sector is among the most resource-intensive industries globally, with large-scale infrastructure projects generating substantial construction waste due to their scale, complexity, and execution uncertainties. While Circular Economy (CE) principles are increasingly promoted to address these challenges, their implementation at project sites remains largely disposal-oriented and insufficiently guided by data-driven prioritization approaches. The study presents a risk-based, site-centric assessment of construction waste streams to support practical CE implementation in large-scale infrastructure projects. Primary waste generation and material consumption data were collected from 58 infrastructure project sites, including metro, nuclear and hydel projects, over one year. The methodology integrates the Waste Generation Index (WGI) to normalize waste against issued material quantities, pareto analysis to identify dominant waste contributors, and Failure Mode and Effects Analysis (FMEA) to diagnose process-level failures based on severity, occurrence, and detectability. The study distinguishes between high-volume waste streams, including Construction and Demolition (C&D) waste and ferrous scrap, and high-inefficiency waste streams, including electrical waste, wood waste, and plastic waste. Results indicate that C&D waste exhibits the highest concentration of critical risk failure modes, driven by concreting losses and design-execution deviations. Although ferrous waste is largely recycled, the high-risk levels indicate upstream inefficiencies such as cutting losses and limited reuse of steel off cuts. Electrical waste emerges as a hidden high-risk hotspot, showing high waste intensity and risk even though its total quantity is relatively small. The findings demonstrate that effective CE interventions should consider both waste dominance and process risk, rather than waste quantity alone.*

***Keywords:*** *C&D waste; Circular economy;Llarge-scale infrastructure projects; Sustainable construction practices; Waste Generation Index (WGI).*

## 1. INTRODUCTION

The construction industry plays a pivotal role in economic growth and infrastructure development; however, it is also one of the most resource-intensive and waste-generating

[1] Post Graduate Student, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India; Senior Engineer, L&T Construction, Chennai, Tamil Nadu, India, maneeshapaidi198@gmail.com, orcid.org/0009-0005-8807-0533
[2] Assistant Professor, Department of Civil Engineering, National Institute of Technology (NIT) Tiruchirappalli, Tamil Nadu, India, lsanthosh@nitt.edu, orcid.org/0000-0003-2997-0599
[3] Head Environment, Heavy Civil Infrastructure IC, L&T Construction, Chennai, Tamil Nadu, India, mouli.durai1@lntecc.com

sectors globally (Hossain et al., 2024). Large quantities of materials such as cement, aggregates, steel, timber, and electrical components are consumed during construction activities, resulting in substantial generation of C&D waste, ferrous and electrical waste (Ginga et al., 2020). In rapidly urbanising countries such as India, the accelerated pace of infrastructure development has intensified concerns related to waste management, landfill dependency, and resource efficiency (CPCB, 2018). Indian infrastructure projects generate large volumes of mineral-based C&D waste, with concrete accounting for approximately 65% and bricks and masonry materials for nearly 25% of total C&D waste (Bhattacharyya et al., 2013). Despite this high material intensity, waste management practices in infrastructure projects remain largely disposal-oriented, relying heavily on landfilling or low-value recycling, leading to avoidable material losses and environmental impacts (Blumhardt, 2018).

The environmental implications of these practices are significant. Construction activities account for nearly 40% of global raw material consumption and generate approximately 25-35% of landfill waste worldwide (Munaro et al., 2023). Rising material costs, limited landfill capacity, and increasingly stringent regulatory mechanisms such as Extended Producer Responsibility (EPR) and updated C&D Waste Management Rules have increased compliance pressure on construction organizations (Badi & Murtagh, 2019; Ababio & Lu, 2022). However, fragmented project delivery systems, inadequate waste segregation, and poor data traceability continue to constrain effective waste management and resource recovery at the execution stage (Ezekwu, 2025).

In response to these challenges, the Circular Economy (CE) has emerged as a promising alternative to the traditional linear 'take-make-dispose' model, aiming to decouple economic growth from resource depletion and environmental degradation. In the construction sector, CE emphasises retaining material value through strategies such as reduction at source, reuse, recycling, repair, refurbishment, and recovery across extended life cycles (Hossain et al., 2024). Unlike conventional end-of-life waste management approaches, CE prioritises upstream interventions, including improved design coordination, procurement planning, process optimisation, and closed-loop material flows (Guerra et al., 2021; Amudjie et al., 2025). When effectively implemented, CE practices can reduce waste generation, lower project costs, and improve overall sustainability performance. Despite growing policy emphasis and industry awareness, implementation of CE principles in construction remains limited, particularly at the project execution stage. Existing research and practice show limited use of data-driven, site-level prioritisation approaches capable of identifying where CE interventions can deliver maximum impact. To address these gaps in research and practice, the present study adopts a quantitative, site-centric approach to evaluate CE applicability in large-scale infrastructure projects in India. Using primary data from multiple active project sites, the study integrates waste quantification, efficiency normalisation, and root cause analysis to support targeted and evidence-based CE implementation during project execution.

## 2. LITERATURE REVIEW

In construction, the principles of a CE revolve around the reduction of materials at the source, the reuse of components, the recycling of C&D waste, the repair and refurbishment of assets, and the design for building adaptability and disassembly. Most

of the research consistently highlights their effectiveness in waste prevention, environmental impact mitigation, and resource efficiency increase.

## 2.1 CE STRATEGIES AND PRACTICAL LIMITATIONS

A wide range of CE strategies applicable to construction projects has been proposed in the literature, including sustainable design, modular construction, prefabrication, reuse of materials, and recycling of C&D waste (Hossain et al., 2024). However, despite the growing volume of CE related research in construction, much of the literature remains conceptual and strategic, focusing on frameworks, principles, and policy-level recommendations rather than operational implementation (Guerra et al., 2021; Munaro & Tavares, 2023). In practice, CE implementation in construction remains heavily dominated by recycling-based approaches. Higher-order strategies such as reuse, repair, refurbishment, and industrial symbiosis are comparatively underdeveloped, particularly in large infrastructure projects. This indicates that circularity in construction is often addressed through downstream waste management rather than upstream interventions targeting design coordination, procurement planning, and execution-stage process optimization (Guerra et al., 2021).

Several studies have identified the integration of lean construction principles as a complementary pathway for improving CE performance. Lean practices such as waste minimisation, just-in-time material delivery, and prefabrication reduce material losses and improve process efficiency, thereby supporting circular objectives at the site level. Execution-stage strategies, including source segregation, workforce training, and recycling incentives, have been reported as beneficial, especially in developing country contexts (Benachio et al., 2021; Wu et al., 2024). Nevertheless, these studies often rely on qualitative assessments or isolated case examples, limiting their generalisability. Few comprehensive quantitative analyses across multiple construction sites make it difficult to validate CE strategies at scale.

Recent studies have increasingly examined CE implementation in large-scale infrastructure projects, highlighting challenges associated with high material intensity, complex supply chains, and extended execution periods. Infrastructure projects such as transportation systems and energy facilities generate significant volumes of mineral-based waste and require coordinated planning for effective material recovery and reuse (Hasselsteen et al., 2025). Recent research emphasises the importance of circular material flows, including reuse of materials, adoption of recycled aggregates, and integration of secondary resources in construction processes; however, practical implementation remains limited due to operational and supply chain constraints (Krajewska et al., 2025). Furthermore, existing studies indicate that despite increasing interest in circular construction, most applications remain project-specific and lack standardised, data-driven evaluation across multiple sites, limiting scalability and broader adoption of CE practices (Mohandes et al., 2026).

## 2.2 PROJECT-LEVEL CONSTRAINTS FOR CE IMPLEMENTATION

Despite the availability of CE strategies, their adoption within the construction sectors, particularly at the project level, is constrained by multiple systemic and operational barriers. Fragmented supply chains, stakeholder misalignment, and weak coordination between design, procurement, and execution stages are repeatedly identified as major obstacles to effective CE implementation at project level (Badi & Murtagh, 2019). While

policy instruments such as landfill taxes, Extended Producer Responsibility (EPR) schemes, and sustainability regulations act as important drivers, their translation into consistent site-level practices remains limited (Ababio & Lu, 2022; Munaro et al., 2023).

Operational constraints at the site-level further restrict circular implementation. Inadequate waste segregation, material contamination, insufficient on-site storage facilities, and the absence of structured waste handling plans reduce the recoverability and reuse potential of construction materials. These challenges are particularly pronounced in large-scale infrastructure projects, where complex workflows, multiple subcontractors, and schedule pressures often result in reactive, disposal-oriented waste management practices (Nunes et al., 2012; Akinade et al., 2015; Galvez et al., 2018).

## 2.3 CIRCULAR ECONOMY ASSESSMENT APPROACHES

Assessment of CE performance in construction has predominantly relied on environmental evaluation tools, particularly Life Cycle Assessment (LCA). While LCA provides valuable insights into environmental impacts, it often lacks operational resolution and offers limited guidance for decision-making during project execution. Economic feasibility and process-level inefficiencies are frequently underrepresented in LCA studies, reducing the usefulness of existing frameworks for stakeholders responsible for site operations (Pomponi & Moncaster, 2017).

Although Material Flow Analysis (MFA) is commonly used to quantify construction waste streams, many studies focus on absolute waste quantities without relating them to total material consumption or project scale (Hasselsteen et al., 2025). This limits meaningful comparison across projects of different sizes. Without indicators such as waste intensity per unit area or material input, it becomes difficult to separate waste driven by project magnitude from waste caused by process inefficiencies. As a result, high-volume waste streams may be prioritized simply due to their size, while proportionally inefficient streams are overlooked, potentially diverting CE efforts away from areas with greater optimization potential. Few studies integrate waste quantification with risk-based prioritization approaches, limiting the ability to translate material flow insights into actionable site-level interventions.

## 2.4 EMPIRICAL RESEARCH GAPS AND THE INDIAN CONTEXT

Existing research shows real-world limited availability of empirical, project-level studies examining CE implementation in active construction projects. This gap is even more pronounced in the Indian context, where existing studies largely focus on policy analysis, regulatory frameworks, or generalised waste management practices, with minimal emphasis on quantitative assessment and execution-stage diagnosis in infrastructure projects (Hill et al., 2023). Although government initiatives such as the Construction and Demolition Waste Management Rules (2016), resource efficiency strategies proposed by NITI Aayog, and related policy reforms have strengthened regulatory direction, and corporate ESG initiatives have increased sustainability reporting, anecdotal evidence indicates that these efforts largely remain compliance or disclosure oriented.

Furthermore, only a few studies systematically link waste quantification to structured root cause analysis. Without identifying the process-level failures contributing to waste generation, CE strategies risk remaining generic and difficult to operationalize both at the project level and organisational level. The limited integration of waste quantification,

efficiency normalisation, and risk-based prioritisation represents a key limitation in current research. Addressing these gaps with empirical evidence from Indian infrastructure projects during the project execution stage forms the basis of the present study.

# 3. METHODOLOGY

The present study adopts a project-level, mixed-method research approach to evaluate the applicability of CE principles in large-scale infrastructure projects. The methodology integrates quantitative waste assessment and performance-based indicators with qualitative validation through site observations and expert interviews in the investigated projects. The methodological framework is designed to address two core objectives:

i. Quantify major construction waste streams and assess material efficiency using normalised performance indicators

ii. Identify and prioritise the root causes of waste generation through structured, risk-based analysis

A bottom-up, project-centric approach is employed to ensure that findings reflect actual construction practices.

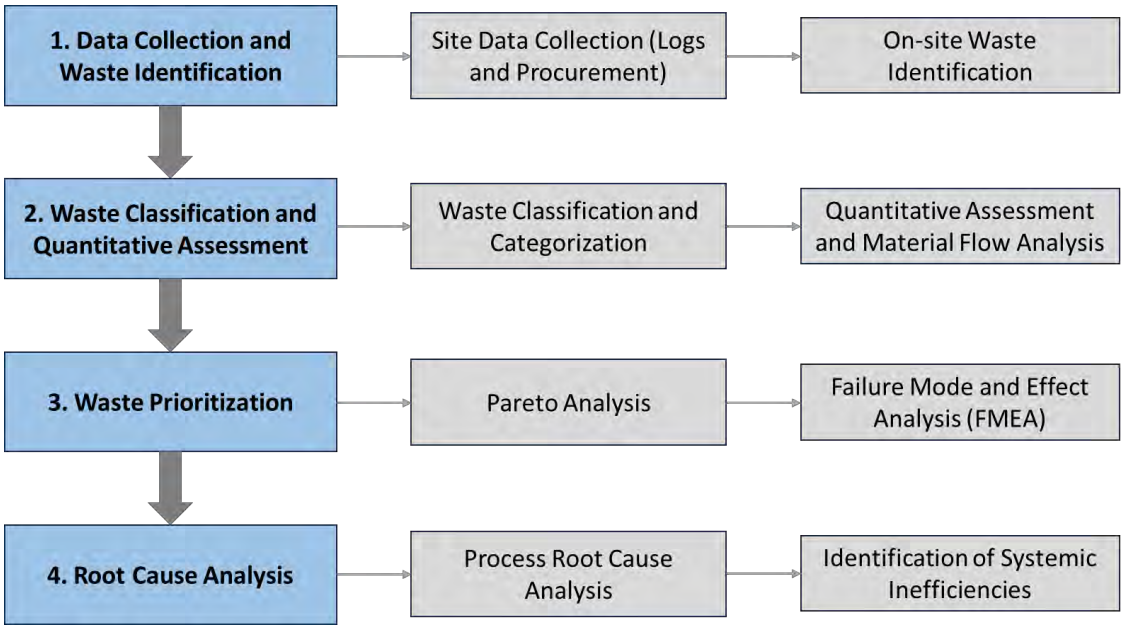



*Figure 1: Methodology framework*

The overall methodology is illustrated in Figure. 1.

## 3.1 DATA COLLECTION AND WASTE IDENTIFICATION

The study is based on primary waste management data collected from 58 large-scale infrastructure project sites over a period of one year (2024-25), covering civil, mechanical, and electromechanical works. The projects included nuclear, metro, and hydel infrastructure works characterised by high material intensity, repetitive construction operations, and extended execution periods, making them suitable for large-scale waste and circular economy assessment.

The dataset comprised site waste registers, monthly environmental reports, material movement logs, and procurement and issue records documenting waste generation, reuse, recycling, sale, and disposal pathways. All waste quantities were standardised to tons to enable aggregation and cross-project comparison. Waste streams were classified into hazardous and non-hazardous categories in accordance with hazardous waste rules, contractual Environmental Management Plans (EMP), and prevailing site practices. Waste output data were analysed alongside material input baselines derived from procurement and issue records to support quantitative assessment and material flow analysis across project types. Site observations were conducted to validate reported data and document on-ground waste handling, segregation, and storage practices. Examples of waste segregation and on-site waste handling practices observed during field visits are illustrated in Figure 2.

*Figure 2: Waste segregation at project sites*

For data validation and interpretation, expert interviews were conducted with seven project engineers, six environmental personnel and site management teams from the respective project sites. Each interview lasted approximately 25-30 minutes with project engineers and around 40 minutes with environmental personnel, focusing on execution-stage constraints influencing waste generation and management practices. Secondary data, including applicable codes and policy documents, were used to provide regulatory context and methodological support.

## 3.2 WASTE CLASSIFICATION AND QUANTIFICATION

Waste streams generated during construction activities were identified across multiple work fronts, including concrete and masonry waste, ferrous and reinforcement scrap, timber and formwork waste, electrical and MEP scrap, packaging waste, and miscellaneous site waste. Identified waste streams were categorised into hazardous and non-hazardous waste in accordance with applicable regulatory definitions.

An overview of the study design, including project classification, waste categorization, and data collection sources, is illustrated in Figure 3. Quantitative assessment was carried out to determine the volume and proportion of each waste stream over the study period.

All quantities were standardized to a common unit to enable aggregation and comparison across project types.

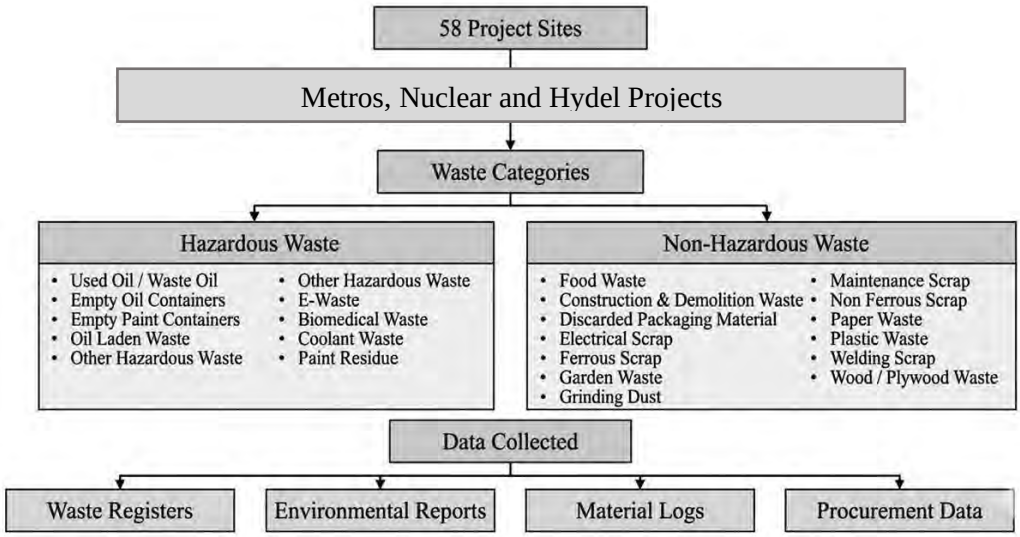



*Figure 3: Study overview of infrastructure project waste assessment*

To evaluate material efficiency, waste quantities were normalized against corresponding material issue quantities using the Waste Generation Index (WGI), defined as the ratio of waste generated to material issued for construction activities.

### 3.3 WASTE PRIORITISATION AND ROOT CAUSE ANALYSIS

To prioritise waste streams for detailed analysis, pareto analysis, an 80/20-based method for identifying the few (20%) contributors responsible for the majority of outcomes (80%) - was applied to identify dominant contributors to overall waste generation at the organizational level. This enabled distinction between high-volume waste streams and those requiring focused intervention. For prioritised waste streams, Failure Mode and Effects Analysis (FMEA) was employed as a structured root-cause analysis tool. Potential failure modes contributing to waste generation were identified across design, procurement, material handling, storage, execution, and supervision stages. Each failure mode was evaluated based on severity, occurrence, and detectability, and corresponding Risk Priority Numbers (RPNs) were calculated. This risk-based approach facilitated systematic prioritization of process failures contributing to waste generation and provided a quantitative basis for identifying CE intervention points.

## 4. PROJECT SITE-LEVEL WASTE ASSESSMENT

This section presents a structured assessment of waste generation and management practices at the project site level. The analysis focuses on quantifying waste streams, classifying material categories into hazardous and non-hazardous waste, and examining disposal and recovery pathways across different infrastructure project types. By integrating waste output data with material input records, the assessment enables evaluation of material efficiency, identification of high-impact waste streams, and benchmarking of circular economy performance across sites.

## 4.1 QUANTITATIVE ASSESSMENT OF HAZARDOUS WASTE STREAMS

Hazardous waste generation across the studied projects was dominated by oil-related waste streams, reflecting the intensive use of heavy machinery and equipment.

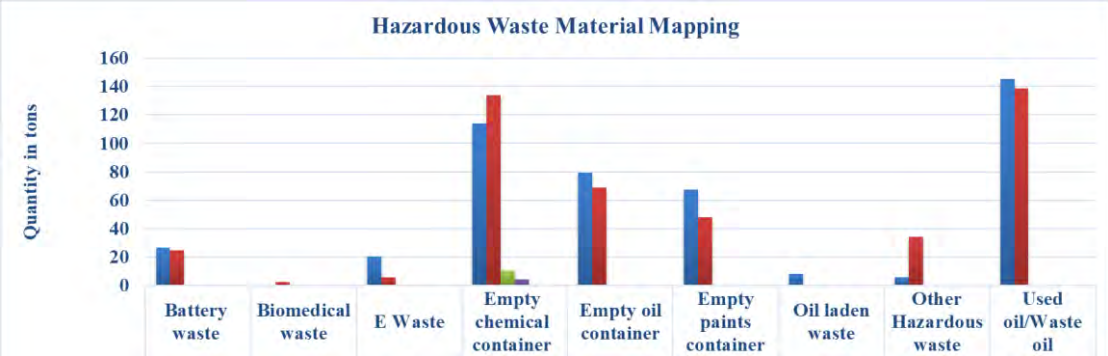



*Figure 4: Hazardous waste material mapping*

Used oil accounted for approximately 51% of total hazardous waste, followed by empty oil containers (25%) and empty paint containers (19%). Lower-volume hazardous streams such as e-waste, biomedical waste, and oil-laden waste contribute less than 5% of the total quantity.

Material flow analysis as represented in Figure.4, revealed that over 85% of hazardous waste was sold to authorised recyclers, indicating strong regulatory compliance and a mature external disposal ecosystem. Internal reuse or recycling was minimal (≈3%), largely restricted by safety considerations and statutory controls. A small but significant fraction of hazardous waste (≈11%) was recorded as generated but not yet disposed, indicating temporary storage inventories or reporting lags. Overall, hazardous waste management was found to be compliance-driven and externally dependent, leaving limited scope for discretionary CE interventions at the site level.

## 4.2 QUANTITATIVE ASSESSMENT OF NON-HAZARDOUS WASTE STREAMS

Non-hazardous waste constituted the largest share of total waste generation and exhibited substantial variability across project types.

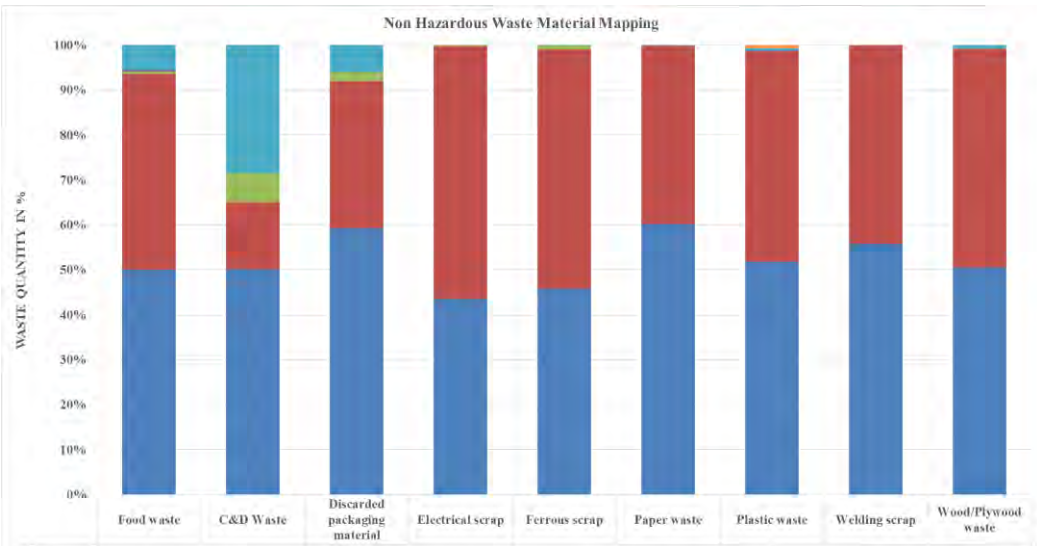



*Figure 5: Non-Hazardous waste material mapping*

C&D waste emerged as the dominant stream, accounting for approximately 17.5% of total non-hazardous waste, followed by ferrous scrap (13.4%). Other streams included wood/plywood waste, plastic waste, packaging waste, and biodegradable waste. Material flow analysis, as represented in Figure.5, showed that nearly 50% of non-hazardous waste was sold to external recyclers, driven primarily by ferrous and non-ferrous scrap markets. However, internal reuse and recycling accounted for only 2.4%, indicating significant untapped circular potential, particularly for C&D waste, packaging materials, and temporary works. Approximately 10% of non-hazardous waste was sent to landfill, while 37.6% remained categorised as generated but not yet disposed, highlighting inventory accumulation and documentation gaps. These findings establish non-hazardous waste streams, especially C&D waste and ferrous scrap as priority areas for CE analysis.

### 4.3 PROJECT-TYPE-WISE WASTE GENERATION CHARACTERISTICS

Waste generation patterns varied significantly across project types. Metro projects generated the highest absolute waste quantities, dominated by C&D waste arising from excavation, mass concrete, rework, and interface coordination issues. Nuclear projects were primarily characterised by high ferrous scrap generation linked to reinforcement cutting and fabrication activities. Hydel projects, although smaller in total waste volume, exhibited higher on-site reuse of excavation material due to logistical and geographical constraints. These variations underline the need for project-specific waste management strategies, rather than a uniform approach across infrastructure typologies.

### 4.4 WASTE GENERATION INDEX (WGI) ANALYSIS

To evaluate material efficiency, waste quantities were normalised against material issue quantities using the WGI (refer Table 1).

*Table 1: WGI Range*

| WGI Range | Category |
|---|---|
| < 0.01 (1%) | Very Low |
| 0.01 - 0.03 (1-3%) | Low |
| 0.03 - 0.06 (3-6%) | Moderate |
| 0.06 - 0.10 (6-10%) | High |
| > 0.10 (10%) | Very High |

The analysis revealed that while concrete and welding consumables consistently exhibited very low WGI values across project types, electrical materials recorded the highest WGI values (>0.10), identifying them as a recurring inefficiency hotspot. Ferrous and wood waste exhibited moderate WGI values, suggesting opportunities for improved planning, detailing, and reuse cycles. The WGI analysis provided a quantitative basis for distinguishing high-volume waste streams from high-inefficiency waste streams, informing subsequent prioritisation.

## 5. WASTE PRIORITISATION

Following the site-level waste assessment, a structured prioritisation approach was adopted to identify high-impact waste streams requiring targeted intervention. Since waste quantity alone does not fully reflect operational risk or inefficiency, both volume-based and risk-based analytical methods were applied. The prioritisation process

integrates Pareto analysis to identify dominant waste contributors and FMEA to evaluate process-level risk intensity, enabling data-driven selection of waste streams for circular economy interventions.

## 5.1 PARETO-BASED WASTE PRIORITISATION

Pareto analysis revealed a pronounced concentration of waste generation across a limited number of streams, as illustrated in the Pareto chart in Figure.6. C&D waste from Metro projects alone contributed approximately 63% of total organisational waste, while ferrous waste from Metro and Nuclear projects contributed an additional ~26%.

*Figure 6: Pareto chart*

Together, these streams accounted for nearly 84% of total waste generation, validating the applicability of the Pareto principle for targeted intervention. In contrast, wood and plastic wastes formed a Pareto 'long tail', lower in absolute quantity but exhibiting disproportionately high WGI values, indicating inefficiencies that may be overlooked when prioritisation is based solely on volume.

## 5.2 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

To move beyond quantity-based prioritization, FMEA was employed to systematically identify process-level failures contributing to waste generation. Severity (S), Occurrence (O), and Detection (D) scores were assigned based on site observations, expert inputs, WGI values, and Pareto results. Risk Priority Numbers (RPNs) were calculated to rank failure modes according to risk criticality. The formulated RPN bands are:

- RPN ≥ 250 → Critical (Immediate intervention required)
- RPN 200-250 → High (Process optimization needed)
- RPN 100-200 → Moderate
- RPN < 100 → Low

The calculated RPN values form the basis for prioritizing waste streams for corrective action and development of CE strategies in subsequent analysis. The FMEA focused on major waste streams, including C&D waste, ferrous waste, electrical waste, wood waste,

and plastic waste. The results revealed substantial variation in risk intensity across streams, highlighting that waste-related risk is governed not only by quantity, yet by severity of impact, frequency of occurrence, and detectability of failures.

# 6. ROOT CAUSE ANALYSIS

A root cause analysis was conducted to identify the underlying process-level drivers contributing to waste generation and elevated risk levels. The objective was to move beyond surface-level metrics and examine operational, planning, and coordination failures influencing each major waste category. By linking Risk Priority Numbers (RPNs) with specific construction practices, the analysis provides actionable insights for targeted circular economy interventions.

| Risk Category | | | Priority Bands | |
|---|---|---|---|---|
| | | RPN Range | ≥ 250 | 200 — 249 |
| RPN | Critical | ≥ 250 | • **C&D Waste** (majority of failure modes) | • **C&D Waste** (majority of failure modes)<br>• **Electrical Waste** (key failure modes) |
| | • Immediate intervention required | | | |
| High | High | 200 – 249 | • **Ferrous Waste**<br>• Select Wood Waste modes | |
| | • Process optimization essential | | | |
| RPN | Moderate | 100 – 199 | • **Plastic Waste**<br>• Secondary Wood Waste modes | |
| | • Improvement desirable | | | |
| Low | Low | <100 | – | |

*Figure 7: Risk priority matrix*

The resulting risk intensity across waste streams is visualised using a risk matrix as represented in Figure.7, which categorises failure modes based on severity and occurrence levels to highlight critical intervention areas.

## 6.1 CONSTRUCTION AND DEMOLITION WASTE: DOMINANT CRITICAL RISK STREAM

C&D waste exhibited the highest concentration of critical RPN values (240–288), establishing it as the most risk-intensive stream. Key failure modes included over-excavation beyond design depth, handling and pouring losses during concrete, absence of planned reuse for excavated material, and rework arising from design-execution mismatches. These failures are primarily driven by planning deficiencies, conservative assumptions, and weak process control rather than material behavior alone. This finding aligns with existing studies that identify C&D waste as the dominant waste stream in infrastructure projects, driven by rework, over-excavation, and material handling losses (Hossain et al., 2024; Wu et al., 2024). However, the present study further shows that these streams also exhibit high process-level risk, highlighting the need for risk-based prioritisation.

## 6.2 FERROUS WASTE: HIGH RISK WITH EFFECTIVE DIVERSION

Ferrous waste failure modes recorded high yet non-critical RPN values (≈190–224). While near-complete diversion through recycling mitigates disposal impacts, elevated RPNs highlight upstream inefficiencies related to cutting losses, congested detailing, and

limited internal reuse of off-cuts. This indicates a reliance on downstream recycling rather than preventive material optimisation. This is consistent with literature reporting high recycling rates for ferrous waste in construction projects (Benachio et al., 2021; Munaro et al., 2023). However, the findings highlight persistent upstream inefficiencies, indicating that recycling alone does not address material losses.

### 6.3 ELECTRICAL WASTE: HIGH-INTENSITY HIDDEN HOTSPOT

Electrical waste emerged as a high-risk efficiency hotspot, despite low absolute quantities. Failure modes such as cable length miscalculation and scrapping due to late design changes recorded RPN values up to 280, explaining the consistently high WGI values observed earlier. This stream demonstrates how low-volume waste can translate into significant cost and risk due to high severity and poor detectability.

### 6.4 WOOD AND PLASTIC WASTE: LONG-TAIL INEFFICIENCY ZONE

Wood and plastic wastes occupied the moderate-risk band (RPN 140–210). Although their quantities are small, inefficiencies related to handling, storage, moisture exposure, and lack of reuse mechanisms reduce reuse cycles and increase replacement demand. These streams represent low-cost, high-return intervention opportunities through procedural and planning improvements.

By integrating WGI, Pareto analysis, and FMEA, the study demonstrates a structured, risk-based approach to identifying priority waste streams for CE implementation in large-scale infrastructure projects. The findings confirm that effective circular interventions must target both dominant waste streams and hidden inefficiency hotspots, rather than focusing on waste quantity alone. The study addresses the lack of empirical, site-level evidence on CE implementation in Indian infrastructure projects and demonstrates the value of integrating waste quantification, efficiency normalisation, and risk-based analysis. The combined use of WGI, Pareto analysis, and FMEA advances methodological rigor beyond conceptual CE frameworks. From a practical standpoint, the findings provide contractors and project managers with a replicable decision-support framework for prioritising waste streams and targeting execution-stage circular interventions. The results emphasise that effective CE implementation requires moving beyond disposal efficiency toward quantification-driven diagnosis and process-level optimisation.

Existing studies mainly focus on high-volume waste streams and recycling-based approaches for CE implementation (Guerra et al., 2021; Munaro et al., 2023). However, this study shows that volume-based prioritisation can overlook high-inefficiency waste streams with significant operational risk. Unlike prior work based on qualitative or single-project studies, this research provides multi-site, data-driven evidence linking waste quantification with risk-based prioritization and root cause analysis, offering a more differentiated understanding of CE implementation in large-scale infrastructure projects.

## 7. CONCLUSIONS

The study presented a data-driven, site-centric evaluation of construction waste streams in large-scale infrastructure projects to support practical CE implementation at the project execution stage. Using primary data from 58 infrastructure projects in India, the study integrated the WGI, Pareto analysis, and FMEA to move beyond conventional volume-

based waste assessment toward efficiency- and risk-based prioritisation. The findings reveal that C&D waste from metro projects constitutes the dominant waste hotspot, contributing nearly two-thirds of total organisational waste and exhibiting the highest concentration of critical risk failure modes. These risks are primarily driven by planning deficiencies, design-execution mismatches, conservative excavation practices, and the absence of structured reuse planning, rather than material-related constraints. As a result, C&D waste represents the most impactful leverage point for CE interventions in large-scale infrastructure projects.

Although ferrous waste achieves near-complete diversion through external recycling, elevated RPN highlight persistent upstream inefficiencies related to cutting losses, congested reinforcement detailing, and limited internal reuse of off-cuts. This underscores a key limitation of recycling-dominated CE practices and emphasises the need to shift focus from disposal efficiency toward preventive material optimisation. The study identifies electrical waste as a high-intensity hidden inefficiency hotspot. Despite low absolute quantities, electrical waste consistently exhibited very high WGI and RPN values due to cable length miscalculations, late design changes, and poor detectability of losses. These findings demonstrate the value of integrating normalised efficiency metrics with risk-based analysis to uncover inefficiencies that may otherwise remain overlooked. Wood and plastic wastes form a Pareto long tail, reflecting moderate risk driven by handling, storage, and planning deficiencies, and offering low-cost opportunities for procedural improvement.

Overall, the study demonstrates that effective CE implementation in infrastructure projects requires prioritisation based on both waste dominance and process risk, rather than waste quantity alone. It provides a replicable decision-support tool for practitioners to identify and target high-impact CE interventions. Future research should focus on evaluating the technical and economic feasibility of prioritised CE strategies to translate diagnostic insights into actionable implementation pathways.

## 8. REFERENCES

Ababio, B. K., & Lu, W. (2023). Barriers and enablers of circular economy in construction: A multi-system perspective towards the development of a practical framework. *Construction Management and Economics*, *41*(1), 3–21. https://doi.org/10.1080/01446193.2022.2135750

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., & Arawomo, O. O. (2018). Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *Journal of Cleaner Production*, *180*, 375–385. https://doi.org/10.1016/j.jclepro.2018.01.022

Amudjie, J., Agyekum, K., Adinyira, E., Amos-Abanyie, S., & Botchway, E. A. (2025). Implementing the principles of circular economy in the construction industry: Exploratory and confirmatory factor analyses of strategies. *Construction Innovation*, *25*(3), 761–786. https://doi.org/10.1108/CI-10-2022-0270

Badi, S., & Murtagh, N. (2019). Green supply chain management in construction: A systematic literature review and future research agenda. *Journal of Cleaner Production*, *223*, 312–322. https://doi.org/10.1016/j.jclepro.2019.03.132

Benachio, G. L. F., Freitas, M. D. C. D., & Tavares, S. F. (2021). Interactions between lean construction principles and circular economy practices for the construction industry. *Journal of Construction Engineering and Management*, *147*(7), 04021068. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002082

Bhattacharyya, S. K., Minocha, A. K., Garg, M., Singh, J., Jain, N., Maiti, S., & Singh, S. K. (2013). Demolition wastes as raw materials for sustainable construction products. *CSIR-CBRI Newsletter*, *33*(2), 1–2. https://cbri.res.in/pdf/newsletter_apr_jun_2013.pdf

Blumhardt, H. (2018). Trashing waste: Unlocking the wasted potential of New Zealand's Waste Minimisation Act. *Policy Quarterly*, *14*(4). https://doi.org/10.26686/pq.v14i4.6545

Central Pollution Control Board (CPCB). (2017/2018). *Guidelines on environmental management of construction and demolition (C&D) waste in India*. Ministry of Environment, Forest and Climate Change, Government of India. https://prana.cpcb.gov.in/assets/pdf/c_and_d_guidelines_1.pdf

Ezekwu, E. (2025). Sustainable supply chain practices: Driving efficiency, reducing waste, and promoting circular economy models. *International Journal of Science and Research Archive*, *14*(1), 1167–1181. https://doi.org/10.30574/ijsra.2025.14.1.0206

Gálvez-Martos, J. L., Styles, D., Schoenberger, H., & Zeschmar-Lahl, B. (2018). Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling*, *136*, 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016

Ginga, C. P., Ongpeng, J. M. C., & Daly, M. K. M. (2020). Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials*, *13*(13), 2970. https://doi.org/10.3390/ma13132970

Guerra, B. C., Shahi, S., Mollaei, A., Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: A global scan of trends and opportunities. *Journal of Cleaner Production*, *324*, 129125. https://doi.org/10.1016/j.jclepro.2021.129125

Hasselsteen, L., Damgaard, A., Otovic, A. P., Birgisdóttir, H., & Kanafani, K. (2025). Tracing resource flows and reducing environmental impacts during construction: Assessment framework for on-site waste efficiency. *Journal of Cleaner Production*, *521*, 146243. https://doi.org/10.1016/j.jclepro.2025.146243

Hill, W., Jalloul, H., Movahedi, M., & Choi, J. (2023). Sustainable management of the built environment from the life cycle perspective. *Journal of Management in Engineering*, *39*(2), 03123001. https://doi.org/10.1061/JMENEA.MEENG-4759

Hossain, M. S., Lopa, N. Z., Khatun, M., & Rahim, S. T. (2024). Enablers of circular economy implementation in built environment sector of developing countries: Evidence from Bangladesh. *Circular Economy and Sustainability*, *4*(3), 2287–2311. https://doi.org/10.1007/s43615-024-00392-4

Krajewska, A., & Siewczyńska, M. (2025). Circular economy in the construction sector in materials, processes, and case studies: Research review. *Sustainability*, *17*(15), 7029. https://doi.org/10.3390/su17157029

Mohandes, S. R., Fan, A., Zou, J., Taiwo, R., Shakor, P., & Banihashemi, S. (2026). Advancing circular economy adoption through investigating RFID technology in construction. *Engineering, Construction and Architectural Management*, 1–34. https://doi.org/10.1108/ECAM-05-2025-0851

Munaro, M. R., & Tavares, S. F. (2023). A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Cleaner and Responsible Consumption*, *8*, 100107. https://doi.org/10.1016/j.clrc.2023.100107

Nunes, K. R. A., & Mahler, C. F. (2020). Comparison of construction and demolition waste management between Brazil, European Union and USA. *Waste Management & Research*, *38*(4), 415–422. https://doi.org/10.1177/0734242X20902814

Oshilalu, A. Z. (2024). Sustainability meets scalability: Transforming energy infrastructure projects into economic catalysts through supply chain innovation. *International Journal of Research Publication and Reviews*, *5*(12), 762–779. https://doi.org/10.55248/gengpi.5.1224.3417

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Wu, H., Weng, X., Li, Y., Liu, S., Ma, J., Chen, R., & Bao, Z. (2025). Critical construction waste minimization strategies for a circular economy in developing countries: A contractor's perspective in China. *International Journal of Environmental Science and Technology*, *22*(12), 11211–11228. https://doi.org/10.1007/s13762-024-06150-1

Sampath, Y.K.K., Jayalath, J.A.C.D., Piranavan, S. and Jayasena, H.S., 2026. Optimising investment decisions in homestay tourism: A cost and performance analysis of coastal regions in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14thWorld Construction Symposium*, 10-11July 2026, Sri Lanka. pp.1265-1277. DOI: https://doi.org/10.31705/WCS.2026.92. Available from: https://ciobwcs.com/papers/

# OPTIMISING INVESTMENT DECISIONS IN HOMESTAY TOURISM: A COST AND PERFORMANCE ANALYSIS OF COASTAL REGIONS IN SRI LANKA

**Y.K.K. Sampath[1], J.A.C.D. Jayalath[2], S. Piranavan[3] and H.S. Jayasena[4]**

## *ABSTRACT*

*Tourism plays a vital role in the economy of Sri Lanka, with homestay accommodations emerging as a key component of community-based tourism. However, the successful development and operation of homestays are influenced by multiple factors, creating challenges for investors and operators. These challenges often result in inefficient investment decisions, underperforming accommodation ventures, and missed opportunities for local economic development. Despite the growing trend of homestay establishments in coastal regions, limited research has been conducted to systematically identify the critical factors affecting their development. Therefore, the main aim of this research is to identify and analyse the key factors influencing the development of homestay accommodations in the coastal regions of Sri Lanka. Accordingly, the study investigates three primary dimensions: cost-related factors, including initial investment and operational expenses; tourist preference factors, focusing on the attributes that influence visitors' selection of homestays; and social, environmental, and cultural constraints within the Sri Lankan context. Data were collected through a combination of literature review and semi-structured interviews with relevant stakeholders. Mean comparison and thematic analysis were employed to evaluate and prioritise the critical factors affecting homestay development. The findings provide valuable insights for homestay operators and potential investors, enabling more informed decision-making and contributing to the sustainable development of the homestay sector in Sri Lanka.*

***Keywords:*** *Coastal Region; Constraints; Cost Elements; Homestay; Tourist Preference.*

## 1. INTRODUCTION

Among South Asian countries, Sri Lanka possesses significant tourism potential due to its natural beauty and cultural heritage (Gamalath, 2021). The southern coastal belt of

[1]Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, sampathykk.21@uom.lk
[2]Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, , cdeshanjayalath@gmail.com
[3]Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, sivasothypiranavan27@gmail.com
[4]Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, suranga@uom.lk

Sri Lanka, particularly from Beruwala to Mirissa and Tangalle, has emerged as one of the most popular tourist regions in the country. This area attracts visitors due to its scenic beaches and various tourism activities, including whale watching, turtle watching, snorkelling, surfing, and coastal recreational experiences (Dharmasena et al., 2023). Consequently, a range of accommodation facilities, including luxury hotels, guesthouses, and alternative lodging options have developed in this region to cater to the increasing demand from tourists (Wijesundara, 2022).

In recent years, tourists have increasingly demonstrated a preference for alternative forms of accommodation, particularly homestays (Thapa, 2017). A homestay can be defined as a form of lodging where visitors reside within a local household, enabling a more immersive and personalised travel experience. Beyond offering economic advantages for travellers, homestays facilitate meaningful social and cultural exchange by allowing close interaction with host communities, while simultaneously generating income opportunities for residents (Dias et al., 2022).

Within the Sri Lankan context, the concept of home-stay accommodations has gained increasing popularity in recent years, especially in the southern coastal regions (Patwal et al., 2023). Homestay offers many benefits, such as experiencing the local culture, learning about different cultural practices in a homely environment, improving language skills, and many more (Gautam, 2024).They contribute to strengthening social cohesion, promoting community empowerment, and advancing gender equity by enhancing women's leadership and reducing prevailing social stigmas (Bandusena et al., 2023).

In response to the growing demand for alternative accommodation options, many local households have increasingly engaged in providing small-scale lodging facilities for tourists. Recognising the potential contribution of this sector to tourism development and community-based economic growth, the Sri Lanka Tourism Development Authority (SLTDA) has introduced guidelines and regulatory frameworks for homeowners seeking to establish and operate registered homestay accommodations (Sri Lanka Tourism Development Authority, 2020). In addition to complying with SLTDA requirements, homestay operators are expected to obtain approvals from relevant authorities, including the Urban Development Authority (UDA) and the respective municipal councils. Despite the existence of these regulatory mechanisms, a considerable proportion of accommodation providers continue to operate without formal registration, indicating a gap between regulatory requirements and actual industry practices.

However, the demand for rental accommodation is influenced by a range of factors, including tourists' preferences for specific facilities, services, and nearby attractions (Pina & Delfa, 2005). Despite the increasing interest in homestay investments, many homeowners undertake such developments without a comprehensive understanding of construction costs, operational expenses, or prevailing market demand (Magno et al., 2018).This knowledge gap can adversely affect the financial viability and profitability of these ventures. Moreover, conventional pricing and investment evaluation methods often fail to adequately capture the dynamic nature of tourism demand and fluctuating market conditions (Ndaguba & Van Zyl, 2024). Given that homestays primarily cater to budget-conscious travellers, it is essential for investors to conduct thorough feasibility assessments prior to committing financial resources (Patwal et al., 2023). Failures may

result in inefficient investment decisions, underperforming accommodation ventures, and missed economic opportunities for local communities.

Recent studies emphasise the need for more adaptive and evidence-based approaches to overcome these challenges and support informed decision-making in tourism-related investments (Ndaguba & Van Zyl, 2024). Accordingly, the aim of this study is to identify and analyse the key factors influencing the development and investment viability of homestay accommodations in the coastal regions of Sri Lanka. To achieve this aim, the study is guided by the following objectives: 1) To identify the initial and operational cost components associated with homestay accommodations. 2) To examine the key factors influencing tourist preferences for homestay accommodations. 3) To analyse the social, environmental, and cultural constraints affecting the development and operation of homestays within the Sri Lankan context. The first and second objectives of the study were addressed through the literature review, followed by ranking the identified factors based on respondents' perceptions. The third objective was examined using both literature findings and respondents' views to assess the impacts of those factors. Finally, the study aimed to identify the cost-related and demand-related factors that required greater attention for the effective development and formalization of homestay accommodations.

## 2. LITERATURE REVIEW

Since investment decisions should first consider the investor's financial capacity, this study initially focuses on cost-related factors before examining preference and demand-related factors associated with homestay accommodations. The study identifies the key cost items associated with homestay accommodation development and determine their relative priorities. In addition, it sought to examine tourists' preferences for staying in homestays and assess the influence of these preferences on income generation. Accommodation plays a fundamental role in tourism development as one of the key components of the tourism system, together with attractions, accessibility, and ancillary services (Sedai, 2011). In the southern coastal region of Sri Lanka, various types of accommodation are available, including hotels, boutique hotels, guesthouses, and homestays, which cater to diverse tourist segments and preferences (Ministry of Foreign Affairs, Foreign Employment and Tourism, 2023). Among those types of accommodation, home stays generally offer more affordable accommodation options with basic facilities, making them attractive to budget-conscious travellers (Adhikari, 2020; Chiu et al., 2017). These accommodation types contribute to tourism development by increasing accommodation capacity while also enabling local communities to participate directly in tourism activities (Ministry of Foreign Affairs, Foreign Employment and Tourism, 2023).

Despite these advantages, several challenges persist within the homestay sector, which lead to inefficient investment decisions, underperforming accommodation enterprises, and missed economic opportunities for local communities. In this context, it is important to examine the key constraints faced by investors, including initial capital requirements, ongoing operational costs, managing demanding factors, and socio-cultural considerations that influence both the development and management of homestay accommodations (Idahosa & Ebhuoma, 2020; Petruzzi et al., 2023).

## 2.1 INITIAL INVESTMENT COST ELEMENTS OF HOME-STAY ACCOMMODATION

Initial investment constitutes a critical factor influencing the establishment of homestay accommodation businesses. Such operations are typically initiated by private homeowners who convert portions of their residences into tourist accommodation to generate supplementary income. These investments are intended to provide basic yet comfortable facilities that satisfy tourist needs while preserving a home-like environment (Khan et al., 2020).

The initial investment generally comprises several cost components related to property development, facility provision, and regulatory compliance. Key elements include construction costs, development of attached bathrooms, acquisition or leasing of land or property, furniture and room amenities, and installation of essential utilities such as water and electricity (Daniels, 1994; Qiao et al., 2021). Additional facilities, including kitchens, laundry equipment, and household appliances, are often incorporated to enhance guest comfort and the overall homestay experience (Patwal et al., 2023; Yu et al., 2022).

Beyond physical infrastructure, legal and administrative requirements such as tourism registration, health and safety certification, and local authority approvals also contribute to initial investment costs (Pasanchay & Schott, 2021). The level of investment varies depending on the type and quality of accommodation provided. Higher investment may enable operators to offer superior facilities and attract more guests; however, excessive capital expenditure may reduce profitability if not supported by sufficient demand (Pawlicz & Napierala, 2017). The principal initial cost components identified in the literature, which influence the establishment and viability of homestay accommodations, are summarised in Table 1.

*Table 1: Initial cost elements influencing home stay accommodations*

| Initial Cost Element | Reference |
|---|---|
| Construction cost | (1), (2) |
| Acquisition of land or property cost | (3), (4) |
| Bedroom, furniture, and amenities cost | (5) |
| Kitchen and laundry facilities | (6), (7) |
| Electricity, water supply, and washing machine cost | (7) |
| Legal approval cost, registration cost | (8) |

1 - (Daniels, 1994), 2 - (Khan & Su, 2003), 3- (Amalia & Febrian, 2022), 4 - (Qiao et al., 2021), 5 - (Sedai, 2011), 6 - (Patwal et al., 2023), 7 - (Yu et al., 2022), 8 - (Pasanchay & Schott, 2021)

## 2.2 OPERATIONAL COST ELEMENTS OF HOME-STAY ACCOMMODATION

Operational costs denote the recurrent expenditures required to manage and maintain accommodation facilities and deliver services to guests (Amalia & Febrian, 2022). The primary component is labour, encompassing wages and related expenses necessary to sustain service quality (Arbelo et al., 2017). Homestays also incur utility costs, including electricity and water, which may vary with occupancy levels and length of stay (Aldubyan & Krarti, 2022). Maintenance and repair costs represent another key

element, as ongoing upkeep is essential to preserve service standards and guest satisfaction (Au-Yong et al., 2019).

Additional operational expenditures include waste management, safety and security measures, and housekeeping services, all of which uphold hygiene and safety standards within the accommodation (Janjua et al., 2021). Moreover, marketing and promotional activities such as website maintenance, social media engagement, and online advertising are necessary to attract tourists and sustain market visibility in a competitive tourism sector (Gulati, 2024). Based on the literature, several operational cost elements influencing home stay operations have been identified and are presented in Table 2.

*Table 2: Operational cost elements influencing home stay accommodations*

| Operational Cost Element | Reference |
|---|---|
| Electricity, housekeeping, and laundry service bills | (1) |
| Waste management/ disposal of garbage cost | (2) |
| Maintaining cost | (3) |
| The guests and the premises are safe | (4) |
| Marketing cost (Website, Advertisement) | (5) |
| Labor, the driver of energy consumption, and regular maintenance costs | (6), (7) |
| Booking.com, Airbnb, and Agoda booking costs. | (8) |

1- (Amalia & Febrian, 2022), 2- (Janjua et al., 2021), 3- (Aldubyan & Krarti, 2022), 4- (Kunjuraman & Hussin, 2017), 5- (Kartal et al., 2025), 6- (Arbelo et al., 2017), 7- (Ihsan & Alshibani, 2018), 8- (Lamis et al., 2022)

It is observed that cost-related factors are one of the major challenges that investors face at the initial stage of developing homestay accommodations. The initial investment is a major barrier for investors. Therefore, financial planning strategies are important for the development of homestay accommodations.

As cost control strategies smaller public areas and efficient room layouts can also help save on future costs of heating and cleaning (Arbelo et al., 2017). The incorporation of green building features such as good insulation, double glazing, solar passive design, LED lighting and solar hot water systems may incur higher initial costs but can save on long-term costs (Xiao, 2023). Cost or budget methods can be employed to arrive at target costs for each room (construction and fit-out) and design to the target costs(Gössling & Lund-Durlacher, 2021). The Balanced Scorecard can be employed to manage costs while maintaining quality of service, learning and sustainability.

## 2.3 CRITICAL ATTRIBUTES INFLUENCING TOURIST PREFERENCES FOR HOME-STAYS

Homestays represent a distinctive form of accommodation that enables tourists to engage directly with local communities and experience authentic cultural practices. Unlike conventional hotels, homestays offer a personalized, family-oriented environment in which guests may participate in everyday local activities and consume home-prepared meals (Dash, 2022).

Several attributes influence tourists' preferences when selecting homestay accommodation. These include host hospitality, cleanliness and hygiene, safety and security, affordability, and opportunities to experience local culture and traditions (Chen, 2023; Patwal et al., 2023). The availability of comfortable facilities, such as well-furnished rooms, kitchen amenities, and reliable internet access, may also affect accommodation choices (Sánchez-Franco & Rey-Moreno, 2022). Location-related attributes are particularly significant in coastal tourism contexts. Proximity to the beach and scenic ocean views strongly influence tourists' choices and willingness to pay premium prices (Hamilton, 2007). Empirical evidence further indicates that accommodation located near the coastline tends to attract higher tourist demand (Perez-Sanchez et al., 2018). Accordingly, the major attributes influencing tourist preferences for homestays, as identified in the literature, are summarised in Table 3.

*Table 3: Key attributes influencing tourist preferences for home stays in the southern coastal region*

| Preference for home stays in the region | Reference |
|---|---|
| Local culture, living style and homemade foods | (1), (2) |
| Cleaning and hygiene | (2), (3) |
| Warm familial feel | (5) |
| Safety and security | (3), (6) |
| Law price range | (6) |
| Distance to the beach | (8), (9), (10) |
| Kitchen facilities | (4) |

1- (Dash, 2022), 2- (Chen, 2023), 3- (Luekveerawattana, 2024), 4- (Sánchez-Franco & Rey-Moreno, 2022), 5- (Janjua et al., 2021), 6- (Patwal et al., 2023), 7- (Perez-Sanchez et al., 2018), 8- (Mendoza-González et al., 2018), 9- (Hamilton, 2007), 10 - (Perez-Sanchez et al., 2018)

## 3. METHODOLOGY

This study adopts a mixed-method approach, integrating qualitative and quantitative techniques to analyse factors influencing the development of homestay tourism in the coastal regions of Sri Lanka. The research includes a background study, literature review, primary data collection, and data analysis, enabling a comprehensive understanding of the research problem through both numerical and qualitative insights (Ishtiaq, 2019). The study is guided by three objectives: (1) to identify initial and operational cost components, (2) to examine factors influencing tourist demand, and (3) to analyse social and cultural constraints affecting homestay development. These objectives were initially addressed through the literature review, which provided a partial identification of key factors based on existing studies. To ensure contextual relevance, these factors were further validated and refined for the Sri Lankan context through semi-structured interviews with homestay owners. The data collection period was from January to February 2026 extending for 03 weeks. A total of 15 respondents were selected using snowball sampling, which is suitable for accessing participants with relevant experience. This qualitative approach primarily supported the validation of literature findings.

Data were analysed using manual thematic analysis to identify patterns related to cost factors, tourist preferences, and socio-cultural constraints. Mean comparison was also applied to prioritise the significance of identified factors, with Microsoft Excel and Word supporting the analysis. The methodology enables a structured identification of key factors influencing homestay investments. Although developing strategies is not a primary objective, the discussion section highlights the need for such strategies to address identified challenges and constraints.

# 4. FINDINGS AND ANALYSIS

## 4.1 ANALYSIS OF CAPITAL AND OPERATIONAL COSTS IN HOMESTAY ACCOMMODATION BUSINESSES

The cost components identified through the literature review were further validated through semi-structured interviews with homestay owners. Respondents were asked to rate each cost item on a scale from 0 (not impactful) to 5 (highly impactful) based on their experience in establishing and operating homestay accommodations.

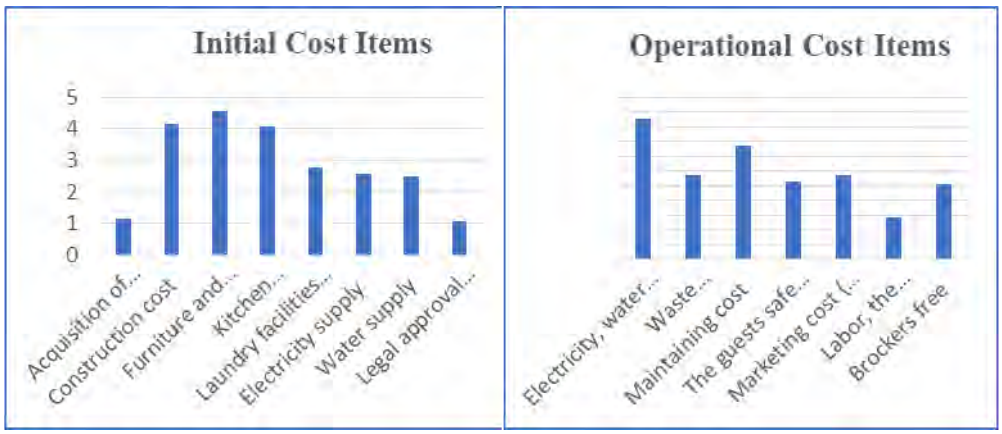



*Figure 1: Initial and operation cost items analysis*

The results were analysed using mean value comparison and are illustrated in the Figure 1. The findings indicate that furniture and kitchen equipment represent the most significant initial investment components, followed closely by construction costs. This suggests that homestay owners prioritise the provision of essential amenities and comfortable living spaces to enhance guest experience. Investment in furniture, room facilities, and kitchen equipment is particularly important in the homestay sector, as these elements directly influence tourists' perceptions of comfort and hospitality within a home-like environment. Other than the respondents also mentioned that, *"construction-related expenses also remain relatively high, reflecting the need for renovations, interior modifications, and the development of facilities such as attached bathrooms to meet basic accommodation standards*."

In contrast, legal approvals and land acquisition were identified as the least impactful initial cost items. This finding reflects the typical operational model of homestays in Sri Lanka, where homeowners utilise existing residential properties rather than acquiring new land or constructing purpose-built accommodation facilities. Additionally, many small-scale homestay operators either face minimal regulatory requirements or incur limited administrative costs during the registration process, which further reduces the

financial burden associated with legal approvals. According to the respondents mentioned that *"We have not registered the accommodation because there is no requirement for us to register it*." This indicates a lack of awareness and understanding regarding the importance of registration and the relevant regulatory requirements.

About operational costs, the analysis reveals that utility expenses, particularly electricity and water bills, constitute the highest recurring costs, followed by maintenance expenses. These findings highlight the ongoing financial commitment required to maintain service quality, ensure facility functionality, and provide essential services for guests. Regular maintenance activities, including repairs, cleaning, and replacement of household equipment, are necessary to sustain acceptable accommodation standards and maintain positive tourist experiences.

Conversely, labour costs were reported as the least significant operational expense. This outcome reflects a distinctive characteristic of homestay businesses, where most operational activities, such as cleaning, guest assistance, and meal preparation, are typically managed by the homeowners themselves or by family members.

## 5. ANALYSIS OF DEMANDING FACTORS IN HOME-STAY ACCOMMODATION

The demand-related factors identified through the literature review were further validated through the interview responses and ranked using mean value comparison. Respondents evaluated each factor on a scale from 0 (not impactful) to 5 (highly impactful) based on their experience hosting tourists. The results are presented in Figure 2.

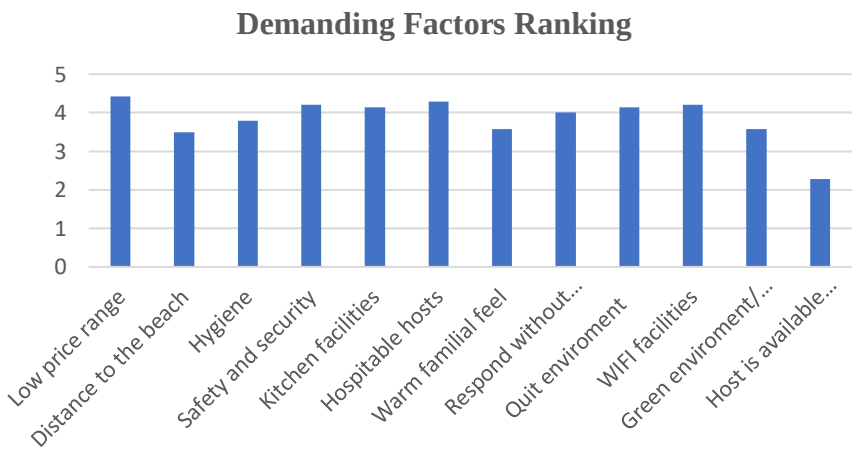



*Figure 2: Demanding factors ranking*

The analysis indicates that low price range, safety and security, hospitable hosts, and the availability of Wi-Fi facilities are among the most influential factors shaping tourist preferences for homestay accommodations. Furthermore, respondents are suggesting that, "tourists selecting homestays generally seek affordable accommodation combined with a safe environment and welcoming hospitality. The presence of friendly hosts and reliable communication facilities further enhances the overall visitor experience and satisfaction. In addition, factors related to the quality of the surrounding environment, such as a quiet environment and green or natural surroundings, were rated relatively

high. This highlights that many tourists prefer homestays located in peaceful settings that provide closer interaction with nature, which is often a distinctive attraction of coastal destinations.

Conversely, factors such as host availability received comparatively lower ratings. Respondents added that, "*while interaction with hosts is appreciated, tourists may value a certain level of independence and privacy during their stay*". Overall, the findings emphasise that affordability, safety, hospitality, and a pleasant natural environment play a crucial role in shaping tourist demand for homestay accommodations. These aspects should therefore receive greater attention when planning and managing homestay businesses in coastal regions.

*Figure 3: Significant cost and demand factors*

The figure 3 illustrates the significant cost and demand factors.

### 5.1 SOCIAL, ENVIRONMENTAL, AND CULTURAL CONSTRAINTS

The latter part of the interviews focused on identifying the social, cultural, environmental, and regulatory constraints associated with homestay development within the Sri Lankan context. Respondents highlighted that, "*several social and cultural challenges have emerged alongside the expansion of homestay businesses. In particular, concerns were raised regarding the involvement of children in tourism-related activities, as this may negatively affect their educational progress and long-term personal development*".

Interview findings also revealed that many homeowners initiate homestay ventures by following prevailing tourism trends, often without adequate language skills or prior operational experience. This lack of preparedness can result in inconsistencies in service quality and may contribute to trust-related concerns among tourists. In several instances, respondents reported that, *"tourists who had made prior reservations decided not to stay upon arrival due to unmet expectations and inadequate facilities"*. Overall, these issues highlight important gaps in service delivery, management capacity, and regulatory awareness.

## 6. DISCUSSION

The findings emphasise the need for improved guidance, training, and institutional support to ensure the sustainable development of homestay accommodations in Sri Lanka. Accordingly, it is important to develop appropriate strategies and raise awareness among homestay owners to help minimise initial and operational costs while maintaining satisfactory service standards for tourists. The literature review identified several strategies that could help overcome existing constraints, and some practical approaches suggested by respondents were also considered during the interviews. For

example, many owners have already adopted energy-efficient practices, such as the use of LED lighting and energy-saving appliances. Research also indicates that effective energy management practices, including smart HVAC systems and renewable energy integration, can reduce energy consumption by approximately 10–20% (Menegaki, 2025). Therefore, authorities and relevant institutions should actively disseminate knowledge on cost-effective construction methods and energy-efficient technologies to help reduce both initial and operational costs.

In terms of socio-cultural aspects, respondents emphasised the importance of awareness and educational guidance, particularly for children involved in tourism-related activities. With proper communication and guidance, cultural barriers and social concerns can be addressed more effectively (Jiang & Zhang, 2024). Accordingly, training programmes and capacity-building initiatives for homestay owners could improve service quality, management practices, and communication with tourists. Overall, relevant authorities and institutions have a crucial role in supporting homestay development in Sri Lanka's coastal regions. Through appropriate strategies, training initiatives, and regulatory guidance, homestay investments can be optimised while promoting sustainable and responsible tourism practices.

## 7. CONCLUSIONS

This study identified key factors influencing the development of homestay accommodations in the coastal regions of Sri Lanka, with reference to the southern coastal area. The analysis focused on cost factors, demand determinants, and the social, cultural, and environmental challenges associated with establishing and operating homestays. The findings indicate that these factors play a significant role in shaping the development and investment viability of homestay businesses. Although the level of influence may vary across different social, cultural, and geographical contexts, the study recommends that collaboration between business owners and relevant authorities can address these existing challenges. The development of appropriate strategies, regulatory support, and awareness programmes is therefore important to promote better investment decisions, maintain service quality in homestay accommodations, and support sustainable growth in the sector.

## 8. REFERENCES

Adhikari, B. B. (2020). Steps taken for development of home stay tourism in Nepal. *NUTA Journal*, *7*(1–2), 18–30. https://doi.org/10.3126/nutaj.v7i1-2.39928

Aldubyan, M., & Krarti, M. (2022). Impact of stay home living on energy demand of residential buildings: Saudi Arabian case study. *Energy*, *238*, 121637. https://doi.org/10.1016/j.energy.2021.121637

Amalia, F. R., & Febrian, A. W. (2022). Comparative analysis of activity-based costing and traditional methods in determining basic room rates in Didu's Homestay Banyuwangi. *International Journal of Applied Business*, *6*(1), 52-66. https://doi.org/10.20473/tijab.v6.I1.2022.33238

Arbelo, A., Pérez-Gómez, P., & Arbelo-Pérez, M. (2017). Cost efficiency and its determinants in the hotel industry. *Tourism Economics*, *23*(5), 1056–1068. https://doi.org/10.1177/1354816616656419

Au-Yong, C. P., Chua, S. J. L., Ali, A. S., & Tucker, M. (2019). Optimising maintenance cost by prioritising maintenance of facilities services in residential buildings. *Engineering, Construction and Architectural Management*, *26*(8), 1593–1607. https://doi.org/10.1108/ECAM-07-2018-0265

Bandusena, P., Dissanayaka, N., & Silva, D. A. C. S. (2023). Tourism impacts on socio-economic development of residential community in Ella destination, Sri Lanka. *CINEC Academic Journal*, *6*(1), 36–45. https://doi.org/10.4038/caj.v6i1.117

Chen, Y. (2023). *Enhancing homestay tourism in Thailand: Insights from young Chinese tourists.* Chulalongkorn University. https://doi.org/10.58837/CHULA.IS.2023.218

Chiu, W. H., Lai, Y. T., & Chi, H. R. (2017). *Service innovation in the lodging industry: A perspective of customer value.* International Conference on Service Systems and Service Management, Dalian, China. https://doi.org/10.1109/ICSSSM.2017.7996226

Daniels, S. (1994). The hot desk shuffle. *International Journal of Productivity and Performance Management*, *43*(7), 7-7. https://doi.org/10.1108/EUM0000000004008

Dash, S. P. (2022). Exploring the prospects of homestays in Indian tourism and hospitality industry as an alternate preference for stay. *International Journal of Built Environment and Sustainability*, *9*(3), 1–10. https://doi.org/10.11113/ijbes.v9.n3.935

Dharmasena, M. D. M., Dharmaratne, D., Lankeshwari, S., & Siriwardena, S. (2023). Economic and environmental impact of tourism on coastal areas based on Mirissa. *Journal of Tourism & Hospitality*, *12*(4), 1-9. https://www.researchgate.net/profile/Damsi-Dharmaratne/publication/381482300_Economic_and_Environmental_Impact_of_Tourism_on_Coastal_Areas_Based_on_Mirissa/links/667071faa54c5f0b94691978/Economic-and-Environmental-Impact-of-Tourism-on-Coastal-Areas-Based-on-Mirissa.pdf

Dias, M. A. J. R., Mubarak, K. M., & Ali, M. I. (2022). An analysis on successfulness of homestay operation in cultural heritage destinations in Sri Lanka. *Journal of Tourism Economics and Applied Research.* *6*(1), 39 – 52. https://jtear.uoctourism.com/publication/2022volume6/issue1/An_Analysis_on_Successfulness_of_Homestay_Operation_in_Cultural.pdf

Gautam, B. (2024). A review on benefits of homestay tourism in Nepal. *Kalika Journal of Multidisciplinary Studies*, *6*(1), 132–144. https://doi.org/10.3126/kjms.v6i1.72374

Gössling, S., & Lund-Durlacher, D. (2021). Tourist accommodation, climate change and mitigation: An assessment for Austria. *Journal of Outdoor Recreation and Tourism*, *34*, 100367. https://doi.org/10.1016/j.jort.2021.100367

Gulati, S. (2024). Exploring the generational influence on social media-based tourist decision-making in India. *Information Discovery and Delivery*, *52*(2), 185-196. https://doi.org/10.1108/IDD-11-2022-0115

Hamilton, J. M. (2007). Coastal landscape and the hedonic price of accommodation. *Ecological Economics*, *62*(3–4), 594–602. https://doi.org/10.1016/j.ecolecon.2006.08.001

Idahosa, L. O., & Ebhuoma, E. E. (2020). Limitations to sustainable resource management in the global South: Evidence from the accommodation industry. *Tourism and hospitality management*, *26*(2), 337–358. https://doi.org/10.20867/thm.26.2.4

Ihsan, B., & Alshibani, A. (2018). Factors affecting operation and maintenance cost of hotels. *Property Management*, *36*(3), 296-313. https://doi.org/10.1108/PM-04-2017-0023

Ishtiaq, M. (2019). Book review Creswell, J. W (2014). Research design: Qualitative, quantitative and mixed methods approach. Thousand Oaks, CA: Sage. *English Language Teaching*, *12*(5), 40. https://doi.org/10.5539/elt.v12n5p40

Janjua, Z. U. A., Krishnapillai, G., & Rahman, M. (2021). A Systematic literature review of rural homestays and sustainability in tourism. *Sage Open*, *11*(2), https://doi.org/10.1177/21582440211007117

Jiang, R., & Zhang, X. (2024). Cross-cultural communication and conflict resolution in tourism. *Journal of Social Science Humanities and Literature*, *7*(4), 6-10. https://doi.org/10.53469/jsshl.2024.07(04).02

Kartal, C., Yucel, R., & Yucel, Ş. (2025). Home sharing model in tourism management in the context of marketing and sustainability. *ULUSLARARASI AKADEMİK BİRİKİM DERGİSİ*, *8*(4). https://akademikbirikimdergisi.com/index.php/uabd/article/download/376/421

Khan, N., Hassan, A. U., Fahad, S., & Naushad, M. (2020). Factors affecting tourism industry and its impacts on global economy of the world. *SSRN Electronic Journal*, https://doi.org/10.2139/ssrn.3559353

Khan, M. M., & Su, K. D. (2010). Service quality expectations of travellers visiting Cheju Island in Korea. *Journal of Ecotourism*, 1(2), 114-125. https://doi.org/10.1080/14724040308668138

Kunjuraman, V., & Hussin, R. (2017). Challenges of community-based homestay programme in Sabah, Malaysia: Hopeful or hopeless? *Tourism Management Perspectives*, *21*, 1–9. https://doi.org/10.1016/j.tmp.2016.10.007

Lamis, N. A., Yuliana, Y., & Ferdian, F. (2022). Analysis of homestay lodging promotion in Maninjau village. JELAJAH: *Journal of Tourism and Hospitality*, *4*(1), 20-27. https://doi.org/10.33830/jelajah.v4i1.3726

Luekveerawattana, R. (2024). Key factors facilitating homestay success: A focus on cultural and natural values. *Cogent Social Sciences*, *10*(1), 2341479. https://doi.org/10.1080/23311886.2024.2341479

Magno, F., Cassia, F., & Ugolini, M. M. (2018). Accommodation prices on Airbnb: Effects of host experience and market demand. *The TQM Journal*, *30*(5), 608–620. https://doi.org/10.1108/TQM-12-2017-0164

Mendoza-González, G., Martínez, M. L., Guevara, R., Pérez-Maqueo, O., Garza-Lagler, M. C., & Howard, A. (2018). Towards a sustainable sun, sea, and sand tourism: The value of ocean view and proximity to the coast. *Sustainability*, *10*(4), 1012. https://doi.org/10.3390/su10041012

Menegaki, A. N. (2025). Powering down hospitality through a policy-driven, case-based and scenario approach. *Energies*, *18*(2), 328. https://doi.org/10.3390/en18020328

Ministry of Foreign Affairs, Foreign Employment and Tourism. (2023). Ministry of tourism. https://tourismmin.gov.lk/web/index.php/en/about-us/overview-of-the-ministry

Ndaguba, E. A., & Van Zyl, C. (2024). Data-driven approach to optimizing property management strategies: Spatial modeling analytics of short-term rentals. *International Journal of Housing Markets and Analysis*, *17*(7), 44–75. https://doi.org/10.1108/IJHMA-08-2024-0117

Pasanchay, K., & Schott, C. (2021). Community-based tourism homestays' capacity to advance the sustainable development goals: A holistic sustainable livelihood perspective. *Tourism Management Perspectives*, *37*, 100784. https://doi.org/10.1016/j.tmp.2020.100784

Patwal, A. S., Rana, V., & Pathak, V. K. (2023). Predictors influencing the choice of lodging option: A systematic literature review of homestays. *Journal of Tourism and Services*, *14*(26), 263-284. https://doi.org/10.29036/jots.v14i26.536

Pawlicz, A., & Napierala, T. (2017). The determinants of hotel room rates: An analysis of the hotel industry in Warsaw, Poland. *International Journal of Contemporary Hospitality Management*, *29*(1), 571–588. https://doi.org/10.1108/IJCHM-12-2015-0694

Perez-Sanchez, V. R., Serrano-Estrada, L., Marti, P., & Mora-Garcia, R. T. (2018). The what, where, and why of Airbnb price determinants. *Sustainability*, *10*(12), 4596. https://doi.org/10.3390/su10124596

Petruzzi, M. A., Marques, C., & Campos, A. C. (2023). Socio-cultural impacts of peer-to-peer accommodation on host communities. *International Journal of Tourism Research*, *25*(1), 123–136. https://doi.org/10.1002/jtr.2555

Pina, I. P. A., & Delfa, M. T. D. (2005). Rural tourism demand by type of accommodation. *Tourism Management*, *26*(6), 951–959. https://doi.org/10.1016/j.tourman.2004.06.013

Qiao, H. H., Wang, C. H., Chen, M. H., Su, C. H. J., Tsai, C. H. K., & Liu, J. (2021). Hedonic price analysis for high-end rural homestay room rates. *Journal of Hospitality and Tourism Management*, *49*, 1-11. https://doi.org/10.1016/j.jhtm.2021.08.008

Sánchez-Franco, M. J., & Rey-Moreno, M. (2022). Do travelers' reviews depend on the destination? An analysis in coastal and urban peer-to-peer lodgings. *Psychology & Marketing*, *39*(2), 441–459. https://doi.org/10.1002/mar.21608

Sedai, R. C. (2011). Tourist accommodation facilities in the major tourist areas of Nepal. *Nepal Tourism and Development Review*, *1*(1), 102-123. https://doi.org/10.3126/ntdr.v1i1.7374

Singh, A. (2021). Basic steps of doing research. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3925363

Sri Lanka Tourism Development Authority. (2024). *Registration/Renewal guidelines*. https://www.sltda.gov.lk/en/download-2

Ernawati, N. M., Arjana, I. W. B., & Sitawati, A. A. R. (2019). Tourist accomodation: A host-tourist matched for Batur geotourism. *Journal of Indonesian Tourism and Development Studies, 7*(2), 74-82. https://doi.org/10.21776/ub.jitode.2019.07.02.03

Thapa, B., & Malini, H. (2017). Guest reasons for choosing homestay accommodation: An overview of recent researches. *Asia Pacific Journal of Research, 1*(4), 169-175. https://www.researchgate.net/profile/Bimal-Thapa/publication/360101981_GUEST_REASONS_FOR_CHOOSING_HOMESTAY_ACCOMMODATION_AN_OVERVIEW_OF_RECENT_RESEARCHES/links/62624a6fbca601538b5df7dc/GUEST-REASONS-FOR-CHOOSING-HOMESTAY-ACCOMMODATION-AN-OVERVIEW-OF-RECENT-RESEARCHES.pdf

Wijesundara, N. (2022) Hidden motives of hoteliers to incorporate with sustainable tourism practices: A case study of down-south of Sri Lanka. *International Journal of Tourism & Hospitality Reviews, 9*(2), 01–05. https://doi.org/10.18510/ijthr.2022.921

Gamalath, K. A. I. L. (2021). Beautiful, natural places and tourist attractions in Sri Lanka. *The Institute of Biopaleogeography named under Charles R. Darwin, 3,* 1-44. https://psjd.icm.edu.pl/psjd/element/bwmeta1.element.psjd-15a82bae-f611-4656-86c1-89a4c4bb4326/c/IBPG_3__2021__1-44.pdf

Xiao, K. (2023). Research on cost management and control in China's budget hotels. *Tourism Management and Technology Economy, 6*(4), 60-67. https://doi.org/10.23977/tmte.2023.060410

Yu, M., Cheng, M., Yu, Z., Tan, J., & Li, Z. (2022). Investigating Airbnb listings' amenities relative to hotels. *Current Issues in Tourism, 25*(19), 3168-3185. https://doi.org/10.1080/13683500.2020.1733497

Jayalath, J.A.C.D. and Kulatunga, U., 2026. Optimising community participation in post-disaster crisis response: Evidence from the "Ditwah" cyclone, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1278-1291. DOI: https://doi.org/10.31705/WCS.2026.93. Available from: https://ciobwcs.com/papers/

# OPTIMISING COMMUNITY PARTICIPATION IN POST-DISASTER CRISIS RESPONSE: EVIDENCE FROM THE "DITWAH" CYCLONE, SRI LANKA

**J.A.C.D. Jayalath[1], and U. Kulatunga[2]**

## *ABSTRACT*

*Community participation is an important component of effective disaster response and recovery. However, understanding the behavioural drivers that motivate individuals to participate in community-based disaster response, as well as the challenges and constraints influencing such participation, remains limited, particularly in developing country contexts. This study addresses this gap by examining community participation that emerged following the 2025 Cyclone Ditwah in Sri Lanka by methodologically applying the theory of Planned Behaviour for understanding community participation in post-disaster recovery in developing-country settings. The research adopts a single embedded case study approach. Data were collected through document review and five semi-structured interviews with key initiators and volunteers involved in two major initiatives: a community kitchen programme and a digital rescue coordination platform. Findings were manually analysed and reveal that social, cultural, emotional, and contextual drivers strongly motivate community participation. Digital platforms also played a critical role in enabling rapid coordination and information sharing during the crisis. However, challenges such as resource constraints, misinformation, and operational difficulties in managing volunteer networks must be addressed to optimize community Participation in future disaster response initiatives.*

***Keywords:*** *Behavioural Drivers; Community Participation; Ditwah Cyclone; post-disaster; Theory of Planned Behaviour.*

## 1. INTRODUCTION

Disasters can cause immediate and long-term impacts on physical and emotional well-being, as well as indirect effects such as evacuation, social disruption, financial loss, lifestyle changes, damage to healthcare facilities, and shifts in social and socioeconomic conditions (Azhar *et al*., 2022). To accelerate recovery and implement large-scale emergency responses to disasters, governments collaborate with state authorities, international relief agencies, and nongovernmental organisations. However, post-disaster recovery processes often fall short due to inefficiencies and poor management (Ngulube, 2024). Disasters often stimulate strong social responses, including reciprocal support among individuals and communities (Dinger et al., 2020), inspired volunteerism and

[1] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, charukaj@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

collective assistance among affected populations (Danasekara, 2025). In such contexts, individuals who feel capable of contributing and expressing their abilities are more likely to assist others (Xu *et al.,* 2024*)*. Such behaviour plays a crucial role in shaping how individuals and communities respond to extreme adversity (Bansidhar, 2025; Stanculescu & Petruta, 2025). Although community participation, including local skills, experiences, ideas, and values, has become a critical foundation for successful recovery and livelihood restoration in the post-disaster phase (Kaklauskas *et al*., 2009), its potential is still underutilised. In this context, global studies highlight that community participation can significantly improve the effectiveness of disaster recovery and relocation processes (Ngulube, 2024).

Unlike in many Western countries, behavioural theories and models are still limitedly applied in disaster preparedness and emergency management in developing countries (Azhar *et al*., 2022). Consequently, knowledge about the factors influencing emotional and behavioural responses to emergencies remains limited (Gu *et al.*, 2021). To address this gap, the present study applies the Theory of Planned Behaviour (TPB) to examine community participation in post-disaster crisis response within the Sri Lankan context. The study identifies context-specific behavioural dimensions influencing participation and demonstrates the methodological applicability of TPB for understanding community participation in post-disaster recovery in developing-country settings. Given the complex interaction of influencing factors and their varying importance, effective post-disaster management strategies that incorporate community participation must be tailored to specific local conditions and contexts (Kaklauskas *et al*., 2009).

Sri Lanka, a tropical island with diverse climatic zones and complex geographical features, is highly vulnerable to various natural disasters (Samaraweera *et al*., 2024). Flood-related damage has occurred almost annually over the past 40 years, ranging from localised flooding to nationwide disasters (World Bank, 2025). Between 2010 and 2025, natural disasters affected 15,586,967 people, displaced 1,497,277 individuals, and caused 1,328 deaths (De Silva *et al*., 2026). Most recently, the country experienced one of the most catastrophic disasters in its recent history, the "Ditwah" cyclone (Ditwah Disaster Relief Platform, 2026). As in many other countries, the government faced significant challenges managing post-disaster recovery independently and therefore relied on support from multiple sectors, including international relief agencies and nongovernmental organisations (Senanayke & Amaratunga, 2026). ). Despite persistent gaps in areas such as food security, health and safety, water and sanitation, and shelter coordination (Disaster Management Centre, 2025), community participation and public generosity have played a crucial role in supporting recovery efforts (Senanayke & Amaratunga, 2026). .

The effectiveness of such participation largely depends on the community's capability to respond to disasters (Nian *et al*., 2019). Various contextual, cultural, social, emotional, and behavioural drivers influence the development of community behaviours and consequently strengthen community participation in post-disaster crisis response (Al-Dahash *et al*., 2022; Nian *et al*., 2019; Staub & Vollhardt, 2008; (Xu *et al.,* 2024*)*. Therefore, identifying these key drivers and understanding their roles in shaping post-disaster human behaviour is essential for maximizing the benefits of community participation in recovery efforts.

However, policymakers often overlook community involvement in post-disaster planning, which can lead to ineffective recovery and reconstruction processes (Ngulube, 2024). Accordingly, this study contributes to the disaster management literature by applying TPB within post-disaster crisis response and providing empirical evidence on the behavioural drivers that shape community participation in Sri Lanka. Therefore, this paper aims to systematically examine the key drivers that strengthen community participation in post-disaster crisis response, as well as the challenges and constraints faced by communities during their involvement, to optimise community participation in post-disaster response within the Sri Lankan context. The paper first examines factors influencing community participation in post-disaster response and ways to enhance participation. It then outlines the case study, presents and analyses primary data, and concludes with key insights and future directions.

# 2. LITERATURE REVIEW

## 2.1 FACTORS AND DRIVERS AFFECTING COMMUNITY PARTICIPATION IN POST-DISASTER RECOVERY

The critical role of human behaviour in designing and implementing effective emergency response actions been widely recognised (Al-Dahash et al., 2022). Several behavioural theories have been developed to explain human decision-making, including the Theory of Reasoned Action (TRA), Value-Belief-Norm (VBN) theory, and the Theory of Planned Behaviour (TPB) (Fishbein & Ajzen, 1975; Stern et al., 1999). The VBN theory effectively explains environmentally motivated actions; however, it provides limited insight into intention–behaviour relationships in contexts that require consideration of both psychological and infrastructural factors. The Theory of Reasoned Action (TRA) explains that behavioural intention is shaped by attitudes and subjective norms (Fishbein & Ajzen, 1975). However, it assumes complete volitional control, limiting its applicability to the real world where individuals face structural and situational constraints. To address this, Ajzen (1991) extended the TRA into the Theory of Planned Behaviour (TPB) by incorporating perceived behavioural control, enabling consideration of both internal and external influences on behaviour. Among these, TPB provides a comprehensive framework for analysing community behaviour in crisis response by integrating cognitive, social, and situational determinants of behaviour (Al-Dahash *et al*., 2022).

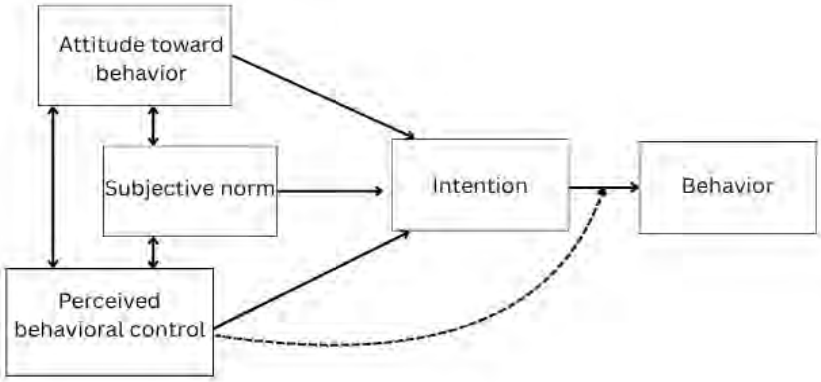



*Figure 1: Theory of planned behavior*

According to TPB, behavioural intention is shaped by three key variables: attitude toward the behaviour, subjective norm, and perceived behavioural control (Yuriev et al., 2020). Therefore, promoting community participation in post-disaster crisis response requires understanding these behavioural drivers and how they interact within the TPB framework.

### 2.1.1 Attitude Toward the Behavior

Within the TPB, attitudes toward behaviour refer to individuals' positive or negative evaluations of engaging in a particular action. In the context of post-disaster situations, attitudes shaped by personal values, emotions, beliefs, and psychological experiences significantly influence the willingness of individuals to participate in community-based crisis response (Bansidhar, 2025). Personality-related factors such as attitudes, wishes, desires, and knowledge about hazards have been identified as important determinants affecting behavioural responses during disasters (Al-Dahash *et al*., 2022).

Psychological motivations play a key role in fostering community participation. Helping others who experience similar suffering can reduce survivor's guilt while providing individuals with a renewed sense of meaning in life (Staub & Vollhardt, 2008). This empathy-driven helping encourages active support for affected communities. Likewise, religious beliefs and spiritual values shape positive attitudes toward helping behaviour (Al-Dahash *et al*., 2022). In many cultural contexts, religious and philosophical traditions emphasize compassion, charity, and moral duty. For instance, in India, prosocial behaviour (voluntary actions intended to benefit others) is deeply embedded in principles such as *seva* (selfless service), *dharma* (righteous duty), and *karma* (moral causality), which promote compassion and service to others (Bansidhar, 2025). Natural disasters can strengthen spiritual engagement, leading individuals to participate in prayer or other spiritual activities that reinforce moral responsibility toward community support (Azhar *et al*., 2022).

Prosocial behaviour during disasters is influenced by several psychological and situational drivers, including empathy, altruism, moral obligation, personal values, beliefs, mood, and emotions (Bansidhar, 2025; Dewangan *et al.*, 2025). Survivors often report sharing food, clothing, and emotional support, with many describing their motivation as altruistic (Staub & Vollhardt, 2008). Additionally, situational factors such as perceived risks and benefits can influence individuals' willingness to help (Bansidhar, 2025). Together, these factors strengthen prosocial tendencies and enhance community participation in post-disaster crisis response.

Experiencing suffering itself can also stimulate helping behaviour. The concept of Altruism Born of Suffering suggests that individuals who endure hardship often reassess life's meaning and become more compassionate, increasing behaviours such as donating money, donating blood, volunteering, and participating in rescue efforts (Xu *et al.*, 2024). Similarly, individuals who experience trauma often develop stronger prosocial attitudes and participate in short-term emergency volunteering (Xu *et al.*, 2024). In resilience literature, altruism and prosocial behaviour are also recognised as characteristics of resilient and socially competent individuals, sometimes contributing to the emergence of community leaders during crises (Charney, 2004). Finally, place attachment and emotional connections to communities further strengthen positive attitudes toward helping behaviour. Anthropological research shows that attachment to place can influence disaster-related behaviour (Al-Dahash *et al*., 2022). Residents who feel emotionally

connected to their community often view themselves as direct stakeholders responsible for protecting community livelihoods during crises (Nian *et al.*, 2019). Community attachment, comprising emotional, cognitive, and behavioural dimensions, therefore, motivates participation in collective actions such as community support, volunteering, and local crisis response (Nian *et al.*, 2019).

### 2.1.2 Subjective Norm

Within the TPB, subjective norms refer to perceived social expectations and pressures that influence individuals' behaviour. In post-disaster contexts, social identity and collective expectations play a crucial role in shaping community participation in crisis response. Following disasters, attributes of social identity such as in-group solidarity and interdependency beliefs encourage collective actions that support recovery efforts (Stanculescu & Petruta, 2025). People react automatically to disaster trauma, which strengthens their sense of belonging to a social group or community (Al-Dahash *et al*., 2022). This trauma response can act as a psychological trigger that promotes collective action through prosocial behaviour.

Social identity is closely associated with shared norms, values, interests, and emotions, which influence individuals' perceptions of risk and their behavioural responses during disasters (Al-Dahash *et al*., 2022). Consequently, social norms and group values become key drivers of community participation in post-disaster crisis response. Similarly, ideologies and worldviews shaped by cultural group membership influence behavioural expectations within communities (Al-Dahash *et al*., 2022), while religious beliefs often function as social norms guiding collective behaviour and moral obligations to help others (Bansidhar, 2025).

Cultural context further strengthens these influences. Behaviour during hazards is often embedded in cultural traditions and social values, rather than determined solely by the level of threat (Kulatunga, 2010). Certain societies inherently promote prosocial behaviour through collectivist orientations, familial and intergenerational bonds, community networks, reciprocity, and social obligations (Bansidhar, 2025). In countries such as India, prosocial behaviour is deeply rooted in cultural norms, religious values, ritual giving, and communal support practices (Bansidhar, 2025). Similarly, family characteristics and family and social expectations act as protective factors that enhance community resilience (Staub & Vollhardt, 2008). During the post-disaster phase, survivors often develop a sense of shared fate, strengthening social cohesion and collective action. This shared experience promotes expected mutual support, coordination of behaviour, and collective efficacy, enabling communities to self-organise during crises (Cvetković, 2023). In addition, post-traumatic growth can strengthen group cohesion, further encouraging collective participation in community-based disaster response (Xu *et al.*, 2024).

### 2.1.3 Perceived Behavioral Control

Within the Theory of Planned Behaviour, perceived behavioural control refers to individuals' perceptions of their capacity, resources, and ability to perform a behaviour. In post-disaster contexts, it reflects the extent to which individuals feel capable of contributing to community-based crisis response and recovery.

Individuals who have experienced disasters and possess relevant capabilities often take proactive roles in recovery processes. Residents with skills and experience may organise

community disaster reconstruction groups, establish community crisis response teams, and promote disaster awareness within communities (Danar & Pushpalal, 2014). These actions highlight the importance of leadership ability and perceived competence in facilitating organised community responses. Similarly, individuals are more likely to assist others when they perceive themselves as strong enough to shift attention beyond personal survival toward helping those in need, reflecting a belief in their ability to help (Staub & Vollhardt, 2008).

Resilience research also identifies personal resilience capacity as a factor that strengthens individuals' confidence and preparedness for disaster response (Staub & Vollhardt, 2008). Prosocial behaviour is further supported by reciprocity, self-efficacy, and empowerment, which enhance individuals' perceived control over their ability to contribute to community recovery (Bansidhar, 2025). Such perceptions of competence and empowerment encourage greater community participation in post-disaster crisis response. Strong communities also provide supportive environments that promote collective action and coping with uncertainty during crises (Grube & Storr 2018). When facing uncertainty, individuals often rely on familiar knowledge and past experiences to address immediate needs, frequently responding automatically without extensive deliberation (Dinger *et al*., 2020). This reliance on existing knowledge and capabilities influences how effectively communities organise and respond to post-disaster challenges. Additionally, post-traumatic growth may strengthen individuals' ability to support others, further enhancing participation in community-based recovery efforts (Xu *et al.*, 2024*)*. . However, several barriers may also limit prosocial behaviour, including concerns for personal safety, lack of resources, restricted access to affected areas, emotional distress, time constraints, and previous negative experiences (Bansidhar, 2025).

In summary, the identified drivers influencing community participation are summarized in Table 1.

*Table 1: Behavioural drivers influencing community participation*

| Variable | Identified behavioral drivers | References |
|---|---|---|
| Attitude toward the behavior | Personal attitudes and motivations; hazard knowledge and awareness; empathy and compassion; altruism and prosocial orientation; religious, ethical, and moral values; emotional responses and perceived personal benefits; place attachment and sense of responsibility. | (Al-Dahash et al., 2022), (Staub & Vollhardt, 2008), (Bansidhar, 2025), (Azhar et al., 2022), (Dewangan et al., 2025), (Staub & Vollhardt, 2008), (Xu *et al.*, 2024*)*, (Charney, 2004), (Nian et al., 2019) |
| Subjective norm | Social identity and group solidarity; socio-cultural, religious, and traditional norms; family and community networks; reciprocity and social obligations; family and social expectations; collective efficacy, behaviour coordination, and group cohesion. | (Stanculescu & Petruta, 2025), (Al-Dahash et al., 2022), (Bansidhar, 2025), (Kulatunga, 2010), (Staub & Vollhardt, 2008), (Cvetković, 2023), (Xu *et al.*, 2024*)* |
| Perceived behavioral control | Previous experience and capability; leadership ability and self-efficacy; resilience and empowerment; ability to manage uncertainty and apply existing knowledge; resource and access | (Danar & Pushpalal, 2014), (Staub & Vollhardt, 2008), (Bansidhar, 2025), (Grube & Storr, 2018), (Dinger et al., |

| Variable | Identified behavioral drivers | References |
|---|---|---|
| | constraints; emotional and time-related constraints. | 2020), (Xu *et al.*, 2024) , (Bansidhar, 2025) |

When examining these factors, it becomes evident that they are shaped by surrounding environmental, social, cultural, and economic contexts. As these conditions vary across regions and local settings, understanding the key drivers, their potential utilisation, and the main challenges and constraints within the local context is essential for optimising community participation in post-disaster crisis response.

# 3. RESEARCH METHODOLOGY

This research followed a systematic sequence of stages; each aligned with specific objectives. The process began with an extensive literature review to establish a theoretical foundation and develop a comprehensive understanding of the key behavioural drivers shaping community participation in post-disaster crisis response, as well as the challenges and constraints associated with implementing such participation. The second phase employed a case study approach to explore the key behavioural drivers (Yin, 2018), contributing to successful community participation in post-disaster response within the Sri Lankan context. Simultaneously, the study examined the main challenges and constraints related to implementing community participation initiatives during post-disaster recovery.

This study adopted an exploratory qualitative research design to enable an in-depth understanding of behavioural dynamics in a real-world post-disaster context. Accordingly, a single embedded case study design was adopted to investigate community-driven disaster response initiatives that emerged following Cyclone Ditwah in Sri Lanka. This approach enables an in-depth examination of behavioural drivers influencing community participation in a real-world context. The community kitchen initiative and the online rescue coordination platform were treated as embedded units within the broader case, enabling comparative insights while maintaining the contextual integrity of the post-disaster response environment. Primary data were collected through interviews with initiators and key role players, along with document review within the case study framework.

A purposive sampling technique was employed to select interview participants based on their direct involvement in post-disaster response activities and their ability to provide rich, experience-based insights relevant to the study objectives. In total, five key informants were selected, including initiators and active coordinators of the identified community-driven initiatives. The sample size is considered appropriate for this exploratory qualitative case study, where depth of insight and contextual understanding are prioritised over statistical generalisation. Data collection was guided by the principle of information richness rather than numerical representation, consistent with qualitative case study research practice (Yin, 2018).

The collected qualitative data were analysed using manual content analysis. Manual content analysis was selected due to the exploratory nature of the study and the relatively small dataset, allowing for an in-depth interpretation of contextual meanings and participant experiences while ensuring alignment with the study objectives.

Finally, the discussion section examines strategies to improve the effectiveness and efficiency of community participation in future disaster response initiatives.

# 4. DATA COLLECTION

## 4.1 CASE STUDY BACKGROUND: "DITWAH" CYCLONE

On 27th November 2025, Cyclone "Ditwah" triggered the most extensive flooding and landslide damage experienced in Sri Lanka in the past two decades, affecting approximately 2.3 million people across all 25 districts of the country (Disaster Management Centre, 2025). The total damage was estimated at US$4.1 billion, equivalent to around 4 percent of the country's 2024 GDP (World Bank, 2025). According to the Office of the Resident Coordinator (Disaster Management Centre, 2025), the Disaster Management Center reported that, as of 29 December 2025, the cyclone had resulted in 646 fatalities, with 173 people still missing. In addition, local authorities indicated that hundreds of houses were destroyed, key transport corridors were disrupted, and several thousand more became unsafe due to structural damage or landslide risks (International Organization for Migration, 2026).

Under these circumstances, government agencies faced significant challenges in managing post-disaster recovery independently. Consequently, community participation emerged as a critical support mechanism in responding to the crisis.

## 4.2 STAGE I: FINDINGS FROM DOCUMENT REVIEW

In response to the November 2025 Cyclone Ditwah floods in Sri Lanka, community kitchens and volunteer-driven initiatives were rapidly established to provide hot meals to thousands of displaced families, particularly in severely affected areas (Danasekara, 2025). What emerged during these early days was not a planned national programme, but rather a spontaneous movement of ordinary citizens responding to the urgent needs of others (Mohamed, 2025). Such grassroots initiatives illustrate how community members can quickly mobilise support through social obligations, compassion, and a sense of collective responsibility.

One notable example was the Wijerama Community Kitchen, which distributed more than one hundred thousand meals within a week and delivered dry food, clothing, and basic medicines to over 75 locations across the island (Sunday Observer, 2025). The initiative was organised into three main sections, including the preparation and distribution of cooked meals, receiving, managing, and distributing donated items, and handling records (Sunday Observer, 2025). These practices reflect the emergence of self-organized coordination, collective efficacy, and the effective use of local capabilities within community-driven disaster response.

Individual participation within the initiative reflected deeper emotional and social motivations. For instance, a volunteer who had lost family members in a landslide continued to work in the kitchen to support affected communities. Notably, assistance was provided without regard to colour, religion, ethnicity, or language, highlighting the strong sense of collective responsibility and social solidarity that emerged during the crisis. Similarly, many beneficiaries remained unaware of the identities of those preparing or sending the aid they received (Sunday Observer, 2025). This illustrates a quiet form of mutual trust and solidarity that often develops during disasters. In situations of extreme

uncertainty, such actions demonstrate how empathy, a sense of shared fate, social identity, compassion, and collective action can guide community responses and strengthen social cohesion.

In addition, there was a need for development communications following a natural disaster, and digital platforms have proven to be very useful for development communications following natural disasters like cyclones (Kapucu, 2012). After Ditwah Cyclone, digital platforms, including social media tools, assisted in shifting communication and developing early warning systems (Lokumannage, 2025). According to Lokumannage (2025), digital and social media platforms run after the ditwah cyclone focused on raising awareness, encouraging donations and volunteerism. The government agencies, disaster management bodies, non-governmental agencies, as well as social agencies, can be utilised these platforms to coordinate the rebuilding programs, as well as share the verified information (World Health Organization, 2020). They enhanced fund raising initiatives aimed at rebuilding houses and livelihoods (Lokumannage, 2025).

However, the document review also highlights certain challenges associated with community-led relief distribution, where disputes occurred among adults over donated goods (Mohamed, 2025). issues such as digital divides, disinformation, unverified information that may hamper the efforts and imbalances in access to technology mitigated the impact of the digital platform campaign, especially in the rural areas (Lokumannage, 2025). These situations illustrate the complex behavioural dynamics that may arise during disaster contexts and highlight the importance of managing resources, expectations, and coordination effectively within community-based response initiatives.

## 4.3 STAGE II: FINDINGS FROM INTERVIEWS WITH INITIATORS AND KEY ROLE PLAYERS

In this stage, five respondents were interviewed to understand the implementation process, community support, and challenges encountered in coordinating the community kitchen and online rescue operations. Three respondents (R1–R3) were key contributors to the Wijerama community kitchen, while two respondents (R4–R5) were Sri Lankan technology entrepreneurs who developed the digital platform *floodsupport.org* to support rescue coordination and relief efforts. Reflecting on the motivation behind the initiative, R1 stated, *"Disasters are not unfamiliar to us, yet the empathy and compassion within our communities often surpass the destruction they cause."* This perspective reflects how prior disaster experiences can strengthen empathy and a sense of personal responsibility to support affected communities.

Several respondents emphasised the emotional and moral motivations behind their participation. R2 explained that *"In the end, the satisfaction of helping others and saving lives makes the fatigue fade away."* Similarly, R3 noted that volunteers contributed in different ways, stating that *"Some volunteers joined after work, others took turns, and some even took leave to contribute."* These responses demonstrate that participation was not driven by external incentives but by intrinsic motivational factors such as moral satisfaction and emotional reward. This suggests that in post-disaster contexts, attitude toward behaviour operates as an affective-moral construct rather than a purely rational cost–benefit evaluation. R2 further observed that people from different ethnic and religious backgrounds worked together without expecting recognition, highlighting how solidarity, a sense of shared fate, and shared humanitarian values can encourage cooperative behaviour during crises. This indicates that subjective norms in this context

were not limited to perceived social pressure, yet were embedded in collective identity and intergroup solidarity, where normative influence operates through shared humanitarian consciousness.

In some cases, individuals even redirected personal resources to support affected families. For instance, some parents reportedly used money originally planned for Christmas celebrations to purchase clothes for children affected by the disaster. These actions illustrate how personal attitudes, moral values, and social responsibility can influence community participation in disaster response. This behaviour reflects the transformation of normative beliefs into direct behavioural action under crisis conditions, where moral obligation overrides planned resource allocation. Additionally, one participant described their involvement as similar to conducting a **"***dansal,"* indicating how religious traditions, beliefs, and cultural practices can also shape motivations for helping behaviour. This highlights the integration of cultural-religious norms into behavioural drivers, suggesting that subjective norms in the Sri Lankan context are strongly mediated by religiously grounded moral frameworks, which function as behavioural reinforcement mechanisms.

Beyond the kitchen operations, online platforms enabled wider coordination by allowing citizens to share updated information on damaged infrastructure, identify relief camps, and communicate urgent needs. Such digital exchanges helped volunteers coordinate donations, identify priority locations, and respond more efficiently to emerging needs. This demonstrates that perceived behavioural control was not only an individual-level perception but was significantly enhanced through digital infrastructure, which functioned as an enabling system that expanded individuals' capacity to act.

R4, a key initiator, explained that at the operational level, requests submitted through the platform were verified by volunteers who contacted affected individuals to confirm their situation and identify the most urgent cases. However, R4 noted that the number of requests increased rapidly, creating operational challenges and requiring the recruitment of additional volunteers through online networks. According to R5, who played a key role in volunteer coordination, the rapid onboarding of new volunteers initially created difficulties because many were unfamiliar with the verification process and digital system. To address this challenge, organizers introduced hourly online training sessions and standardised communication scripts to ensure consistent interactions with affected individuals. This suggests that behavioural effectiveness in disaster response depends not only on willingness but also on procedural knowledge and operational literacy, expanding perceived behavioural control to include skill-based and institutional learning dimensions.

Another major challenge highlighted by R4 was prioritising rescue requests, as available rescue resources were limited, and not all cases could be addressed immediately. Volunteers were required to assess the urgency of requests and prioritise vulnerable groups such as pregnant women, elderly individuals, sick patients, and children. This highlights a critical constraint where resource scarcity introduces ethical decision-making pressures that influence behavioural execution. According to R5, the nature of this work also created emotional pressure for volunteers, who frequently handled distress calls from individuals seeking urgent help. Despite these challenges, confirmation messages indicating successful rescues played an important role in maintaining motivation and morale among volunteers.

## 5. DISCUSSION

Community disaster resilience and response have become important social priorities attracting increasing attention from researchers and policymakers across multiple sectors (Jehoshaphat & Oghenah, 2021). The Cyclone Ditwah case study illustrates how community participation, supported by both social networks and digital platforms, can significantly strengthen post-disaster response efforts. Understanding the psychological drivers that motivate individuals to assist others during disasters is essential for designing interventions that effectively mobilise local communities and ensure culturally appropriate and sustainable outcomes (Bansidhar, 2025). However, the evidence from this study suggests that these drivers are not purely psychological yet are structurally embedded within social, cultural, and technological systems. However, the findings reveal complex behavioural dynamics within community-led initiatives, including opportunistic behaviours and perceived behavioural control factors that may hinder the effectiveness of collective action. While positive behavioural drivers such as attitudes and subjective norms strongly encouraged participation in the Sri Lankan context, several challenges emerged, including limited resources, lack of experience or knowledge, restricted access to affected areas, volunteer fatigue, time constraints, and uncertainty during emergencies. These constraints demonstrate that perceived behavioural control is a key structurally sensitive TPB component in disaster contexts, acting as the primary mediator between intention and actual participation. Figure 2 illustrates the key behavioural drivers identified in Table 1 and their alignment with major post-disaster activities observed in this case study, while highlighting the associated constraints, challenges, and behavioural control factors that should be considered in strategy development.

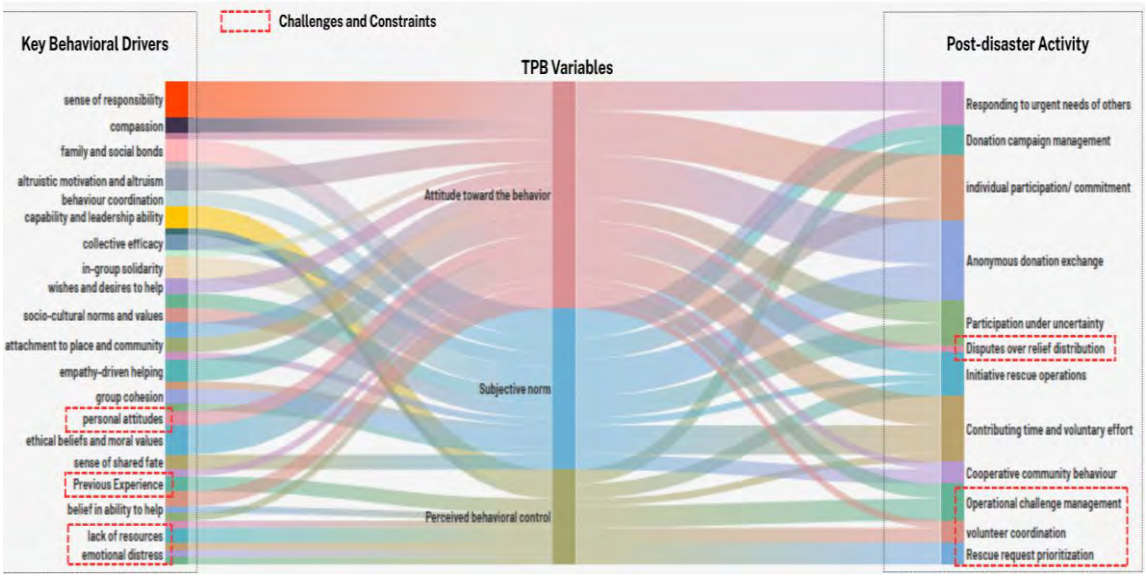



*Figure 2: Key behavioral drivers and their alignment with post-disaster activities*

Addressing these constraints requires context-sensitive, human-centred, and data-driven strategies that integrate community participation into decision-making processes. Importantly, the findings suggest that enhancing behavioural outcomes requires strengthening not only individual motivation yet institutional coordination capacity and digital infrastructure readiness. Notably, as online platform systems can support more effective crisis communication and contribute to the development of explicit knowledge

resources (Kaklauskas et al., 2009), their development may reduce rumours and misinformation during emergencies that often hinder response operations (Gu et al., 2021). In this study, digital platforms emerged as behavioural enablers that directly enhanced perceived behavioural control by reducing uncertainty and improving response coordination efficiency. In addition, programs that foster kindness, empathy, and the ability to understand others' perspectives have been shown to increase prosocial behaviour among early adolescents while improving emotional well-being (Stanculescu & Petruta, 2025). Notwithstanding, the case study indicates that behavioural drivers influencing community participation may evolve over time during disaster response; therefore, authorities should implement context-sensitive strategies that mobilise community support at appropriate stages of recovery, including fundraising initiatives, volunteer mobilisation, and labour donation programmes.

Lastly, strengthening collaboration between authorities, institutions, and local communities can improve the effectiveness and sustainability of recovery initiatives and enhance resilience in disaster-affected areas (Ngulube, 2024). Although the post-disaster period represents a vulnerable stage for affected regions, it also provides opportunities for institutional learning and long-term development (Nian et al., 2019), and effective coordination with optimised community participation during this phase can support recovery while building stronger and more resilient communities. Overall, the study contributes to TPB literature by demonstrating that behavioural drivers in post-disaster contexts are dynamically activated, structurally constrained, and culturally embedded, thereby extending the explanatory boundaries of the theory in developing-country disaster settings.

## 6. CONCLUSIONS

Community participation engagement plays a vital role in post-disaster response and recovery, particularly in the Sri Lankan context, where strong social ties and collective values encourage voluntary support during crises. Drawing on the Theory of Planned Behaviour (TPB), this study identified attitudes, subjective norms, and perceived behavioural control as key drivers of community participation, while also highlighting several challenges that may affect its effectiveness. Understanding these factors is essential for optimising community involvement and informing future disaster management strategies. The study contributes to the disaster management literature by providing empirical insights into the behavioural drivers influencing community participation in a developing-country disaster context. This study is subject to certain limitations. The findings are based on a single case study and five semi-structured interviews; therefore, they should be interpreted within the context of the selected case rather than generalised to all disaster settings. Future research should investigate multiple disaster contexts and develop analytical models to better understand how behavioural drivers interact and evolve during different phases of post-disaster response and recovery.

## 7. REFERENCES

Al-Dahash, H., Kulatunga, U., & Allali, B. (2022). Factors affecting risk perception during terrorist attacks. *International Journal of Disaster Risk Reduction, 73*. https://doi.org/10.1016/j.ijdrr.2022.102870

Azhar, N., Jaes, L., Rameli, N., Maula, A., Kamaruddin, Y., & Abdullah, M. H. (2022). Application of behavioural model to disaster preparedness in a developing country: Malaysia. *Journal of Social Transformation and Regional Development, 4*(2), 30–36. https://doi.org/10.30880/jstard.2022.04.02.004

Bansidhar, M. (2025). Pro-social behaviour among populace in Kutch during the 2001 earthquake: A qualitative exploration. *Research Journal of English Language and Literature (RJELAL).* https://doi.org/10.33329/rjelal.13.2.414

Danasekara, I. (2025, December 3). Cyclone Ditwah: Sri Lanka updates. *BBC News.* https://www.bbc.com/news/articles/c058n10727po

Bosnjak, M., Ajzen, I., & Schmidt, P. (2020). The theory of planned behavior: Selected recent advances and applications. *Europe's Journal of Psychology, 16*(3), 352–356. https://doi.org/10.5964/ejop.v16i3.3107

Charney, D. (2004). Psychobiological mechanisms of resilience and vulnerability: Implications for successful adaptation to extreme stress. *American Journal of Psychiatry, 161*, 195–216. https://doi.org/10.1176/appi.ajp.161.2.195

Cvetković, V. M. (2023). A predictive model of community disaster resilience based on social identity influences (MODERSI). *International Journal of Disaster Risk Management, 5*(2), 57–80. https://doi.org/10.18485/ijdrm.2023.5.2.5

Danar, O. R., & Pushpalal, D. (2014). Building community resilience: Conceptual framework and its application in post-tsunami resettlement. *Procedia Economics and Finance, 18*, 489–496. https://doi.org/10.1016/S2212-5671(14)00967-8

De Silva, D. K. M., Warnakulasuriya, S. S. P., & Dharmaratne, S. D. (2026). Natural disasters and population impact in Sri Lanka, 2010–2025. *BMC Public Health.* Advance online publication. https://doi.org/10.21203/rs.3.rs-8925863/v1

Dewangan, T., Sachdeva, D., & Jacob, E. (2025). Psychometric indicators of prosocial behaviour in disaster response interventions. *TPM – Testing, Psychometrics, Methodology in Applied Psychology, 32*(S4), 1007–1012. https://tpmap.org/submission/index.php/tpm/article/view/650

Dinger, J., Conger, M., Hekman, D., & Bustamante, C. (2020). Somebody that I used to know: The immediate and long-term effects of social identity in post-disaster business communities. *Journal of Business Ethics, 166*(1), 115–141. DOI: 10.1007/s10551-019-04131-w

Disaster Management Centre. (2026). *Sri Lanka: Cyclone Ditwah situation report No. 10 (20 March 2026).* https://reliefweb.int/report/sri-lanka/sri-lanka-cyclone-ditwah-situation-report-no-10-20-march-2026

Ditwah Disaster Relief Platform. (2026). *Cyclone Ditwah disaster relief platform.* Retrieved March 27, 2026, from https://ditwah.com/

Fishbein, M., & Ajzen, I. (1975). *Belief, attitude, intention and behavior: An introduction to theory and research.* Addison-Wesley

Grube, L. E., & Storr, V. H. (2018). Embedded entrepreneurs and post-disaster community recovery. *Entrepreneurship & Regional Development, 30*(7–8), 800–821. DOI: 10.1080/08985626.2018.1457084

Gu, M., Guo, H., & Zhuang, J. (2021). Social media behavior and emotional evolution during emergency events. *Healthcare, 9*, 1109. https://doi.org/10.3390/healthcare9091109

International Organization for Migration. (2026). *DTM Cyclone Ditwah assessment report: Nuwara Eliya District (March 2026).* https://dtm.iom.int/reports/sri-lanka-cyclone-ditwah-assessment-report-nuwara-eliya-district-march-2026

Jehoshaphat, J. D., & Oghenah, B. (2021). Building resilience through local and international partnerships: Nigeria experiences. *International Journal of Disaster Risk Management, 3*(2). https://doi.org/10.18485/ijdrm.2021.3.2.2

Kaklauskas, A., Amaratunga, D., & Haigh, R. (2009). Knowledge model for post-disaster management. *International Journal of Strategic Property Management, 13*(2), 117–128. https://doi.org/10.3846/1648-715X.2009.13.117-128

Kapucu, N. (2012). Disaster and emergency management systems in urban areas. *Cities, 29*(Supplement 1), S41–S49. https://doi.org/10.1016/j.cities.2011.11.009

Kulatunga, U. (2010). Impact of culture towards disaster risk reduction. *International Journal of Strategic Property Management, 14*(4), 304–313. https://doi.org/10.3846/ijspm.2010.23

Lokumannage, A. (2025). Social media campaigns for the development of Sri Lanka after the Ditwah Cyclone. *Social Science and Humanities Journal, 9*(12), 9639–9641. https://doi.org/10.18535/sshj.v9i12.2159

Mohamed, S. (2025, December 28). *Cyclone Ditwah reveals Sri Lanka's true colours.* Sunday Observer. https://www.sundayobserver.lk/2025/12/28/shabeer-mohamed/68759/cyclone-ditwah-reveals-sri-lankas-true-colours/

Ngulube, N. K. (2024). Building back better together: Exploring community engagement in post-disaster recovery efforts – A review. *Journal of Multidisciplinary Research Advancements, 2*(2), 138–149. 10.3126/jomra.v2i2.73082

Nian, S., Zhang, J., Zhang, H., Zhang, J., Li, D., Wu, K., & Yang, L. (2019). Two sides of a coin: A crisis response perspective on tourist community participation in a post-disaster environment. *International Journal of Environmental Research and Public Health, 16*(12), 2073. https://doi.org/10.3390/ijerph16122073

Samaraweera, W. G. R. L., Dharmadasa, R. A. P. I. S., Kumara, P. H. T., & Bandara, A. S. G. S. (2024). Evidence of climate change impacts in Sri Lanka: A review of literature. *Sri Lanka Journal of Economic Research, 11*, 69–94. https://doi.org/10.4038/sljer.v11i2.205

Senanayke, M., & Amaratunga, D. (2026). Editorial: The Ditwah precedent: reforming disaster risk governance frameworks in Sri Lanka. *International Journal of Disaster Resilience in the Built Environment, 17*(3), 317–320. https://doi.org/10.1108/IJDRBE-04-2026-174

Stanculescu, E., & Petruta, R. T. (2025). The benefits of a school intervention for prosocial behaviour and psychological well-being in early adolescents. *Current Psychology, 44*(6), 5216–5226. https://doi.org/10.1007/s12144-025-07353-6

Staub, E., & Vollhardt, J. (2008). Altruism born of suffering: The roots of caring and helping after victimization and other trauma. *American Journal of Orthopsychiatry, 78*(3), 267–280. https://doi.org/10.1037/a0014223

Stern, P. C., Dietz, T., Abel, T. D., Guagnano, G. A., & Kalof, L. (1999). A value–belief–norm theory

of support for social movements: *The case of environmentalism. Human Ecology Review*, 6(2),

81–97

Sunday Observer. (2025, December 7). *Cyclone Ditwah must be a turning point*. Sunday Observer. https://www.sundaytimes.lk/251207/plus/cyclone-ditwah-must-be-a-turning-point-622760.html

World Bank. (2025). *Global Rapid Post-Disaster Damage Estimation (GRADE) Report : Cyclone Ditwah 2025 - Sri Lanka (English).* https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099122225074016363

World Health Organization. (2020). *Risk communication and community engagement (RCCE) action plan guidance: COVID-19 preparedness and response*. https://www.who.int/publications/i/item/risk-communication-and-community-engagement-%28rcce%29-action-plan-guidance

Xu, D., Li, Y., & Ye, Y. (2024). Turning pain into strength: Prosocial behaviours in coping with trauma. *European Journal of Psychotraumatology*, 15(1), 2330302. https://doi.org/10.1080/20008066.2024.2330302

Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE

Publications

Yuriev, A., Dahmen, M., Paillé, P., Boiral, O., & Guillaumie, L. (2020). Pro-environmental behaviours through the lens of the theory of planned behaviour: A scoping review. *Resources, Conservation and Recycling, 155*, 104660. https://doi.org/10.1016/j.resconrec.2019.104660

Senevirathne, P.K.V.M., Ashen, J.M.D., Perera, T.D. and Gunawardena, R.L.H., 2026. Performance evaluation of wood-based additives in asphalt binder: A comparative study. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1292-1302. DOI: https://doi.org/10.31705/WCS.2026.94. Available from: https://ciobwcs.com/papers/

# PERFORMANCE EVALUATION OF WOOD-BASED ADDITIVES IN ASPHALT BINDER: A COMPARATIVE STUDY

**P.K.V.M. Senevirathne[1], J.M.D. Ashen[2], T.D. Perera[3] and R.L.H. Gunawardena[4]**

## *ABSTRACT*

*Asphalt is a non-renewable byproduct of petroleum refining and acts as a binder that holds aggregate particles together during compaction in flexible pavements. Increasing traffic loads, heavy commercial vehicle congestion, and significant temperature variations have led to performance limitations in traditional asphalt binders. To improve durability and sustainability, researchers have explored modifying binders with waste materials to enhance their mechanical and rheological properties. This study investigates the efficacy of wood dust (WD) and wood ash (WA) as alternative binder modifiers. These widely available waste materials promote environmental sustainability by reducing waste disposal problems and have the potential to improve asphalt properties. The modification process involves incorporating WD and WA at a rate of 4% by binder weight. The modified binders are evaluated through rheological tests to assess their stiffness, elasticity, and resistance to deformation under different temperature conditions, along with the control mixture (CS). The findings of this research demonstrated improvement in binder performance, increased resistance to aging and thermal variations, and a more sustainable approach to asphalt pavement construction. By incorporating these natural wastes, this study aims to contribute to the development of cost-effective and environmentally friendly road infrastructure. The findings will provide insights into the feasibility of using biomass-derived waste as a bitumen binder modifier in future pavement applications.*

***Keywords:*** *Asphalt Binder; Biomaterials; Performance Evaluation; Sustainable Pavement; Workability; Wood-Based Additives.*

## 1. INTRODUCTION

Bitumen is an essential binder used in flexible pavements to hold the aggregate skeleton. However, conventional binders are facing sustainability challenges because of issues related to premature aging and environmental concerns. Modifying binder with waste materials such as wood dust (WD) and wood ash (WA) is an environmentally friendly way of addressing sustainability challenges. Wood dust is a waste product produced from

[1] Lecturer, Department of Mechatronic & Industrial Engineering, NSBM Green University, Sri Lanka, vihanga.s@nsbm.ac.lk
[2] Undergraduate, Department of Mechatronic & Industrial Engineering, NSBM Green University, Sri Lanka, jmdashen@students.nsbm.ac.lk
[3] Undergraduate, Department of Mechatronic & Industrial Engineering, NSBM Green University, Sri Lanka, tdperera@students.nsbm.ac.lk
[4] Undergraduate, Department of Mechatronic & Industrial Engineering, NSBM Green University, Sri Lanka, rlhgunawardena@students.nsbm.ac.lk

the timber and woodworking industries that is available in large quantities but often disposed of poorly, creating pollution problems. Using wood by-products to modify binder enhances the mechanical and rheological properties of bitumen and pavement performance by improving elasticity, stiffness, durability, and resistance to temperature-related and traffic stresses, and it decreases maintenance and construction costs. From an environmental perspective, using wood with asphalt decreases reliance on petroleum-based products, contributes to waste management practices, and leverages circular economies in our construction and maintenance practices.

This study examined three important aspects of asphalt pavement engineering: workability, mix design optimization, and the inclusion of bio-waste products. Workability describes the ease of placing and compacting asphalt material as it is constructed and is a function of both the type and proportions of materials incorporated into the mix. Workability affects pavement density and long-term durability. Mix design optimization is critical as it balances the proportion of aggregates, binder, and intended additives to achieve the desired mechanical properties in an asphalt pavement when subjected to traffic and environmental stresses. The inclusion of bio-waste products from wood industry operations addresses increasing sustainable opportunities by reusing potential waste products, limiting the use of virgin bitumen, and decreasing the carbon footprint of new road construction. All three examined elements considered in combination represent a holistic approach to creating environmentally sustainable, high-performance asphalt pavements that satisfy engineering requirements alongside general environmental objectives.

In recent decades, numerous studies have explored enhancing the performance of Hot Mix Asphalt (HMA) through bitumen binder modification using various waste products, including waste plastics (Sharma et al., 2020; Nizamuddin et al., 2020; Mashaan et al., 2022), crumb rubber (Loderer et al., 2018; Navarro et al., 2005; Mashaan et al., 2012), waste engine oil and bio-oils (Penki & Rout, 2023; Abbas et al., 2023; Fernandes et al., 2018; Senevirathne et al., 2024). Plastics and rubber, for instance, enhance the deformation resistance and fatigue crack resistance of asphalt, resulting in longer pavement life (Sharma et al., 2020; Nizamuddin et al., 2020; Mashaan et al., 2022). For example, as concluded by Sharma et al. (2020), the addition of waste polyethylene into bitumen improved rutting resistance and stiffness. Crumb rubber (Loderer et al., 2018; Navarro et al., 2005; Mashaan et al., 2012) is also an effective modifier due to its flexibility, reducing temperature susceptibility, and enhancing asphalt fatigue life. Waste engine oil has also been explored for use to revive aged binders, their workability, and recover them to their original state (Penki & Rout, 2023; Abbas et al., 2023; Fernandes et al., 2018; Senevirathne et al., 2024). Gawande et al. (2012) have also shown that waste cooking oil and natural latex can serve as bio-modifiers to enhance flexibility, water resistance, and make the mix sustainable.

Other wastes, such as waste wax and refinery sludges (Singh et al., 2020; Vargas & Hanandeh, 2024), have also been explored. The wastes improve the stability of the binder, reduce permanent deformation, and offer an economic method of pavement construction. Singh et al. (2020) explored the use of sulfur as one type of bitumen modifier and found that it increased stiffness and improved performance under different temperatures. This conforms to worldwide sustainability efforts through the transformation of waste into products of value. Wood dust is one such alternative that can improve the quality of roads and assist in waste management. As millions of tons of wood fiber dust are created

annually, wood dust in asphalt can address both construction issues and waste issues simultaneously. Not only does it increase the pavement lifespan, but it also supports the building of greener infrastructure. Further research with wood dust-modified bitumen can render roads less expensive, stronger, and more sustainable in the coming years.

Despite the growing body of literature on waste-modified binders, several gaps remain. Studies on waste plastics and crumb rubber have primarily focused on deformation resistance and fatigue performance, with limited attention to the workability implications of modifier addition (Sharma et al., 2020; Loderer et al., 2018). Research on bio-oils and waste engine oil has reported inconsistent outcomes with respect to aging resistance and long-term durability (Penki & Rout, 2023; Fernandes et al., 2018). Critically, no study has simultaneously evaluated wood dust and wood ash as binder modifiers under identical experimental conditions, nor has the Arrhenius-based workability framework been applied to wood-based modified binders. This study addresses these gaps by conducting a unified comparative evaluation of WD and WA modifications, encompassing rheological characterisation, Marshall mix design, and workability analysis within a single experimental programme.

The scope of this research included: (i) evaluating the properties of the additives and modifying the conventional binder; (ii) studying the rheological properties of modified binders along with the control binder; (iii) preparing asphalt mixtures incorporating each modifier along with a control sample; (iv) determining the optimum binder content for each asphalt mixture; and (v) conducting the workability analysis.

## 2. MATERIAL ANALYSIS AND SAMPLE PREPARATION

The overall experimental framework adopted in this study is illustrated in Figure 1. The programme encompassed binder modification, material characterisation, mix design, and workability analysis, as detailed in the following sections.

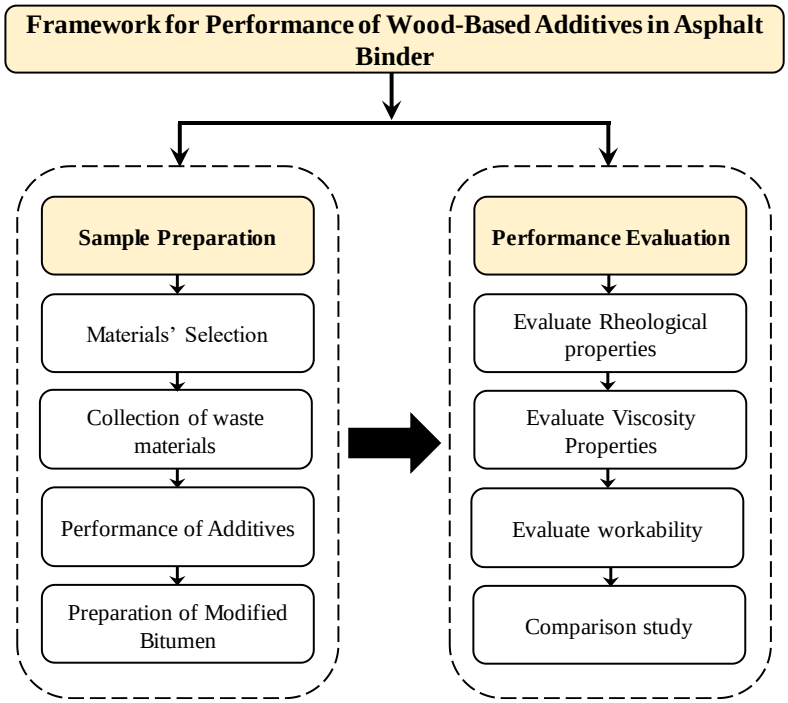



*Figure 1: Experimental framework*

## 2.1. BINDER SELECTION AND MODIFICATION

In this study, VG-30 bitumen was selected as the binder for the preparation of hot mix asphalt (HMA) mixtures. Viscosity Grade 30 (VG-30) is widely used for roads with moderate to high traffic loads due to its favorable viscosity and mechanical properties. Two types of modifications were carried out to enhance the characteristics of the conventional binder by incorporating bio-based additives: wood dust (WD) and wood ash (WA). At first, both additives were oven-dried at 50°C and sieved through a 75-micron sieve. The additives were then blended with the VG-30 bitumen at 150°C using a mechanical high-shear mixer. To prevent the formation of air bubbles, the additives were gradually introduced into the binder during mixing, while maintaining a constant shear rate throughout the entire 30-minute mixing process to ensure uniform dispersion. Three types of binder samples were prepared: a control sample (CS) with unmodified VG-30, a sample modified with 4% (by weight) wood dust (WD), and a sample modified with 4% (by weight) wood ash (WA). Rheological property tests were conducted on all binder samples, and the results are presented in Table 1. The objective of these modifications was to improve the binder's resistance to deformation, enhance workability, promote the utilization of sustainable waste materials, and ultimately improve the overall performance of the asphalt mixtures.

*Table 1: Rheological properties of the binders.*

| Properties | CS | WD | WA |
|---|---|---|---|
| Softening point | 49 °C | 48.5 °C | 49 °C |
| Penetration value (0.1mm) | 58 | 36 | 40 |
| Elastic recovery | 17% | 15% | 15% |
| Mixing temperature | 155-160 °C | 156-162 °C | 159-164 °C |
| Compaction temperature | 145-150 °C | 148-152 °C | 150-154 °C |

## 2.2. AGGREGATE

The aggregate gradation for this study was Bituminous Concrete (BC) 2 (Figure 2) as recommended by the Ministry of Road Transport and Highways (MoRTH, 2013).

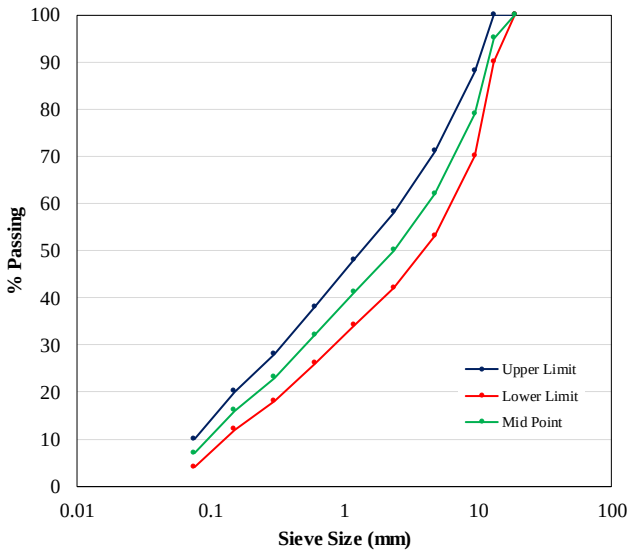



*Figure 2: BC-2 Aggregate gradation*

Property tests were carried out for aggregates according to the international standards and are mentioned in Table 2.

*Table 2: Properties of aggregate*

| Properties | Values | Test method |
|---|---|---|
| Specific gravity (Coarse aggregate) | 2.765 | ASTM C127 |
| Specific gravity (Fine aggregate) | 2.66 | ASTM C128 |
| Aggregate crushing value | 27.33% | IS: 2386 Part IV |
| Aggregate impact value | 9.17% | IS: 2386 Part IV |
| Aggregate soundness value | 7% | IS: 2386 Part V |
| Aggregate stripping value | 97.90% | IS: 6241-1971 |

## 2.3. SAMPLE PREPARATION, TESTING, AND EVALUATION

In this research, three different types of hot mix asphalt (HMA) mixtures were prepared, each utilizing a different binder type: VG-30 bitumen for the control mix (CS), VG-30 modified with wood dust (WD), and VG-30 modified with wood ash (WA). For each HMA mixture, the Marshall stability test was conducted to determine the optimum binder content. Marshall specimens were prepared for each mix using four different binder contents: 4.5%, 5.0%, 5.5%, and 6.0% by weight of the total mix. For each selected binder content, three replicate samples were fabricated, resulting in a total of 12 Marshall specimens for each binder type. The experimental matrix for the study is summarized in Table 3.

*Table 3: Experimental matrix*

| ***Aggregate*** | | | | |
|---|---|---|---|---|
| **Experiment** | | **Samples** | | |
| Specific gravity (Coarse, Fine & Filler) | | 3 | | |
| Aggregate crushing value | | 2 | | |
| Aggregate impact value | | 2 | | |
| Aggregate soundness value | | 2 | | |
| Aggregate stripping value (CM) | | 2 | | |
| Total Samples | | 11 | | |
| ***Binders*** | | | | |
| **Experiment** | **CS** | **WD** | **WA** | **Samples** |
| Softening point | 3 | 3 | 3 | 9 |
| Penetration test | 3 | 3 | 3 | 9 |
| Elastic recovery | 3 | 3 | 3 | 9 |
| Brookfield Viscosity test | 1 | 1 | 1 | 3 |
| Total Samples | | | | 30 |
| ***Asphalt Mixture*** | | | | |
| **Experiment** | **CS** | **WD** | **WA** | **Samples** |
| Mix design | 12 | 12 | 12 | 36 |
| Total Samples | | | | 36 |
| **Grand Total** | | | | **77** |

Figure 3 illustrates the sequential experimental steps followed for the Marshall mix design procedure. Marshall samples were compacted according to specifications for high traffic volume conditions, and the Marshall stability and flow values were measured to evaluate the improvements in mix design properties achieved through the use of the modified binders.

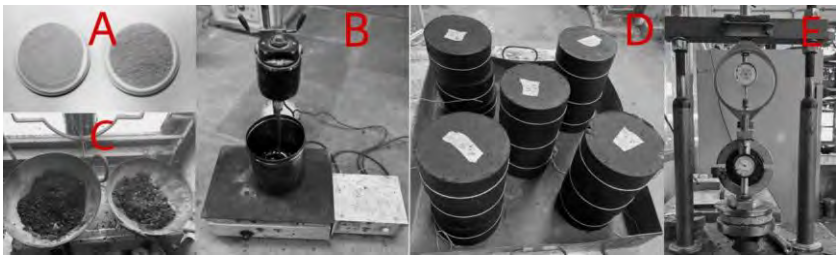



*Figure 3: Sequential experimental steps*

# 3. RESULTS AND DISCUSSION

## 3.1. RHEOLOGICAL PROPERTIES

When comparing the softening point values across all mixtures, it was observed that they exhibited similar softening points. However, the modified binders showed lower penetration values compared to the control mix. Lower penetration values at low temperatures indicate that the modified binders are stiffer and harder, providing greater resistance to deformation under loading conditions, which is advantageous for pavements in high-temperature regions. However, a potential drawback is that increased stiffness can lead to brittleness at low temperatures, increasing the risk of thermal cracking in colder climates.

## 3.2. VISCOSITY ANALYSIS

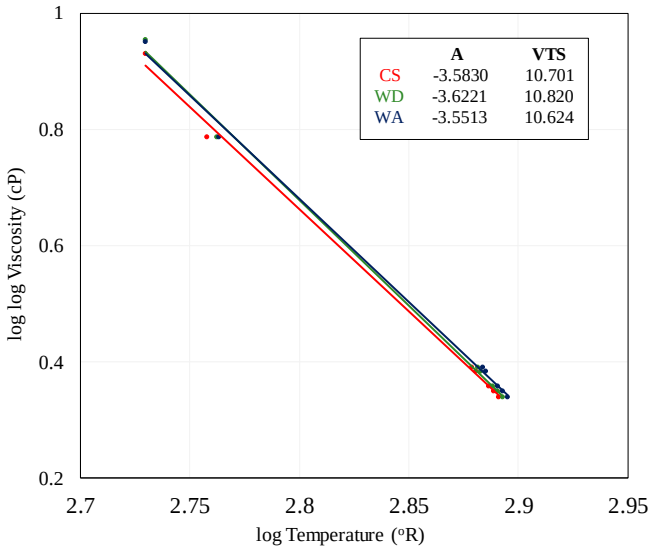



*Figure 4: $A_i$-$VTS_i$ Graph*

The observed viscosity data, along with penetration and softening point data, were used to generate an $A_i$-$VTS_i$ curve (Figure 4) for each binder. Upon examining the $A_i$-$VTS_i$

curve for the CS, WD, and WA, it was found that all three binders exhibit similar temperature susceptibility, as their slopes and intercepts are nearly identical. However, the slope for the CS binder is slightly lower than that of the modified binders, indicating that CS is less sensitive to changes in viscosity with temperature fluctuations. In contrast, both modified binders exhibit higher viscosities at higher temperatures, suggesting a higher susceptibility to rutting under high-temperature conditions. Modified binders also imply a higher susceptibility to thermal cracking at low temperatures compared to the control sample.

## 3.3. MARSHALL MIX DESIGN

The optimum binder content for all mixtures was determined using the Marshall mix design method. During the process, the Marshall stability and flow values were measured for each specimen to obtain the necessary data. Additionally, the theoretical maximum specific gravity (Gmm) was determined for each mixture. After identifying the optimum binder content, volumetric analysis was conducted on the samples prepared with the corresponding binder content. Table 4 presents the optimum binder content and the theoretical maximum specific gravity (Gmm) values for all the mixtures.

*Table 4: Optimum binder content and Gmm values of mixtures*

| Mix | OBC (%) | Gmm |
|---|---|---|
| CS | 4.9 | 2.475 |
| WD | 4.7 | 2.532 |
| WA | 4.9 | 2.603 |

The air voids (Pa), voids filled with asphalt (VFA), voids in the mineral aggregate (VMA), and bulk density were calculated for each set of test specimens. The variations of these properties with binder content, ranging from 4.5% to 6.0%, were analyzed. Furthermore, the changes in Marshall stability and flow values with varying binder content were also examined. All these results are presented in Figure 5. It was observed that modification of the binder led to a reduction in the optimum binder content (OBC), with WD exhibiting the lowest OBC among the mixtures. Although WA showed a similar OBC to the CS, it contained a lower amount of pure bitumen due to the inclusion of 4% wood ash by weight. A lower binder content offers several benefits. First, it directly reduces the amount of bitumen required, leading to significant cost savings in material expenses. Additionally, since bitumen production is associated with carbon emissions, reduced binder usage contributes to lowering the environmental footprint, supporting sustainable construction practices. From a performance perspective, lower binder content enhances the mixture's stiffness, which improves resistance to permanent deformation (rutting) under high traffic loads. Furthermore, it reduces the risk of asphalt bleeding, a phenomenon where excess binder rises to the surface, potentially creating dangerously slippery road conditions.

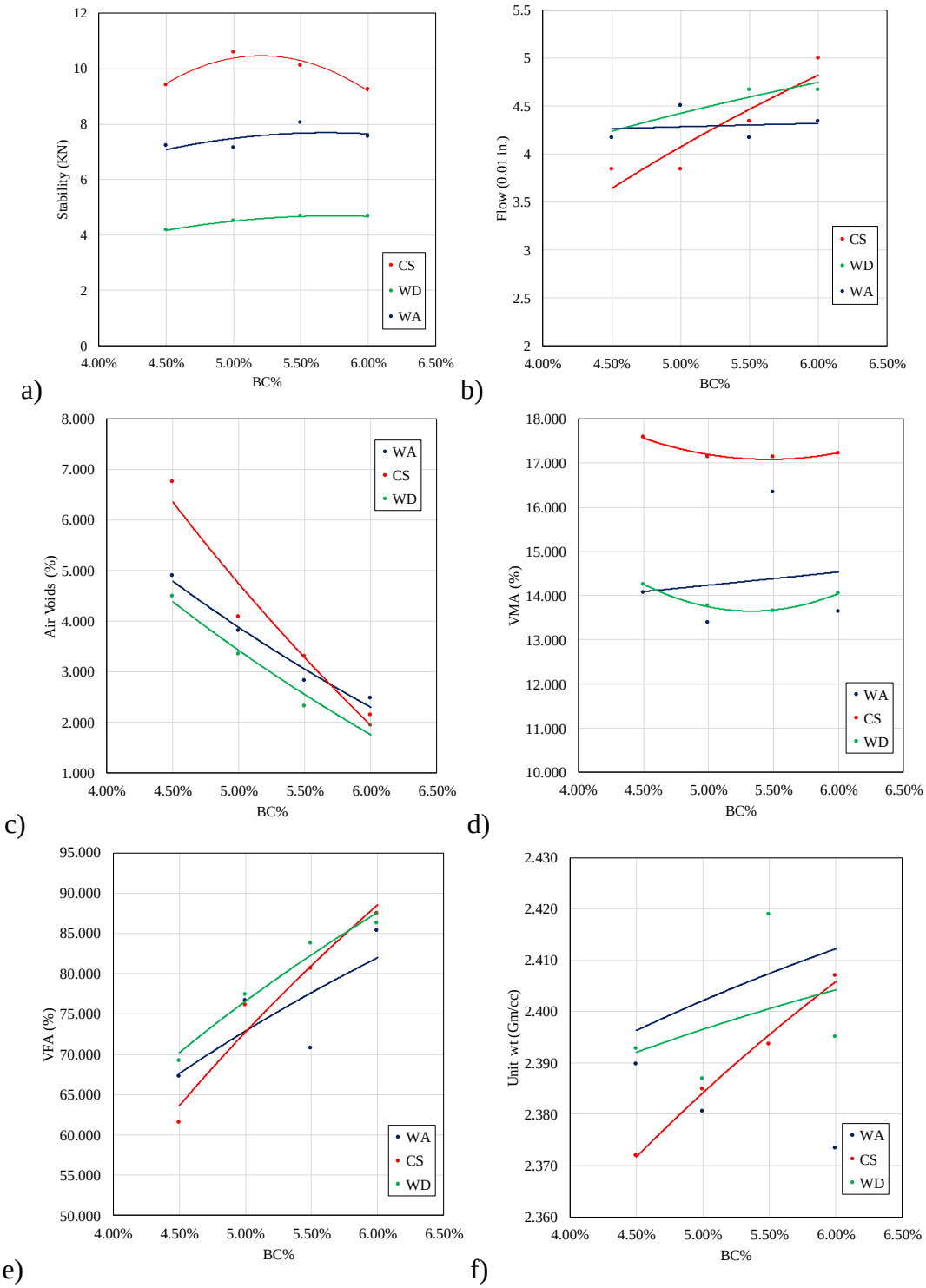



*Figure 5: Marshall mix design plots: (a) Stability vs. Binder content, (b) Flow value vs. Binder content, (c) Air void percentage vs. Binder content, (d) VMA vs. Binder content, (e) VFA vs. Binder content, and (f) Unit weight vs. Binder content*

## 3.4. WORKABILITY ANALYSIS

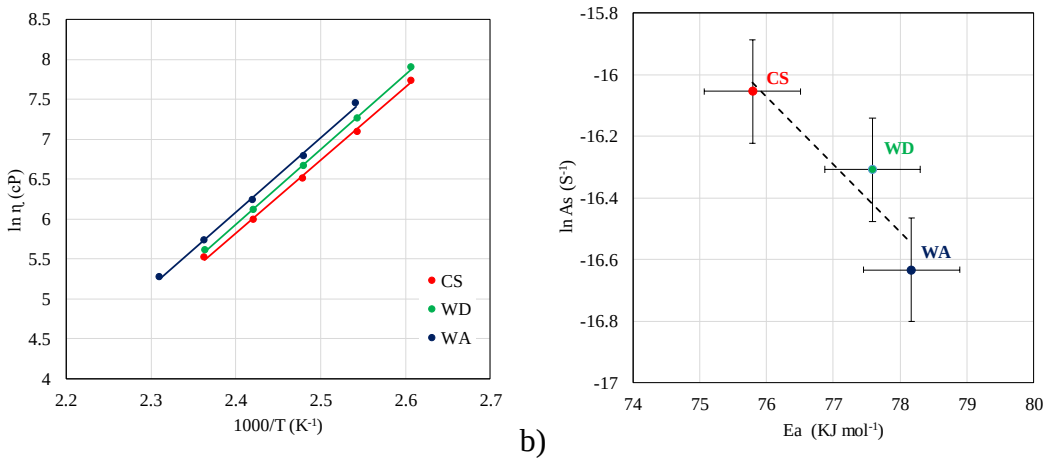
The workability of asphalt mixtures is crucial during the compaction process. Therefore, a workability analysis was conducted for the binders using the Arrhenius equation. Following the approach suggested by Akhil et al. (2023), the viscosity of the binders was

measured as a function of temperature. As shown in Figure 6(a), the temperature dependency of viscosity was evaluated through a plot of ln(η) versus 1000/T. Although the Arrhenius plot traditionally assumes that temperature is not dependent on a dynamic property, in this case, the analysis was approached based on a molecular interpretation of the macroscopic properties. The linear trend observed in the Arrhenius plot indicates that the binders follow Arrhenius behavior within the studied temperature range, allowing the calculation of activation energies (Ea) and pre-exponential factors (As) according to the Arrhenius relationship.

$$ln\eta(T) = lnAs + \frac{Ea}{R} \times \frac{1000}{T} \qquad (01)$$

According to the Arrhenius relationship, $E_a$ represents the activation energy, lnA is the pre-exponential factor, T is the temperature, η is the viscosity, and R is the universal gas constant ($R = 8.314\ J \cdot mol^{-1} \cdot K^{-1}$).

Figure 6(b) illustrates the correlation between Ea and ln(As) for all the binders. The Arrhenius model is based on Transition State Theory (TST), which is commonly used in chemical kinetics to describe reaction rates based on the transition of molecules to an activated state. According to TST, a negative value of ln(As) indicates a negative entropy of formation for the activated state during flow. The results show that the modified samples have the highest activation energy compared to the control binder, suggesting that more energy is required to initiate flow. Furthermore, the lower ln(As) values observed for the modified binders imply that fewer molecular collisions are necessary for the flow process.




a) b)

*Figure 6: (a) Arrhenius plot, and (b) Correlation between the pre-exponential factor (ln As) and the activation energy (Ea)*

## 4. CONCLUSIONS

The objectives of this research were to enhance asphalt binders using wood-based additives. Two modified binders incorporating wood dust (WD) and wood ash (WA) were compared to a standard control binder (CS). A number of tests were conducted to evaluate rheological behavior, viscosity, Marshall mix design properties, and workability of the binders. In addition, the environmental aspects of reusing waste materials were assessed. The key outcomes support the use of wood-based additives in developing stronger, more durable, and sustainable asphalt pavements, and the major findings are summarized below.

With respect to rheological properties and viscosity, the modified binders (WD and WA) exhibited lower penetration values than the control, indicating increased stiffness and improved resistance to deformation under load. Softening points were similar across all binders, confirming that high-temperature softening behavior was not adversely affected by the modifications. Viscosity analysis revealed that the modified binders had higher temperature susceptibility, which may improve rutting resistance at high temperatures but could increase the risk of thermally induced cracking in cold climates. The Ai-VTS curves further confirmed that WD and WA binders have slightly higher viscosity susceptibility than CS, consistent with their potential suitability for high-temperature pavement applications.

Regarding Marshall mix design, the optimum binder content (OBC) was reduced for the WD mixture (4.7%) compared to both CS (4.9%) and WA (4.9%), resulting in cost savings and a reduced environmental impact through lower bitumen consumption. Volumetric properties, including air voids (Pa), VMA, and VFA, were within acceptable limits for all mixtures, confirming structural durability. The reduced binder demand of the WD-modified mixture also contributes to improved stiffness and lower susceptibility to rutting and asphalt bleeding.

In terms of workability, the Arrhenius model established that the modified binders required higher activation energies ($E_a$) for flow, indicating greater thermal stability at elevated temperatures. Despite the increased stiffness, both modified binders retained acceptable workability, allowing adequate compaction during construction.

From a sustainability perspective, the use of wood-based waste materials supports the principles of a circular economy by converting industrial by-products into value-added construction materials. Reduced bitumen consumption directly decreases reliance on petroleum-based products, lowering the overall carbon footprint of pavement construction. Furthermore, incorporating these waste materials into asphalt mixtures contributes to reduced pollution and improved waste management practices, supporting a more environmentally responsible approach to road infrastructure development.

## 5. REFERENCES

Abbas, S., Zaidi, S. B. A., & Ahmed, I. (2023). Performance evaluation of asphalt binders modified with waste engine oil and various additives. *International Journal of Pavement Engineering*, *24*(2), 2128353. https://doi.org/10.1080/10298436.2022.2128353

Akhil, T., Senevirathne, P. K. V. M., & Saha, G. (2023). Quantitative assessment of workability for hot mix asphalt: Inclusive study on mix variables. *Proceedings of the International Conference on Road Safety (ICRS 2023)*.

Fernandes, S. R., Silva, H. M., & Oliveira, J. R. (2018). Developing enhanced modified bitumens with waste engine oil products combined with polymers. *Construction and Building Materials*, *160*, 714–724. https://doi.org/10.1016/j.conbuildmat.2017.11.112

Gawande, A., Zamare, G., Renge, V. C., Tayde, S., & Bharsakale, G. (2012). An overview on waste plastic utilization in asphalting of roads. *Journal of Engineering Research and Studies*, *3*(2), 1–5. https://www.academia.edu/81984313/An_Overview_on_Waste_Plastic_Utilization_in_Asphalting_of_Roads

Loderer, C., Partl, M. N., & Poulikakos, L. D. (2018). Effect of crumb rubber production technology on performance of modified bitumen. *Construction and Building Materials*, *191*, 1159–1171. https://doi.org/10.1016/j.conbuildmat.2018.10.046

Mashaan, N., Chegenizadeh, A., & Nikraz, H. (2022). A comparison on physical and rheological properties of three different waste plastic-modified bitumen. *Recycling*, *7*(2), 18. https://doi.org/10.3390/recycling7020018

Mashaan, N. S., Ali, A. H., Karim, M. R., & Abdelaziz, M. (2012). An overview of crumb rubber modified asphalt. *International Journal of Physical Sciences*, *7*(2), 166–170. https://doi.org/10.1155/2014/214612

Ministry of Road Transport and Highways. (2013). Specifications for road and bridge works (5th rev.). *Indian Roads Congress.*

Navarro, F. J., Partal, P., Martínez-Boza, F., & Gallegos, C. (2005). Influence of crumb rubber concentration on the rheological behavior of a crumb rubber modified bitumen. *Energy & Fuels*, *19*(5), 1984–1990. https://doi.org/10.1021/ef049699a

Nizamuddin, S., Jamal, M., Gravina, R., & Giustozzi, F. (2020). Recycled plastic as bitumen modifier: The role of recycled linear low-density polyethylene in the modification of physical, chemical and rheological properties of bitumen. *Journal of Cleaner Production*, *266*, 121988. https://doi.org/10.1016/j.jclepro.2020.121988

Penki, R., & Rout, S. K. (2023). Next-generation bitumen: A review on challenges and recent developments in bio-bitumen preparation and usage. *Biomass Conversion and Biorefinery*, *13*(11), 9583–9600. https://doi.org/10.1007/s13399-021-01803-4

Senevirathne, P. K. V. M., Akhil, T., & Saha, G. (2024). Use of waste engine oil in hot mix asphalt: Evaluation of workability.

Sharma, S., Sharma, P. K., & Upadhyay, N. (2020). Properties of bituminous binder modified with polyethylene. *Journal of Physics: Conference Series* (Vol. 1531, No. 1, p. 012115). IOP Publishing. https://doi.org/10.1088/1742-6596/1531/1/012115

Singh, M., Jain, K., & Kahlon, S. S. (2020). Use of sulphur as an additive in bitumen: A review. *International Research Journal of Engineering and Technology*, *7*(10), 36–43. https://doi.org/10.1016/j.matpr.2021.09.322

Vargas, C., & Hanandeh, A. E. (2024). The utilisation of polyethylene waste pyrolytic wax as an additive to enhance the performance of virgin and polypropylene-modified bitumen. *International Journal of Pavement Research and Technology*, *17*(4), 929–951. https://doi.org/10.1007/s42947-023-00278-y

Wijesundara, W.M.I.H., Kulatunga, U. and Wimalaratne, P.L.I., 2026. Performance indicators for biomimicry-based construction materials and their operationalisation through augmented reality: A systematic literature review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1303 -1314. DOI: https://doi.org/10.31705/WCS.2026.95. Available from: https://ciobwcs.com/papers/

# PERFORMANCE INDICATORS FOR BIOMIMICRY-BASED CONSTRUCTION MATERIALS AND THEIR OPERATIONALISATION THROUGH AUGMENTED REALITY: A SYSTEMATIC LITERATURE REVIEW

**W.M.I.H. Wijesundara[1], U. Kulatunga[2] and P.L.I. Wimalaratne[3]**

## *ABSTRACT*

*Biomimicry-based construction materials are nature-inspired materials designed to replicate biological structures, processes, and ecosystem functions to enhance sustainability and building performance. Construction plays a major role in global carbon emissions, and construction materials account for a significant proportion of embodied environmental impacts. Therefore, it is understood that biomimicry-based construction materials have been gaining popularity as replacement materials. Thus, the study highlights the need for addressing the gaps in enhanced effectiveness in early stages of decision-making for the biomimicry-based construction materials. Existing studies predominantly evaluate biomimicry-based materials in isolation, while integrated frameworks capable of operationalising environmental, functional, and aesthetic performance indicators through accessible digital decision-support mechanisms remain limited. Accordingly, this study aims to synthesise multidimensional material performance indicators and examine how minimal Augmented Reality (AR)-based visualisation can support early-stage material selection. Furthermore, the relevant literature retrieved is subjected to qualitative content analysis. Therefore, the study highlights aspects of environmental, functional, and aesthetic-perceptual performance indicators, which have been explored as separate domains. Furthermore, the study highlights the unsatisfactory utilisation of augmented reality for visualising sustainability. Therefore, the study proposes a conceptual approach to deliver enhanced effectiveness for visualising augmented reality-based biomimicry-based construction materials.*

***Keywords:*** *Augmented reality; Biomimicry; Construction Materials; Decision-Support Systems; Systematic Literature Review.*

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, wijesundarawmih.25@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, indraniw@uom.lk

# 1. INTRODUCTION

The early-stage selection of construction materials critically influences the sustainability, performance, and lifecycle outcomes of building projects (Ahamed et al., 2022). Biomimicry-based materials, inspired by natural systems, offer significant potential to enhance environmental performance, functional efficiency, and aesthetic quality (Rosario et al., 2023). However, their adoption in practice remains limited, primarily due to fragmented evidence, inaccessible performance data, and the complexity of comparing multiple material attributes during the design phase (Nielsen et al., 2016). Existing studies frequently focus on isolated technical properties, such as embodied Carbon reduction or thermal performance, without integrating these into holistic decision-making frameworks that consider functional, aesthetic, and sustainability dimensions concurrently (Iroegbu & Ray, 2021; Mumcu & Korkmaz, 2025). Moreover, digital tools, including AR, have been applied in construction mainly for visualisation, assembly guidance, or training, rather than as a lightweight decision-support mechanism for material selection (Berryman, 2012). This highlights a critical gap: there is currently no structured approach to operationalise multidimensional performance indicators for biomimicry-based materials in a stakeholder-accessible format that supports early-stage decision-making (Han et al., 2018).

To address this gap, this study adopts a Systematic Literature Review (SLR) methodology, recognised for its rigor in synthesising prior knowledge and identifying conceptual, methodological, and empirical gaps (Briner & Denyer, 2012.; Siddaway et al., 2024). The SLR enables a transparent and reproducible mapping of the interdisciplinary evidence base, encompassing materials science, sustainability assessment, and digital visualisation (Zari & Hecht, 2020). The review focuses on identifying key indicators across environmental, functional, and aesthetic-perceptual dimensions and evaluating the extent to which AR and digital decision-support mechanisms have been applied to facilitate informed material selection (Shufrin et al., 2023; Wang et al., 2025). By systematically analysing peer-reviewed studies from 2016 to 2026, the SLR provides a defensible basis for developing a conceptual framework that integrates these performance indicators into a practical, AR-assisted decision-making process.

Accordingly, the study aims to answer the following research question:

*How can environmental, functional, and aesthetic performance indicators of biomimicry-based construction materials be operationalized through minimal AR-based visualization to support effective early-stage decision-making among diverse construction stakeholders?*

The SLR-driven approach not only identifies the indicators most relevant to biomimicry-based material performance but also reveals critical shortcomings in existing decision-support practices related to operationalisation, stakeholder communication, and technological facilitation. Building upon these findings, the study proposes a conceptual framework that differs from conventional material selection models by integrating sustainability performance indicators with minimal AR-based visualisation to support interactive comparison, stakeholder engagement, and evidence-based decision-making during early design stages (Ngaba et al., 2025). The framework, therefore contributes a novel pathway for bridging the gap between material performance assessment and practical material selection within sustainable construction contexts.

# 2. RESEARCH METHODOLOGY

This study adopted a SLR approach, widely recognised as a fundamental component of rigorous research, which enables the structured synthesis of prior knowledge while identifying conceptual, methodological, and empirical gaps within an emerging research domain (Petticrew & Roberts, 2006). Systematic reviews are particularly suitable for consolidating fragmented research fields and supporting theory and framework development through transparent and reproducible procedures (Man et al., 2024). According to Briner and Denyer (2012), a systematic review must: (1) follow a clearly defined and structured process; (2) employ a transparent and well-documented methodology; (3) be reproducible and capable of being updated; and (4) synthesize evidence relevant to the core research problem. These principles ensure methodological robustness and reduce selection bias. Snyder (2019), further conceptualised the SLR process into three overarching phases: (i) planning, (ii) conducting, and (iii) reporting, which were later operationalised into a practical seven-step guideline for social science research by Petticrew and Roberts (2006). This study strictly adhered to these established methodological guidelines in conducting the systematic review (Briner & Denyer, 2012). The selected approach ensures that the review process is methodical, transparent, and repeatable, while maintaining a strong alignment between the research aim and the analytical outcomes (Riani et al., 2025). The SLR methodology was adopted as this study seeks to develop a conceptual framework to support biomimicry-based construction material selection using augmented reality-assisted visualisation, which requires the structured integration of multidisciplinary evidence spanning materials science, sustainability assessment, and digital decision-support technologies.

## 2.1 DATA COLLECTION AND DATA CLEANING

The systematic review began with the primary research question: *How can sustainability and environmental performance information of biomimicry-based construction materials be operationalized through minimal AR-based visualization to support early-stage decision-making among diverse construction stakeholders?*

A comprehensive keyword search string was developed covering four domains: (1) biomimicry and nature-inspired design, (2) construction and building materials, (3) sustainability and environmental performance indicators, and (4) AR-based visualisation and decision-support tools. A pilot review identified alternative keywords and synonyms. Boolean operators (“AND”, “OR”) and wildcards (“*”) were applied to maximise retrieval sensitivity. The final search string was: (("Biomimicry" OR "Bio-inspired" OR "Nature-inspired") AND ("Construction material" OR "Building material" OR "Green building material*") AND ("Sustainability" OR "Embodied carbon" OR "Environmental performance") AND ("Augmented Reality" OR "AR" OR "Minimal AR" OR "Visualization" OR "Decision support")) *

The search was applied to Scopus and Web of Science for their coverage of high-impact literature in construction, sustainability, and digital technology. Inclusion criteria limited results to titles, abstracts, and keywords; publications from 2016 to 2026; peer-reviewed journals, conferences, reviews, and book chapters; and English-language sources. Grey literature was excluded. The review period from 2016 to 2026 was selected to capture the emergence and rapid development of biomimicry-based material innovation and AR-assisted decision-support applications within construction research. Records were

exported to CSV, imported into Mendeley, and duplicates removed. Titles, abstracts, and full texts were screened to exclude studies unrelated to biomimicry materials, sustainability, or AR decision-support. Studies without empirical relevance or explicit linkage between biomimicry materials, sustainability, and AR visualisation were excluded, resulting in a focused, methodologically justified dataset suitable for framework development. Backward and forward snowball searching was conducted following the initial database screening stage to identify additional relevant studies from reference lists and citation networks. Duplicate records identified during snowball searching were removed through Mendeley reference management software prior to full-text screening.

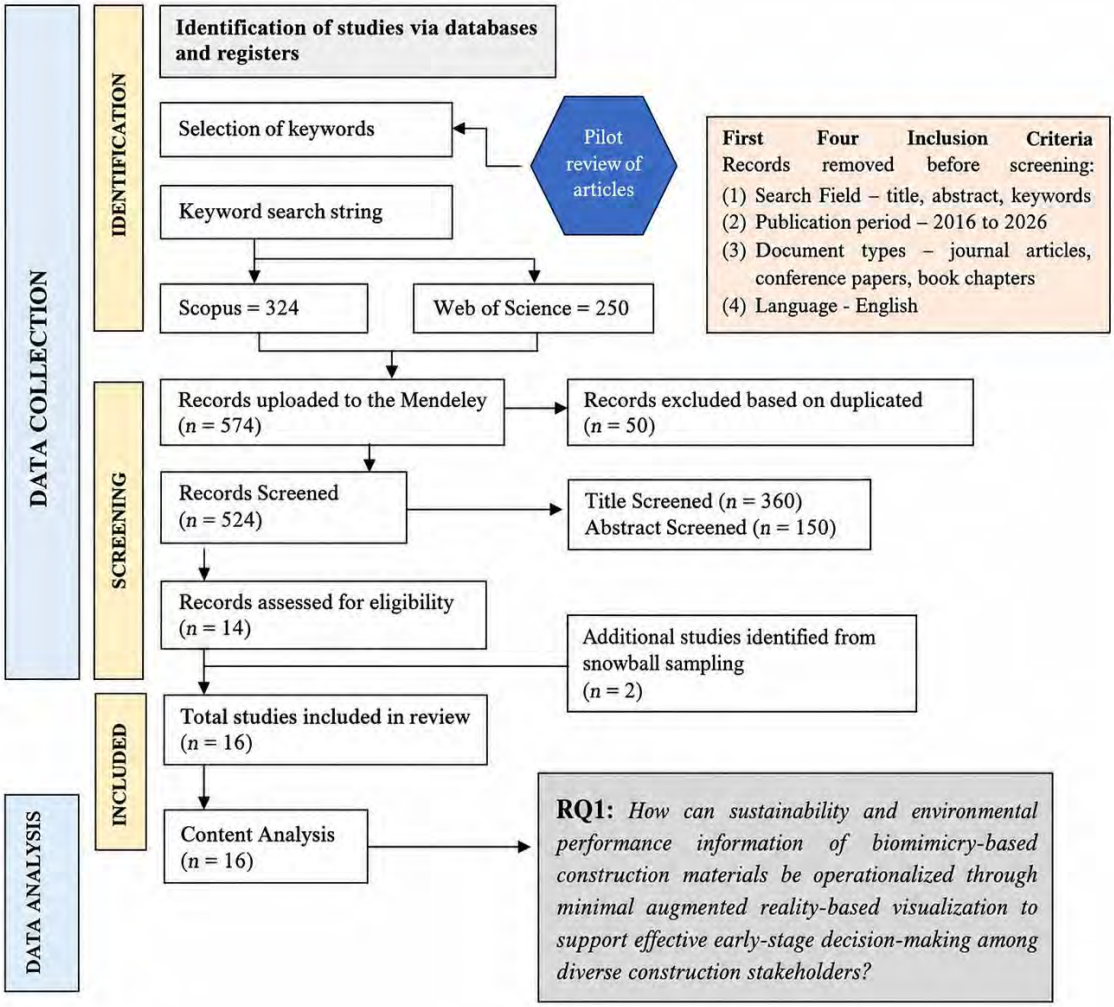



*Figure 1: Overview of research methodology*

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework guided the literature screening and selection process illustrated in Figure 1.

## 2.2 DATA ANALYSIS

As the subsequent step, the findings of the selected studies were synthesised using a qualitative content analysis technique (Briner & Denyer, 2012). Content analysis enables the systematic interpretation of textual data through the identification of recurring

patterns, themes, and relationships, making it particularly suitable for exploratory and framework-building research (Moher et al., 2007).

The analysis was conducted manually, without the use of qualitative analysis software. Manual analysis allowed deeper interpretive engagement with the studies and facilitated the identification and exclusion of conceptually weak or methodologically limited evidence, thereby prioritising high-quality insights (Toyin et al., 2025). Each study was coded based on key dimensions, including: (i) type of biomimicry-based construction material, (ii) sustainability and environmental performance indicators, decision-support or visualization methods employed, and (iii) the role of augmented or minimal AR in facilitating stakeholder understanding. The synthesised findings were systematically organised and reported in the results section of this study (Börner et al., 2012). An overview of the research methodology and screening process is illustrated using a PRISMA flow diagram, developed in accordance with the PRISMA guidelines to ensure transparency, completeness, and reproducibility (Sohrabi et al., 2021).

The final sample size of 16 studies was considered methodologically appropriate due to the highly focused and interdisciplinary nature of the review topic, which combines biomimicry-based materials, sustainability indicators, and AR-assisted decision-support systems. Similar niche construction management SLR studies have employed focused datasets to support conceptual framework development and thematic synthesis.

# 3. FINDINGS

## 3.1 OVERVIEW OF THE INCLUDED STUDIES

The final set included studies comprised of peer-reviewed journal articles, review papers, conference proceedings, and book chapters published between 2016 and 2026, reflecting the growing scholarly interest in biomimicry-based construction materials and sustainability-driven innovation in the built environment (Zari & Hecht, 2020). The reviewed publications were predominantly drawn from journals in materials science, construction engineering, sustainability, biomimetics, and digital construction, highlighting the interdisciplinary nature of the research domain. While a substantial proportion of studies focused on material development and performance optimisation, relatively fewer addressed issues related to material selection, stakeholder decision-making, or communication at the early design stage.

The results of the systematic review revealed 16 publications pertaining to biomimicry-based constructing materials of value for Green building applications. The results of the publications, based on initial research from 2020 to 2022, essentially focused on the assessment of green building performance criteria, which included carbon, biodegradability, and carbon sequestration. As of 2023, the investigations accounted for a wide array of performance criteria, which included thermal resistance, fire safety, durability, and cost. This denotes the fact that stakeholders dealing with green building applications began to understand, from the perspective of biomimicry-based materials, the need to evaluate their effectiveness, both with regard to functionality and the environment. From these scholarly findings, it is ascertainable that biomimicry-based materials, which include bio-cement, mycelium, and algae, had application for green building applications.

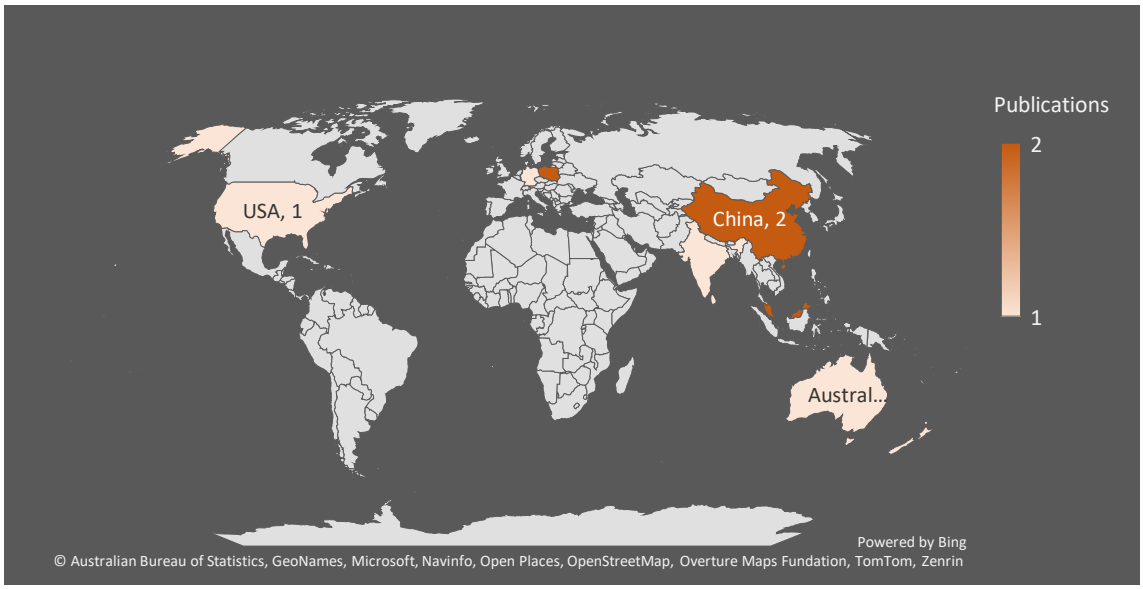



*Figure 2: Worldwide distribution map of publications.*

From 2024 to 2025, these publications grew exponentially, thus revealing models of research from different parts of the world, including Poland, Germany, China, Malaysia, Sri Lanka, New Zealand, the USA, India, concerning their interest in green building applications as demonstrated in Figure 2.

## 3.2 BIOMIMICRY-BASED CONSTRUCTION MATERIALS ADDRESSED IN LITERATURE

Analysis of the included studies revealed that biomimicry-based construction materials are primarily investigated within three broad categories. A significant body of research concentrates on bio-cementitious and self-healing materials, including microbially induced calcite precipitation, enzyme-based binders, and biologically enhanced concrete systems (Amran et al., 2022). These studies consistently report improvements in durability, crack-healing capacity, and reductions in embodied carbon when compared to conventional cementitious materials. Another prominent stream of research focuses on biogenic and bio-derived materials such as mycelium composites, algae-based systems, bamboo, cellulose-based materials, and biochar-enhanced composites (Abdelhady et al., 2023). These materials are frequently associated with benefits such as Carbon sequestration, biodegradability, lightweight construction, and improved thermal performance, particularly in non-structural or envelope applications. A smaller yet emerging set of studies explores nature-inspired surface treatments and adaptive material systems that mimic biological processes such as self-cleaning, moisture regulation, and energy optimisation. Despite the demonstrated environmental and functional advantages, the majority of studies examine these materials in isolation, without embedding them within comparative frameworks that support real-world material selection or design decision-making.

## 3.3 SUSTAINABILITY AND ENVIRONMENTAL PERFORMANCE INDICATORS

The reviewed literature employs a wide range of sustainability and environmental performance indicators to evaluate biomimicry-based construction materials. Embodied carbon and greenhouse gas emission reduction potential emerge as the most frequently

reported metrics, particularly in studies comparing bio-based materials to conventional concrete, insulation, or composite systems. Several studies extend beyond embodied carbon to consider lifecycle performance, including durability, maintenance reduction, and end-of-life biodegradability. Thermal performance, energy efficiency, and material efficiency are commonly assessed, especially for envelope-related applications. However, the analysis reveals considerable inconsistency in indicator selection and reporting formats across studies. Sustainability data are predominantly presented in technical, numerical, or tabular forms, often requiring specialist knowledge to interpret. As a result, the potential of these indicators to inform early-stage design decisions among diverse stakeholder groups remains limited.

### 3.4 DECISION-SUPPORT APPROACHES IN BIOMIMICRY-BASED MATERIAL RESEARCH

Only a limited number of studies explicitly address decision-support mechanisms for biomimicry-based construction materials. Where decision-support is considered, it is typically embedded within advanced engineering models, optimisation algorithms, or artificial intelligence-based assessment tools. While these approaches offer analytical rigor, they often lack accessibility and are unsuitable for rapid, concept-stage material evaluation. Comparative material selection frameworks are rare, and few studies translate sustainability performance data into formats that can support intuitive understanding by architects, clients, or non-technical stakeholders. This indicates a clear disconnect between material innovation research and practical decision-making needs in sustainable building design.

### 3.5 DIGITAL TECHNOLOGIES AND THE ROLE OF AUGMENTED REALITY

Digital technologies, including building information modelling, artificial intelligence, and simulation-based tools, are addressed in several studies; however, their application is largely oriented toward performance optimisation rather than communication or decision support. Augmented reality is predominantly applied in construction training, assembly guidance, or design visualisation contexts. The review found only limited exploration of AR as a tool for supporting sustainable material selection. Moreover, existing AR applications tend to rely on complex, resource-intensive systems, which limit their suitability for early-stage, low-barrier decision-making. Notably, no study was identified that integrates biomimicry-based material evaluation, sustainability indicators, and minimal or lightweight AR visualisation within a unified decision-support framework.

### 3.6 SYNTHESIS OF KEY RESEARCH GAPS

The synthesis of findings across the reviewed studies reveals three interrelated gaps. First, there is an operational gap, whereby biomimicry-based materials demonstrate strong sustainability potential but lack structured tools to support systematic comparison and selection during early design stages. Second, communication gaps persist, as sustainability and embodied carbon information are rarely presented in intuitive or visually accessible formats that cater to diverse stakeholder groups. Third, a technological gap is evident, as the potential of minimal augmented reality to function as a lightweight decision-support mechanism for sustainable material selection remains largely unexplored. The reviewed literature collectively demonstrates that while biomimicry-based materials exhibit strong sustainability and functional potential, existing studies

remain technologically fragmented and insufficiently operationalised for stakeholder-oriented decision-making. This indicates the absence of lightweight, cognitively accessible frameworks capable of translating multidimensional material performance into comparative design-stage evaluation environments.

Using a case diagram in Figure 3 is a graphical representation to explain the interactions between users (decision-makers / project stakeholders) and the AR-based material selection process.

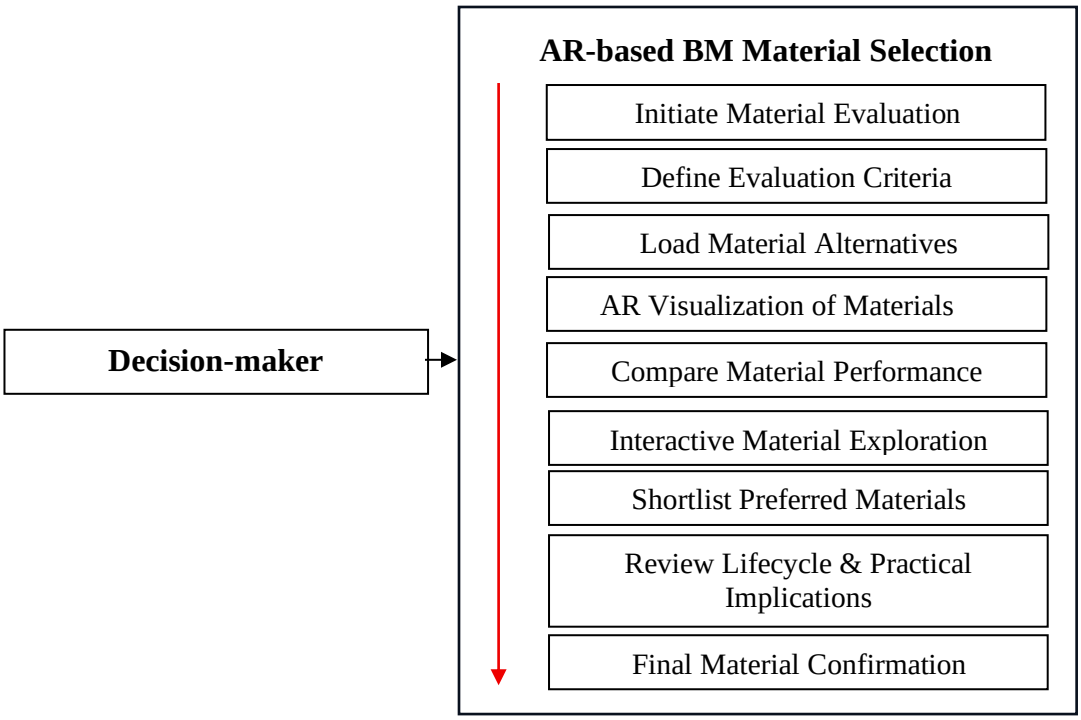



*Figure 3: User case diagram for AR-based visualization*

First, the user must access the Google account or Microsoft account to the application. The successfully logged-in users can access the database by navigating through primary views and main views. The system validates the user credentials and then allows authorised users to access the specific detailed design and real-time data. Through this application, users can access visualisations of Biomimicry and conventional materials, detailed designs, AR visualization instructions, and generate a detailed report.

## 3.7 IMPLICATIONS FOR CONCEPTUAL FRAMEWORK DEVELOPMENT

These findings directly informed the development of a conceptual framework to support the effective adoption of biomimicry-based construction materials. By synthesising evidence from materials science, sustainability assessment, and digital visualization research, the framework integrates material attributes, sustainability indicators, stakeholder decision-making needs, and minimal AR-based visualisation mechanisms. This framework addresses the identified gaps and provides a structured basis for enhancing early-stage material decision-making in sustainable building design.

## 3.8 CONCEPTUAL FRAMEWORK FOR THE MATERIAL SELECTION WITH LIMITED AUGMENTED REALITY BASED ON PERFORMANCE INDICATORS

The conceptual framework outlines the evaluation and selection of biomimicry-based construction materials through an AR-assisted decision-making process. Material assessment serves as the primary input, with AR visualisations aiding stakeholders in informed decision-making (Sparks et al., 2024).

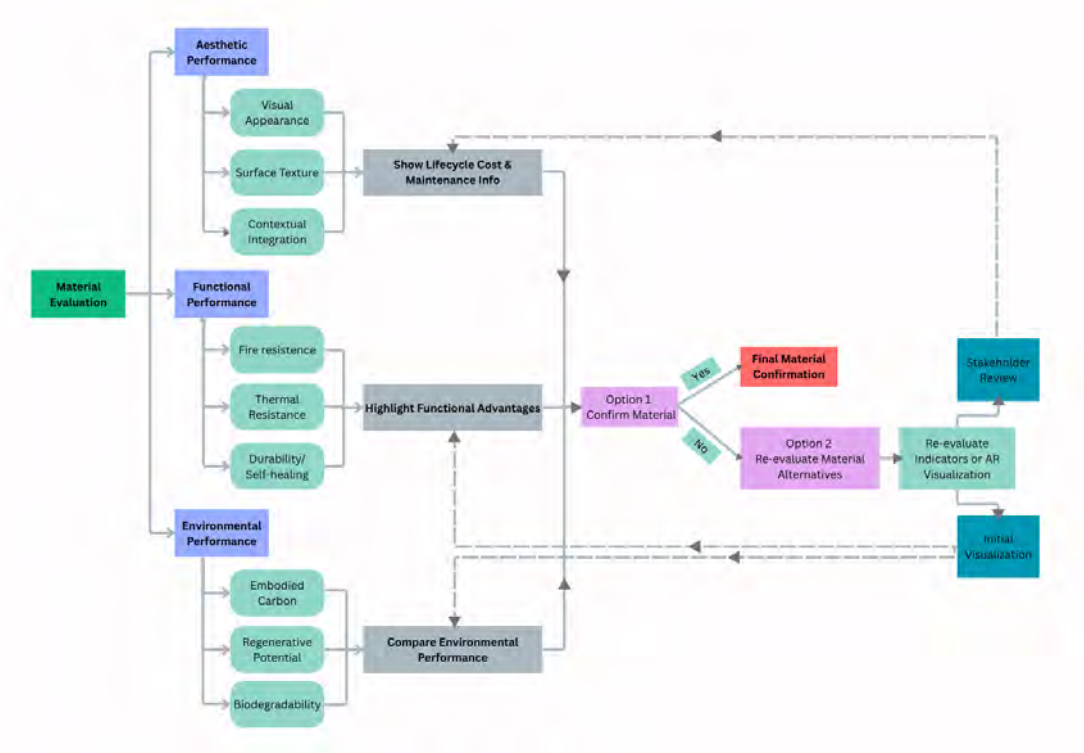



*Figure 4: Conceptual framework*

Stakeholders actively interact with the AR interface throughout the evaluation process, using visualised information to compare material alternatives and support selection decisions. Material evaluation is structured around three intertwined performance areas: aesthetic, functional, and environmental. Aesthetic performance is assessed via visual appearance, surface texture, and contextual integration, relevant to early design stages. Functional performance considers fire resistance, thermal resistance, and durability or self-healing capacity, reflecting safety, comfort, and long-term usability. Environmental performance is measured through embodied carbon, regenerative potential, and biodegradability, addressing sustainability implications.

These indicators are integrated through AR-mediated analysis, transforming complex performance data into interactive visualisations. AR supports comparative assessment of environmental performance, synthesises functional indicators for trade-off analysis, and links aesthetic and lifecycle factors to maintenance and cost information. Initial AR visualisation acts as a cognitive entry point, helping stakeholders make sense of data before technical review.

The framework introduces two decision pathways: one leading to final material confirmation, and another allowing re-evaluation of alternatives, reflecting real-world iterative behavior. At the decision stage, stakeholders assess the AR-supported

comparisons and either confirm a material choice or revisit alternative options for further evaluation. By combining comparison, iteration, and confirmation, it prevents premature decisions and ensures that at least two alternatives are considered. AR functions as more than a visualisation tool; it mediates complex performance and sustainability information for diverse stakeholders.

## 4. CONCLUSIONS

This study systematically reviewed the literature on biomimicry-based construction materials, their performance indicators, and the potential role of AR in supporting material selection decisions. The review identified that existing research predominantly evaluates biomimicry-based materials based on environmental, functional, or aesthetic performance criteria in isolation, with limited attention given to integrated decision-support approaches. Furthermore, while AR technologies have been increasingly applied within construction, their use has been largely confined to visualisation, training, and assembly-related applications rather than material evaluation and selection.

The findings revealed three key gaps within the current body of knowledge. First, there is an operational gap resulting from the absence of structured approaches for comparing biomimicry-based materials during early-stage design decision-making. Second, a communication gap exists because material performance information is commonly presented in technical formats that may be difficult for diverse stakeholders to interpret. Third, a technological gap was identified, as the application of lightweight AR as a decision-support mechanism for sustainable material selection remains largely unexplored. To address these gaps, the study developed a conceptual framework that integrates environmental, functional, and aesthetic performance indicators within an AR-assisted material selection process. The framework demonstrates how AR can be used to communicate multidimensional material performance information through interactive visualisations that support comparison, stakeholder engagement, and iterative decision-making. By incorporating alternative evaluation and re-evaluation pathways, the framework reflects the iterative nature of real-world material selection processes. The study contributes to the growing body of knowledge on sustainable construction materials by synthesising dispersed evidence across biomimicry, material performance assessment, and digital visualisation research. Practically, the framework provides a foundation for developing accessible digital tools that can support stakeholders in understanding and comparing biomimicry-based material alternatives during the early stages of project development. As the framework has been developed through literature synthesis, future research should focus on its empirical validation through expert evaluation, stakeholder workshops, and prototype implementation. Further studies may also investigate the effectiveness of smartphone-based AR applications in improving stakeholder understanding, decision quality, and adoption of biomimicry-based construction materials within real project environments.

## 5. RESEARCH CONTRIBUTIONS

This study contributes to the sustainable construction literature by synthesising fragmented knowledge on biomimicry-based construction materials, material performance indicators, and augmented reality-assisted decision-support approaches. The review identifies environmental, functional, and aesthetic performance indicators commonly used to evaluate biomimicry-based materials and highlights the challenges

associated with their communication and application during early-stage material selection. Conceptually, the study proposes an integrated framework that brings together these multidimensional performance indicators within an AR-assisted decision-making process. The framework responds to the operational, communication, and technological gaps identified in the literature by illustrating how material performance information can be structured and presented in a more accessible manner for stakeholder evaluation.

From a practical perspective, the framework provides a foundation for the future development of decision-support tools that may assist stakeholders in comparing biomimicry-based and conventional material alternatives during the design stage. By emphasising visualisation and comparative assessment, the framework highlights opportunities to improve the communication of sustainability-related material information. The study contributes to the emerging discussion on the role of AR in sustainable construction by extending its application beyond training and visualisation contexts and exploring its potential as a lightweight decision-support mechanism for material evaluation. As the framework was developed through systematic literature synthesis, its contribution is primarily conceptual. Future research is required to validate the framework through stakeholder evaluation, prototype development, and real-world implementation studies.

## 6. REFERENCES

Abdelhady, O., Spyridonos, E., & Dahy, H. (2023). Bio-Modules: Mycelium-Based Composites Forming a Modular Interlocking System through a Computational Design towards Sustainable Architecture. *Designs*, *7*(1), 20. https://doi.org/10.3390/designs7010020

Ahamed, M. K., Wang, H., & Hazell, P. J. (2022). From biology to biomimicry: Using nature to build better structures – A review. *Construction and Building Materials*, *320*, 126195. https://doi.org/10.1016/J.CONBUILDMAT.2021.126195

Amran, M., Onaizi, A. M., Fediuk, R., Vatin, N. I., Muhammad Rashid, R. S., Abdelgader, H., & Ozbakkaloglu, T. (2022). Self-Healing Concrete as a Prospective Construction Material: A Review. *Materials*, *15*(9), 3214. https://doi.org/10.3390/ma15093214

Berryman, D. R. (2012). Augmented Reality: A Review. *Medical Reference Service Quartely*, 212–218.

Börner, K., Boyack, K. W., Milojević, S., & Morris, S. (2012). An Introduction to Modeling Science: Basic Model Types, Key Definitions, and a General Framework for the Comparison of Process Models (pp. 3–22). https://doi.org/10.1007/978-3-642-23068-4_1

Briner, R. B., & Denyer, D. (2012). Systematic Review and Evidence Synthesis as a Practice and Scholarship Tool.

Han, T., Huang, Q., Zhang, A., & Zhang, Q. (2018). Simulation-based decision support tools in the early design stages of a green building-A review. In *Sustainability* (Switzerland) (Vol. 10, Number 10). MDPI. https://doi.org/10.3390/su10103696

Iroegbu, A., & Ray, S. (2021). Bamboos: From Bioresource to Sustainable Materials and Chemicals. *Sustainability*, *13*(21), 12200. https://doi.org/10.3390/su132112200

Man, S. S., Wen, H., & So, B. C. L. (2024). Are virtual reality applications effective for construction safety training and education? A systematic review and meta-analysis. *Journal of Safety Research*, *88*, 230–243. https://doi.org/10.1016/j.jsr.2023.11.011

Moher, D., Tetzlaff, J., Tricco, A. C., Sampson, M., & Altman, D. G. (2007). Epidemiology and reporting characteristics of systematic reviews. *PLoS Medicine*, *4*(3), 447–455. https://doi.org/10.1371/journal.pmed.0040078

Mumcu, Ü., & Korkmaz, H. (2025). FUTURE PROJECTIONS WITH PLANTS THAT BUILT OUR PAST. *International Journal of Agricultural and Natural Sciences E*, *18*(1), 95–104. https://doi.org/10.5281/zenodo.15324502

Ngaba, M. J. Y., Yemele, O. M., Hu, B., & Rennenberg, H. (2025). Biochar application as a green clean-up method: bibliometric analysis of current trends and future perspectives. *Biochar*, *7*(1), 83. https://doi.org/10.1007/s42773-025-00470-2

Nielsen, A. N., Jensen, R. L., Larsen, T. S., & Nissen, S. B. (2016). Early stage decision support for sustainable building renovation - A review. In *Building and Environment* (Vol. 103, pp. 165–181). Elsevier Ltd. https://doi.org/10.1016/j.buildenv.2016.04.009

Ortega Del Rosario, M. D. L. Á., Beermann, K., & Austin, M. C. (2023). Environmentally Responsive Materials for Building Envelopes: A Review on Manufacturing and Biomimicry-Based Approaches. In *Biomimetics* (Vol. 8, Number 1). MDPI. https://doi.org/10.3390/biomimetics8010052

Pedersen Zari, M., & Hecht, K. (2020). Biomimicry for Regenerative Built Environments: Mapping Design Strategies for Producing Ecosystem Services. *Biomimetics*, *5*(2), 18. https://doi.org/10.3390/biomimetics5020018

Petticrew, M., & Roberts, H. (2006). *Systematic Reviews in the Social Sciences*. Wiley. https://doi.org/10.1002/9780470754887

Riani, U., Melkoumian, N., Harvey, D., & Akmeliawati, R. (2025). Learning from Nature: Bio-Inspired Designs and Strategies for Efficient On-Earth and Off-Earth Ventilation Systems. *Biomimetics*, *10*(11), 754. https://doi.org/10.3390/biomimetics10110754

Shufrin, I., Pasternak, E., & Dyskin, A. (2023). Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities. *Applied Sciences*, *13*(23), 12891. https://doi.org/10.3390/app132312891

Siddaway, A. P., Wood, A. M., & Hedges, L. V. (2024). How to Do a Systematic Review: A Best Practice Guide for Conducting and Reporting Narrative Reviews, Meta-Analyses, and Meta-Syntheses. *Annu. Rev. Psychol*, *70*, 747–770. https://doi.org/10.1146/annurev-psych-010418

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Sohrabi, C., Franchi, T., Mathew, G., Kerwan, A., Nicola, M., Griffin, M., Agha, M., & Agha, R. (2021). PRISMA 2020 statement: What's new and the importance of reporting guidelines. *International Journal of Surgery*, *88*, 105918. https://doi.org/10.1016/j.ijsu.2021.105918

Sparks, S. S., Obando, A. G., Li, Y., Chen, S., Yao, S., & Qiu, K. (2024). 3D-printed biomimetic and bioinspired soft actuators. In *IET Cyber-systems and Robotics* (Vol. 6, Number 4). John Wiley and Sons Inc. https://doi.org/10.1049/csy2.70001

Toyin, J. O., Sattineni, A., Wetzel, E. M., Fasoyinu, A. A., & Kim, J. (2025). Augmented reality in U.S. Construction: Trends and future directions. *Automation in Construction*, *170*, 105895. https://doi.org/10.1016/j.autcon.2024.105895

Wang, B., Wang, J., Fang, Z., Zhu, Z., & Gao, N. (2025). Biomimetic components and their mechanisms in the evolution of China's agricultural heritage landscape systems. *Journal of Asian Architecture and Building Engineering*, 1–22. https://doi.org/10.1080/13467581.2025.2608447

Hewage, I.S., Ruwanthika, H.K.P., Piyasena, R.K.N.P, Perera, T.A., Satharasinghe, A., Gunawardena, A. and Halwatura, R.U., 2026. Physicochemical characterisation of polyester and nylon synthetic fibres as potential plant growth substrates for green roof systems: A preliminary study. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1315-1327. DOI: https://doi.org/10.31705/WCS.2026.96. Available from: https://ciobwcs.com/papers/

# PHYSICOCHEMICAL CHARACTERISATION OF POLYESTER AND NYLON SYNTHETIC FIBRES AS POTENTIAL PLANT GROWTH SUBSTRATES FOR GREEN ROOF SYSTEMS: A PRELIMINARY STUDY

**I.S.Hewage[1], H. K. P. Ruwanthika[2], R.K.N.P. Piyasena[3], T.A. Perera[4], A. Satharasinghe[5], A. Gunawardena[6] and R.U.Halwatura[7]**

## *ABSTRACT*

*Green roofs are recognised as effective urban sustainability infrastructure, yet the conventional use of soil-based growing media poses challenges, including high dead loads, progressive structural decomposition, and costly long-term maintenance. This study presents a preliminary physicochemical characterisation of shredded Polyester and Nylon textile waste fabrics as novel, lightweight, synthetic growing substrates for green roof systems, evaluating their suitability against established benchmarks. No plant growth trials were conducted; the scope is limited to laboratory characterisation of key physicochemical properties. Growing medium containers filled with shredded polyester and Nylon fabrics were characterized for bulk density, particle density, total porosity, Water Holding Capacity (WHC), Water Retention Capacity (WRC), pH, and Electrical Conductivity (EC). Mean bulk densities of 0.22 ± 0.015 $gcm^{-3}$ (Nylon) and 0.145 ± 0.019 $gcm^{-3}$ (Polyester) represent reductions of 63-89% relative to conventional green roof soils. Total porosity exceeded 74% for nylon and 84% for polyester, exceeding the FLL minimum of 35%. WHC ranged from 63-66% (Nylon) and 72-78% (Polyester), satisfying the FLL requirement of ≥35% by volume. The water retention curves demonstrated that polyester maintained consistently higher water retention throughout the drying period, retaining approximately 17% of absorbed water, indicating polyester's superior capillary water-holding capacity driven by its fibrous matrix structure. Both substrates exhibited pH values within the optimal horticultural range and EC values indicating minimal salinity stress risk. These preliminary results suggest that recycled synthetic textile waste fibers warrant further investigation as lightweight, chemically inert,*

[1] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, iresharesearch1@gmail.com
[2] Department of Environmental Technology, Faculty of Technology, University of Colombo, 2020t00815@stu.cmb.ac.lk
[3] Research Assistant, Department of Civil Engineering, University of Moratuwa, Sri Lanka, nethmi97praba@gmail.com
[4] Senior Lecturer, Department of Plant Science, Faculty of Science, University of Colombo, Colombo, Sri Lanka., thilini@pts.cmb.ac.lk
[5] General Manger-Head of High Impact Concepts, MAS Innovations-Twinery, Colombo, Sri Lanka, achalasa@masholdings.com
[6] Deputy Director, Central Environmental Authority, Colombo, Sri Lanka., Ajithr@cea.lk
[7] Senior Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangika@uom.lk

*and structurally stable growing media for green roof systems, pending validation through plant growth trials.*

**Keywords:** *Green roof substrate; Growing media; Nylon; Polyester; Synthetic fibre; Urban greening.*

# 1. INTRODUCTION

Rapid urbanisation worldwide has led to the systematic displacement of natural vegetated surfaces by impervious built environments, resulting in a range of well-documented ecological and infrastructural consequences. These include exacerbated Urban Heat Island (UHI) effects, diminished stormwater management capacity, habitat fragmentation, elevated energy consumption in buildings, and deterioration of urban air quality (Getter & Rowe, 2006; Vijayaraghavan, 2016). Green roof technology has emerged as one of the most promising strategies for recovering lost green coverage within dense urban environments, simultaneously delivering stormwater attenuation, thermal insulation, biodiversity enhancement, and extended waterproof membrane life (Dunnett et al., 2008).

A green roof system is typically composed of overlapping functional layers: a structural waterproofing membrane, a root barrier, a drainage layer, a filter fabric, the growing substrate, and the vegetation layer, as illustrated in Figure 1. Among these, the growing substrate is widely regarded as the most critical layer, as it provides physical anchorage, water and nutrient retention, and aeration for root respiration (Ampim et al., 2010, Farrell et al., 2013).

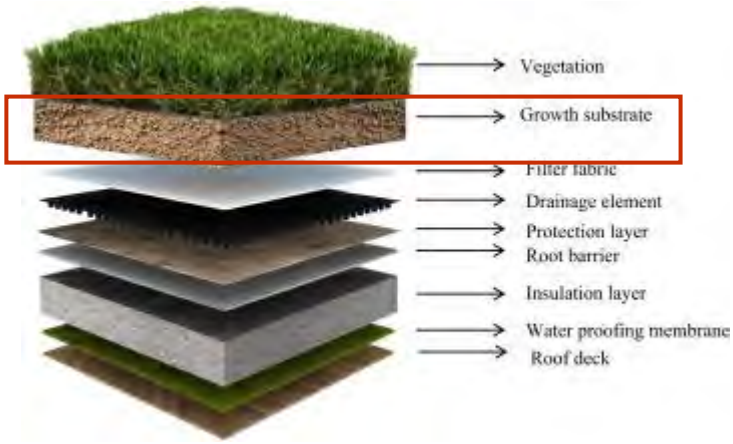



*Figure 1: Overlapped functional layers of the green roof (Vijayaraghavan, 2016)*

Despite substantial advances in green roof technology, soil remains the most commonly employed substrate material in many developing countries, largely due to its local availability and low cost. However, soil-based substrates impose significant dead loads on the roofing structure, exhibit progressive compaction and structural decomposition over time, and demand ongoing maintenance interventions including amendment, topping-up, and weed management (Getter & Rowe, 2006; Vijayaraghavan, 2016).

The ideal green roof growing substrate must satisfy a demanding and often competing set of physicochemical criteria. International guidelines, most notably the German FLL Guidelines (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau [FLL], 2018), stipulate that substrates should exhibit a dry bulk density not exceeding 1,200

kg/m³ (1.2 g/cm³), a total porosity and Water Holding Capacity (WHC) between 35 and 65% by volume, a pH in the range of 6.0-8.5, and an Electrical Conductivity (EC) below 3.5 g/L for extensive systems (Graceson et al., 2013). Meeting these criteria while simultaneously minimising structural weight and long-term maintenance costs remains a core challenge in green roof substrate design.

In response to these challenges, researchers have explored a broad range of alternative and recycled growing media, including crushed brick and tile, pumice and volcanic tuff (Tala et al., 2020), expanded clay aggregates (Graceson et al., 2014), coco-peat blends (Vijayaraghavan & Raja, 2014), rice hulls (Farrell et al., 2013), and biochar (Nguyen et al., 2024). The growing global textile industry generates enormous quantities of synthetic fabric waste, with polyester and nylon constituting the two most widely produced synthetic fiber categories. Both are manufactured from petroleum-derived polymers and are characterised by high durability, chemical inertness, low biodegradability, and pronounced resistance to biological decomposition. These properties, while often cited as environmental liabilities, may in fact confer significant advantages in the context of green roof substrate design, where long-term structural stability and resistance to organic matter breakdown are desirable attributes.

The use of synthetic fibrous materials as plant growing substrates is supported by specific experimental evidence. Studies by Pasian and Frantz (2008) demonstrated that polyethylene terephthalate (PET) fibers can serve as effective soilless growing media for floriculture, while Sharma et al. (2022) documented the compatibility of polyester and nylon agrotextiles with plant root systems. These investigations indicate that polyester and nylon fiber matrices can function as effective plant growing media in soilless cultivation and horticultural systems. Recyclable Polyethylene Terephthalate (PET), which is the same polymer used in polyester fibers, has been investigated as a component of synthetic growing media. These studies suggest that PET-based substrates can serve as a viable alternative growing medium for floriculture and other soilless crop production systems (Pasian & Frantz, 2008). Their investigation demonstrated that PET had already been applied as a growing medium substrate. Therefore, physical support, moisture retention, and appropriate aeration for seedling establishment in the same functional requirements demanded of green roof growing substrates. Furthermore, a substantial literature on agrotextiles, synthetic fabric materials applied directly in agricultural and horticultural settings, corroborates that Nylon and Polyester fibers are compatible with plant root systems and are routinely employed in crop protection, filtration, and root-zone management applications without phytotoxic effects (Sharma et al., 2022). These converging lines of evidence from soilless horticulture, agrotextile science, and Green roof engineering establish a firm scientific foundation for the hypothesis that Polyester and Nylon textile fibers are suitable as growing substrate materials, and motivate systematic characterization of their key physicochemical properties for Green roof application.

Despite the promising conceptual basis for textile-derived substrates and the supporting evidence from adjacent fields, no peer-reviewed study to date has systematically characterised shredded polyester and nylon fabrics as standalone green roof growing media and benchmarked their physicochemical properties against established substrate standards. The present study aims to address this gap by evaluating the bulk density, particle density, total porosity, water holding capacity, water retention capacity, pH, and electrical conductivity of shredded Polyester and Nylon textile substrates and comparing

these parameters against both the FLL guideline thresholds and empirical values reported for conventional and alternative green roof growing media in the literature.

## 2. MATERIALS AND METHODS

The research methodology consisted of the following steps, as illustrated in Figure 2. Each step is briefly described in the sections below.

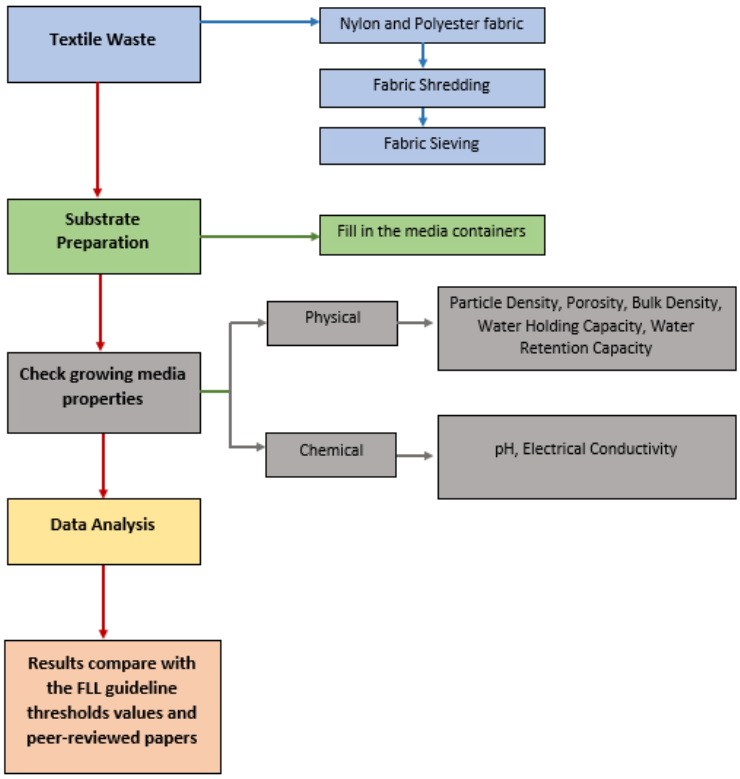



*Figure 2: Flow diagram of the methodology*

### 2.1 SUBSTRATE PREPARATION

Polyester and nylon textile waste fabrics were collected and subjected to mechanical shredding to produce fibrous substrate materials (Figure 3a–d).

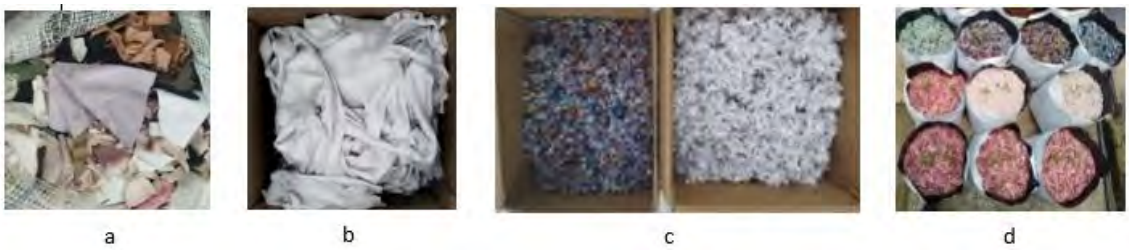



*Figure 3: a: Polyester fabric, b: Nylon fabric, c: Shredded polyester and Nylon, d: Growing media filled to the grow bags*

Shredded fabrics were packed into standardised grow bags to a uniform depth. Four replicate bags were prepared for each substrate type, designated as T1R1–T1R4 (Nylon) and T2R1–T2R4 (Polyester). All bags were prepared under controlled laboratory conditions (temperature: 25 ± 2°C; relative humidity: 60 ± 5%) to ensure consistent

packing density across replicates and to minimise environmental variation in the physicochemical measurements.

### 2.2 PHYSICAL PROPERTY ASSESSMENT

Bulk density (g/cm³) was determined gravimetrically as the ratio of dry substrate mass to the volume occupied within the media (FLL, 2018). Particle density (g/cm³) was measured using a volumetric method with water as the displacement medium (FLL, 2018). Total porosity (%) was calculated using the standard formula:

*Porosity (%) = [1 - (Bulk Density / Particle Density)] × 100.* *(01)*

WHC was determined as the mass of water retained by the substrate after free gravitational drainage, expressed as a percentage of saturated substrate mass (FLL, 2018; Di Gioia et al., 2017). Water Retention Capacity (WRC) was assessed by measuring the percentage of water retained relative to the saturated mass after a defined drainage period (Durpekova et al., 2021).

### 2.3 CHEMICAL PROPERTY ASSESSMENT

The pH of each substrate was determined using a calibrated pH meter in a 1:2.5 substrate-to-distilled water suspension following standard horticultural protocols. EC was measured in the same suspension using a calibrated EC meter and expressed in $\mu Scm^{-1}$ (FLL, 2018).

### 2.4 STATISTICAL ANALYSIS

Descriptive statistics (mean and standard deviation) were computed for all measured parameters across the four replicates of each substrate type. Results were compared against FLL guideline thresholds and published empirical data from peer-reviewed studies on conventional and alternative green roof growing media.

## 3. RESULTS

### 3.1 PHYSICAL PROPERTIES

The physical properties of Nylon and Polyester substrates across all replicates are presented in Table 1.

*Table 1. Physical and chemical properties of nylon and polyester synthetic fiber substrates*

| Synthetic growing media type | Treat ments | Bulk Density (g/cm³) | Particle Density (g/cm³) | Porosit y (%) | WHC (%) | pH | EC (µS/c m) |
|---|---|---|---|---|---|---|---|
| Nylon | T1 | 0.22 ± 0.015 | 0.955 ± 0.050 | 76.87 ± 2.44 | 64.47 ± 1.44 | 7.02 ± 0.16 | 210.3 ± 8.0 |
| polyester | T2 | 0.145 ± 0.019 | 1.063 ± 0.125 | 86.10 ± 2.72 | 76.14 ± 2.19 | 7.04 ± 0.19 | 171 ± 4.56 |

*WHC = Water Holding Capacity; SD = Standard Deviation*

Nylon substrate recorded bulk densities 0.22 ± 0.015 gcm-³, while Polyester replicates exhibited consistently lower bulk density mean 0.145 ± 0.019 gcm-³. Particle density of Nylon growing substrate was 0.955 ± 0.05 gcm-³ and Polyester substrate was 1.063 ± 0.125 gcm-³. Total porosity values ranged from 74.73 to 80% for nylon (mean 76.9 ±

2.4%) and from 84 to 90.4% for polyester (mean 86.1 ± 2.7%). WHC was high across all replicates, with nylon recording a mean of 64.47 ± 1.44% and polyester a mean of 76.14 ± 2.19%. WRC was notably variable, with nylon replicates ranging from 17 to 30% and polyester replicates from 22 to 45%.

## 3.2 WATER RETENTION CURVE OVER TIME

The temporal decline in water retention capacity for both substrate types across a six-day drying period is illustrated in Figure 4.

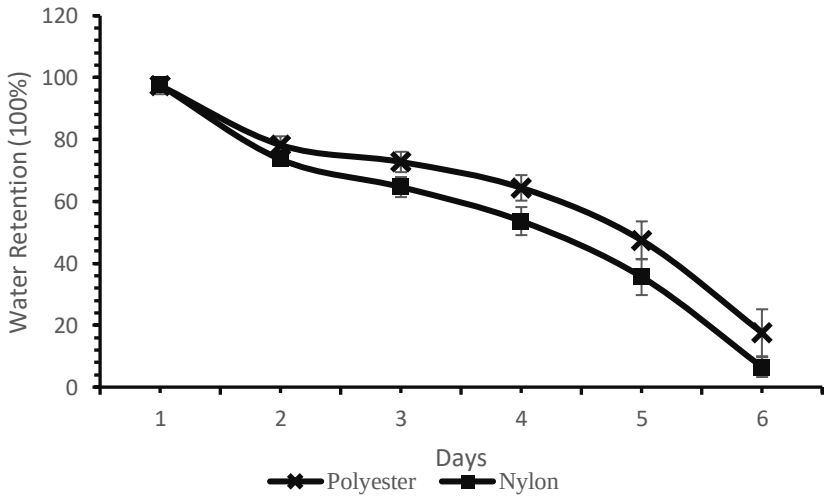



*Figure 4: Water retention curve of Nylon and Polyester synthetic fibre substrates. Error bars represent standard deviation across four replicates (T1R1–T1R4 for Nylon; T2R1–T2R4 for polyester).*

On Day 1, immediately following saturation and initial drainage, both substrates retained near-complete water content: polyester recorded approximately 98% and nylon approximately 96%. Water retention declined progressively for both materials across the observation period, with Polyester consistently retaining a higher percentage of water than Nylon at each time point.

By Day 2, polyester retained 79% and nylon 75% of initial water content. On Day 3, both substrates converged to 70% retention, with Polyester marginally higher. Divergence between the two substrates became more pronounced from Day 4 onwards: by Day 5, Polyester retained 48% while Nylon had declined to 36%. On Day 6, Polyester retained 17% compared with Nylon's near-zero retention (~3%). The error bars visible on Days 5 and 6 for polyester reflect inter-replicate variability in WRC, which is consistent with the higher standard deviation observed in the measured WRC values (Table 1). Nylon's more rapid and complete drainage to near-zero retention by Day 6 indicates a lower capacity to hold water against prolonged evaporative and gravitational losses, while polyester's sustained retention through Day 6 underscores its superior capillary water-holding performance as a green roof growing substrate.

## 3.3 CHEMICAL PROPERTIES

Both substrate types demonstrated near-neutral pH values. Nylon substrates exhibited a mean pH of 7.02 ± 0.16, Polyester substrates showed a mean pH of 7.04 ± 0.19. As shown in Table 2, these values fall well within the FLL-recommended pH range of 6.0 - 8.5 for green roof substrates (Eksi & Rowe, 2019).

*Table 2. Comparison of physicochemical properties of synthetic fiber substrates with conventional and alternative green roof growing media reported in the literature*

| Substrate / Study | Bulk Density (g/cm³) | Porosity (%) | WHC (%) | pH | EC (µS/cm) | Reference |
|---|---|---|---|---|---|---|
| FLL Guideline Thresholds (Extensive) | 0.60-1.20 | ≥35 | 35–65 | 6.0-8.5 | - | (FLL, 2018) |
| Nylon Fiber (This Study) | 0.22 ± 0.02 | 76.87 | 64.47 | 7.02 | 210.3 | This study |
| Polyester Fiber (This Study) | 0.145 ± 0.02 | 86.10 | 76.14 | 7.04 | 171 | This study |
| Perlite | ~0.12-0.24 | ~80.76 | (~15–49) | ~6.5-8.1 | 0-20 | (Ampim et al., 2010; Cakar et al., 2023; Tala et al., 2020) |
| Expanded Clay (LECA) | ~0.23-0.42 | ~78.20 | ~6-50 | 6.5-7.5 | 20 | (Tala et al., 2020), |
| Volcanic Tuff (Coarse) | 0.80–1.50 | 60-80 | 35-55 | 7.0-8.0 | 260-530 | (Tala et al., 2020) |
| Pumice | 0.83 | ~56.22 | ~30-40 | ~7.0 | 300-400 | (Tala et al., 2020) |
| Optimal Mix (Vermiculite + Perlite + Sand + Coco-peat) | 0.431 | ~60-70 | 39.4 | ~6.5-7.0 | 500-100 | (Vijayaraghavan, 2016) |
| Sandy Loam Soil | 1.10-1.40 | 40-55 | 30-60 | 6.5–7.6 | 1100 | (Ampim et al., 2010; Cakar et al., 2023; Papadopoulos & Lieth, 2008; Tala et al., 2020) |
| Crushed Brick + Composted | - | - | 10-32.5 | | - | (Graceson et al., 2013) |
| Sawdust (60:40 organic: base medium | ~0.40-0.60 | ~60-70 | High | ~7.06 | - | (Kader et al., 2024) |
| Biochar-amended | 0.55-0.75 | 58-68 | 38-52 | 6.4-7.8 | 70-700 | (Cao et al., 2014; Francis et al., 2021; Lacarne et al., 2021) |
| coir | 0.19-0.8 | 79.2 | | 6.0 - 6.8 | 861 | (Cakar et al., 2023; Kader et al., 2024) |

| Substrate / Study | Bulk Density ($g/cm^3$) | Porosity (%) | WHC (%) | pH | EC (µS/cm) | Reference |
|---|---|---|---|---|---|---|
| Cocopeat | 1.2-1.9 | - | 86.77 | 5.5-6.72 | 50-770 | (Cakar et al., 2023; Tala et al., 2020) |
| Peat moss | 1.2 | - | 79.28 | 3.5-5.9 | 760 | (Tala et al., 2020) |

*Values represent means or reported ranges. WHC values for polyester and nylon exceed many conventional inorganic substrates while bulk densities are substantially lower.*

Electrical conductivity values were very low for both substrates. Nylon exhibited the highest variability, with EC values 210.3 ± 8.0 $\mu Scm^{-1}$. Polyester substrates recorded EC value 171 ± 4.56 $\mu Scm^{-1}$). All measured EC values are substantially lower than those reported for conventional soil-based substrates in previous studies (Cakar et al., 2023; Kader et al., 2024). The FLL Guideline does not clearly mention the exact EC values.

# 4. DISCUSSION

## 4.1 BULK DENSITY AND STRUCTURAL WEIGHT IMPLICATIONS

The bulk densities recorded for both Nylon 0.22 ± 0.015 $gcm^{-3}$ and polyester 0.145 ± 0.02 $gcm^{-3}$ substrates are remarkably low in comparison to all conventional and most alternative green roof growing media reported in the literature. The FLL guidelines recommend a dry bulk density range of 0.60-1.20 $gcm^{-3}$ for green roof substrates (FLL, 2018; Ampim et al., 2010), while typical sandy loam soil-based substrates commonly used in developing countries exhibit bulk densities of 1.10-1.40 $gcm^{-3}$. Even the lightest recognized inorganic substrates, such as perlite (~0.12 $gcm^{-3}$) and expanded clay (~0.23 $gcm^{-3}$ ) (Cakar et al., 2023; Tala et al., 2020), approach the range recorded for synthetic fiber substrates. The extremely low bulk density of shredded textile substrates translates directly to reduced dead load on roofing structures. This reduction would allow green roof installation on a far wider range of building types, including structures with limited load-bearing capacity that currently preclude conventional extensive green roof deployment. This finding is consistent with the growing recognition in the literature that lightweight substrates are a prerequisite for scaling green roof uptake in densely built urban environments, particularly in tropical and developing-country contexts (Kader et al., 2024; Vijayaraghavan, 2016).

The slightly sub-optimal lower bound of FLL bulk density guidelines 0.60 $gcm^{-3}$ is primarily intended to ensure structural stability and prevent substrate displacement under wind uplift and heavy rainfall. In the case of synthetic fiber substrates, the high inter-fiber entanglement of shredded textiles provides physical matrix stability that may compensate for their ultra-low density. Nevertheless, field validation of substrate stability under operational conditions, including exposure to wind, precipitation, and root penetration, is recommended as a priority for future research (FLL, 2018; Philippi, 2005).

## 4.2 POROSITY, AND WATER HOLDING CAPACITY

Total porosity values of 76.87 % Nylon and 86.10% Polyester substantially exceed the FLL minimum threshold of 35% v/v and compare favorably with high-porosity inorganic substrates such as perlite (80.76%) and expanded clay (78.20%) reported by Tala and Clkar (Tala et al., 2020), (Cakar et al., 2023). Critically, unlike perlite and expanded clay which exhibit low water holding capacity despite high porosity, the textile substrates in this study achieved high WHC values (Nylon: 64.47%; polyester: 76.14%), well above the FLL minimum of 35%.

The high WHC of textile substrates is attributable to their fibrous matrix structure, which creates a network of capillary pores capable of retaining water against gravitational drainage. This combination of high total porosity and high WHC is particularly desirable for green roof substrates, as it simultaneously satisfies the need for adequate air-filled porosity (to prevent waterlogging and support root respiration) and sufficient water retention (to buffer plant water availability during dry periods and contribute to stormwater attenuation) (Carrillo-Angeles et al., 2018; Vijayaraghavan, 2016).

The superior WHC of Polyester relative to Nylon is consistent with differences in the surface chemistry and moisture behavior of these two polymers. Polyester (PET) exhibits low inherent moisture absorption (~0.4% moisture regain) due to the hydrophobic structure and chemical inertness of ester groups (Tala et al., 2020; Viši, 2022), Nylon (polyamide), while structurally similar in fiber form, has a slightly higher inherent moisture absorption (~4.2%), which may contribute to WHC (Hearle, 2001; Vlasveld et al., 2005).

## 4.3 MECHANISMS UNDERLYING THE SUPERIOR WATER RETENTION CAPACITY OF POLYESTER

Water retention capacity (WRC), defined here as the percentage of absorbed water retained by the substrate following a defined gravitational drainage period, was notably higher and more variable in Polyester compared with Nylon growing substrate. While both values remain well within practical ranges for green roof substrates, the consistently higher WRC of Polyester warrants mechanistic examination, as it underpins the material's effectiveness as a moisture buffer between rainfall events.

The superior WRC of polyester relative to Nylon can be attributed to a convergence of polymer-level, fiber-structural, and pore-geometric factors. These factors collectively enhance capillary action through the inter-fiber pore network (Ailenei et al., 2021; Das et al., 2007; Hearle, 2001; Morton & Hearle, 2008; Vlasveld et al., 2005; Wang, 2018; Zhang et al. (2022). These properties also have important implications for green roof water management. Substrates with higher WRC retain a greater proportion of absorbed rainfall within the substrate matrix following storm events, slowing runoff generation and contributing to peak flow attenuation (Vijayaraghavan & Raja, 2014). Polyester substrate recorded a mean WRC of 29.5%, compared with a mean of approximately 18% for Nylon. This difference of approximately 11 percentage points is considered practically significant for green roof applications, as it indicates that polyester retains substantially more water within the substrate matrix during inter-storm dry periods, which can directly support plant survival and stormwater attenuation performance. The wider divergence between the two substrates observed from Day 4 onwards (Figure 4) further underscores this distinction under prolonged drying conditions.

## 4.4 pH SUITABILITY

The pH values recorded for both Nylon (7.02 ± 0.16) and Polyester (7.04 ± 0.19) substrates are well within the FLL-recommended range and the range mentioned in the review paper of 5.5-8.5 (Ampim et al., 2010; Cakar et al., 2023; Papadopoulos & Lieth, 2008; Tala et al., 2020). and align closely with the optimal pH of 7.0 identified by review literature as the most suitable for plant nutrient availability in green roof substrates (Kader et al., 2024; Vijayaraghavan, 2016). A pH near neutrality ensures that a broad spectrum of macro and micronutrients remains plant-available, reducing the need for pH amendment supplements and simplifying substrate management (Kader et al., 2024). The chemically inert nature of synthetic fiber substrates thus presents a pH management advantage over both organic and many inorganic alternative substrates.

## 4.5 ELECTRICAL CONDUCTIVITY AND SALINITY ASSESSMENT

Both synthetic fiber substrate types exhibited optimum electrical conductivity values. Polyester substrates recorded a mean EC of 171 ± 4.56 $\mu Scm^{-1}$, while Nylon substrates showed a mean of 210.3 ± 8. $\mu Scm^{-1}$. Both values are relative to the previous studies (Cakar et al., 2023; Kader et al., 2024). Importantly, the EC of synthetic fiber substrates reflects their chemical inertness; Polyester and Nylon polymers do not release soluble salts, nutrient ions, or ionic compounds into the substrate solution under typical environmental conditions (Vijayaraghavan & Raja, 2014). The exceptionally low EC of both fiber substrates indicates negligible salinity stress risk for plant growth in these media, which is advantageous for a broad range of horticultural species.

## 4.6 COMPARISON WITH PREVIOUS GREEN ROOF SUBSTRATE STUDIES

Placing the present results in the context of the broader green roof substrate literature (Table 2), it is evident that synthetic textile fiber substrates compare favorably across all key physicochemical parameters relative to both conventional and emerging alternative substrates. Their porosity values are among the highest reported for any green roof substrate material, exceedingly even perlite in the case of polyester. Their WHC values substantially exceed those of perlite and expanded clay, the two most compared lightweight substrates, while remaining within or above the FLL-recommended range. The physicochemical profile of synthetic fiber substrates most closely resembles that of mineral wool and rockwool substrates commonly used in plant cultivation (Papadopoulos & Lieth, 2008), which are also synthetic, fibrous, chemically inert, and characterised by low bulk density, high porosity, and high WHC. Textile waste substrates offer the additional environmental benefit of diverting solid waste from landfill, contributing to circular economy objectives within the construction and urban greening sector.

## 4.7 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study has several important limitations that should be acknowledged. First, no plant growth trials were conducted; the findings are limited to laboratory physicochemical characterisation, and plant compatibility, root penetration behaviour, and long-term biological performance in the presence of vegetation remain untested. Second, the study was conducted under controlled indoor laboratory conditions, and field-scale performance may differ due to variable rainfall patterns, solar radiation, temperature fluctuations, and urban heat island effects common to real rooftop environments. Third, the long-term durability and structural integrity of shredded synthetic textile substrates

under sustained wetting-drying cycles, UV exposure, and microbial activity have not been evaluated. Fourth, potential microplastic leaching from polyester and nylon substrates under weathering conditions represents an environmental concern that was outside the scope of this study but warrants dedicated investigation. Fifth, the study examined only two synthetic fibre types; future research should include a broader range of textile waste types, fibre blends, and shredding configurations to identify optimal substrate formulations. Future studies should prioritise plant growth trials under controlled greenhouse conditions, long-term field performance monitoring on real green roof installations, and LifeCycle Assessment (LCA) to quantify the circular economy and environmental benefits of textile waste reuse in green roof systems.

## 5. CONCLUSIONS

This preliminary physicochemical characterisation study demonstrates that shredded Polyester and Nylon textile waste fabrics possess key physicochemical properties that are well aligned with established standards for green roof growing substrate materials, though plant growth suitability remains to be confirmed through dedicated plant trials. Both fiber types exhibited exceptionally low bulk densities (Nylon: 0.22± 0.02 $gcm^{-3}$; Polyester: 0.145± 0.02 $gcm^{-3}$), total porosities exceeding 76.87% and 86.10% respectively, and water holding capacities well above the FLL minimum threshold of 35%. The optimum pH values (7.02, 7.04) respectively, and electrical conductivity values show chemical suitability of these materials as growing substrates for a broad range of horticultural plant species. In comparison with conventional soil-based substrates and established inorganic alternatives such as volcanic tuff, pumice, and crushed brick, synthetic textile fiber substrates offer substantially lower structural dead loads, adequate or superior water retention, and stable chemical conditions, without the pH instability associated with many organic media or the high cost of premium inorganic substrates such as LECA and perlite. The low-cost advantage of these substrates arises specifically from their origin as textile waste that would otherwise be landfilled, making them a cost-competitive option not only due to the near-zero raw material cost, but also due to the avoided disposal costs of waste management, a dual advantage that distinguishes them from other reusable or alternative materials. The chemical inertness and structural resilience of Polyester and Nylon polymers suggest that these substrates would resist long-term decomposition, addressing one of the key limitations of organic growing media under tropical and subtropical climatic conditions.

The findings of this preliminary physicochemical characterisation study indicate that recycled synthetic textile fiber substrates exhibit physicochemical properties consistent with established green roof substrate standards. However, it is important to note that plant growth suitability and field-scale viability have not yet been demonstrated, as the current study is limited to laboratory characterisation. Validation through plant growth trials and field-scale performance testing is required before practical recommendations can be made. Subject to such validation, textile-based growing substrates may offer possibilities for the expansion of green roof systems in weight-constrained and resource-limited urban environments globally.

## 6. ACKNOWLEDGEMENTS

The authors express their gratitude to the Department of Civil Engineering and the Faculty of Textile Engineering, University of Moratuwa, for providing the laboratory

facilities and technical support required for this study. The authors also acknowledge MAS (Pvt) Ltd for financial support and for providing the synthetic textile waste used in this research.

# 7. REFERENCES

Ailenei, E. C., Loghin, M.C., Hoblea, I.A., (2021). New composite materials using polyester woven fabric scraps. *Industria Textila, 72*(1), 62–67. https://doi.org/10.35530/IT.072.01.1837

Ampim, P. A. Y., Sloan, J. J., Cabrera, R. I., Harp, D. A., & Jaber, F. H. (2010). Green roof growing substrates: Types, ingredients, composition and properties. *J. Environ. Hort., 28*(4), 244–252. https://doi.org/10.24266/0738-2898-28.4.244

Cakar, H., Saracoglu, O. A., Akat, H., Kilic, C. C., & Adanacioglu, H. (2023). The potential for using different substrates in green roofs. *Journal of Environmental Engineering and Landscape Management, 31*(1), 44–51. https://doi.org/10.3846/jeelm.2023.18487

Cao, C. T. N., Farrell, C., Kristiansen, P. E., & Rayner, J. P. (2014). Biochar makes green roof substrates lighter and improves water supply to plants. *Ecological Engineering, 71*, 368–374. https://doi.org/10.1016/j.ecoleng.2014.06.017

Carrillo-angeles, I. G., Queijeiro-bolaños, M. E., Malda-barrera, G. X., & Suzán-azpiri, H. (2018). Aesthetic growth of a native tree species with desirable characteristics for urban green areas in arid and semiarid environments. *Urban Forestry & Urban Greening, 33*, 12–15. https://doi.org/10.1016/j.ufug.2018.05.001

Čorak, I., Tarbuk, A., Đorđević, D., Višić, K., & Botteri, L. (2022). Sustainable alkaline hydrolysis of polyester fabric at low temperature. *Materials*, 15(4), 1530. https://doi.org/10.3390/ma15041530.

Das, B., Das, A., Kothari, V. K., Fangueiro, R., & de Araújo, M. (2007). Moisture transmission through textiles: Part II: Evaluation methods and mathematical modeling. *AUTEX Research Journal, 7*(3), 194–216. https://doi.org/10.1515/aut-2007-070305

Di Gioia, F., De Bellis, P., Mininni, C., & Santamaria, P. (2017). Physicochemical, agronomical and microbiological evaluation of alternative growing media for the production of rapini (Brassica rapa L.) microgreens. *Journal of the Science of Food and Agriculture, 97*(4), 1212–1219. https://doi.org/10.1002/jsfa.7852

Dunnett, N., & Kingsbury, N. (2004). Planting green roofs and living walls. *Open Journal of Ecology, 1*(1), 1-8. http://dx.doi.org/10.4236/oje.2011.11001

Durpekova, S., Di Martino, A., Dusankova, M., Drohsler, P., & Sedlarik, V. (2021). Biopolymer hydrogel based on acid whey and cellulose derivatives for enhancement water retention capacity of soil and slow release of fertilizers. *Polymers, 13*(19). https://doi.org/10.3390/polym13193274

Eksi, M., & Rowe, D. B. (2019). Effect of substrate depth and type on plant growth for extensive green roofs in a Mediterranean climate. *Journal of Green Building, 14*(2), 29–44. https://doi.org/10.3992/1943-4618.14.2.29

Farrell, C., Ang, X. Q., & Rayner, J. P. (2013). Water-retention additives increase plant available water in green roof substrates. *Ecological Engineering, 52*, 112–118. https://doi.org/10.1016/j.ecoleng.2012.12.098

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL). (2018). *Green roof guidelines: Guidelines for the planning, construction and maintenance of green roofs.* https://commons.bcit.ca/greenroof/files/2019/01/FLL_greenroofguidelines_2018.pdf

Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. *HortScience, 41*(5), 1276–1285. https://doi.org/10.21273/HORTSCI.41.5.1276

Graceson, A., Hare, M., Monaghan, J., & Hall, N. (2013). The water retention capabilities of growing media for green roofs. *Ecological Engineering, 61*, 328–334. https://doi.org/10.1016/j.ecoleng.2013.09.030

Graceson, A., Monaghan, J., Hall, N., & Hare, M. (2014). Plant growth responses to different growing media for green roofs. *Ecological Engineering, 69*, 196–200. https://doi.org/10.1016/j.ecoleng.2014.03.067

Hearle, J. W. S. (2001). Textile Fibers: A Comparative Overview In K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, S. Mahajan, & P. Veyssière (Eds.), Encyclopedia of materials:

Science and technology (2nd., pp. 9100–9116). Elsevier. https://doi.org/https://doi.org/10.1016/B0-08-043152-6/01643-0

*Kader, S.A., Karunaratne, S., Lizny, M.J.M.F., Asmath, A.M.M., & Zainudeen, U.L. (2022). Analysis of physical and chemical properties of alternative substrate material for sustainable green roofs*. Research Square. https://doi.org/10.21203/rs.3.rs-1224124/v1

Lacarne, I., Dang, M., & Shafie, S., (2021). *Using biochar as an amendment for engineered green roof soil blend*. Ecological Farmers Association of Ontario. https://efao.ca/wp-content/uploads/EFAO-XUrbanFarm-Research-Report-2021-FINAL-audio-17Dec21.pdf

Morton, W. E., & Hearle, J. W. S. (2008). 7 - Equilibrium absorption of water. In W. E. Morton & J. W. S. Hearle (Eds.), *Woodhead Publishing Series in Textiles* (4th., pp. 178–194). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9781845694425.178

Nguyen, C.N., Chau, H.W., Kumar, A., Chakraborty, A., & Muttil, N. (2024). Biochar amendment in green roof substrate: A comprehensive review of the benefits, performance, and challenges. *Applied Sciences, 14*(16), 7421. https://doi.org/10.3390/app14167421

Papadopoulos, A. P., Bar-Tal, A., Silber, A., Saha, U. K., & Raviv, M. (2008). Inorganic and synthetic organic components of soilless culture and potting mixes. In M. Raviv & J.H. Lieth (Eds.), *Soilless culture: Theory and practice* (pp. 505–543). Elsevier. https://doi.org/10.1016/B978-044452975-6.50014-9

Pasian, C. C., & Frantz, J. M. (2008). Evaluating performance and stability of Polyethylene Terephthalate (PET) and cellulose polymer as soilless mix components. In *International Symposium on Soilless Culture and Hydroponics* (pp. 289–296).ISHS. https://doi.org/10.17660/ActaHortic.2009.843.37

Philippi, P.M. (2005). *Introduction to the german fll-guideline for the planning , execution and upkeep of green-roof sites*. Green Roof Service, LLC.

Sharma, N., Allardyce, B., Rajkhowa, R., & Adholeya, A. (2022). A substantial role of agro-textiles in agricultural applications. *Frontiers in Plant Science, 13*, 895740. https://doi.org/10.3389/fpls.2022.895740

Tala, S. A., Al-Ajlouni, M. G., Ayad, J. Y., Othman, Y. A. & Hilaire, R.S. (2020). Performance of six different soilless green roof substrates for the Mediterranean region. *Science of the Total Environment, 730*, 139182. https://doi.org/10.1016/j.scitotenv.2020.139182

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews, 57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119

Vijayaraghavan, K., & Raja, F. D. (2014). Design and development of green roof substrate to improve runoff water quality: Plant growth experiments and adsorption. *Water Research*, *63*, 94–101. https://doi.org/10.1016/j.watres.2014.06.012

Vlasveld, D. P. N., Groenewold, J., Bersee, H. E. N., & Picken, S. J. (2005). Moisture absorption in polyamide-6 silicate nanocomposites and its influence on the mechanical properties. *Polymer, 46*(26), 12567–12576. /https://doi.org/10.1016/j.polymer.2005.10.096

Wang, F. (2018). 11 - Moisture absorption and transport through textiles. In M. Miao & J.H. Xin (Eds.), *Engineering of High-Performance Textiles* (pp. 247–275). Elsevier. https://doi.org/10.1016/B978-0-08-101273-4.00009-3

Zhang, F., Song, B., Li, Y., Zhou, Y., Wang, Y., Xu, Q., & Ma, J. (2022). Breathability and moisture permeability of cellulose nanocrystals hollow microsphere coatings for PET fabrics. *ACS Applied Materials & Interfaces, 14*(1), 1–17. https://doi.org/10.1021/acsami.1c19020

Senevirathne, S.A.A.B., Allis, C. and Guruge, K., 2026. Pivot strategies for lean construction implementation: A Sri Lankan perspective. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1328-1343. DOI: https://doi.org/10.31705/WCS.2026.97. Available from: https://ciobwcs.com/papers/

# PIVOT STRATEGIES FOR LEAN CONSTRUCTION IMPLEMENTATION: A SRI LANKAN PERSPECTIVE

**S.A.A.B. Senevirathne[1], Chamari Allis[2] and A.P.G.K.Veenadhi[3]**

## *ABSTRACT*

*Multiple benefits arise from implementing lean principles, as illustrated in the existing literature. Many studies show that significant challenges are preventing lean implementation in the construction sector from being successful. Thus, one of the most important factors in successfully implementing the lean concept in the construction organization is overcoming difficulties. Consequently, the aim of the study is to examine the application of lean construction principles in Sri Lankan building projects and to identify the most suitable techniques that can improve project efficiency. Moreover, this paper also is looking into the advantages of overcoming barriers to successfully apply the lean approach in Sri Lanka. This study investigates how well Lean Construction methods work when used in construction projects in Sri Lanka. For an extensive understanding of how these strategies affected project performance, both quantitative and qualitative analysis methodologies were used. Accordingly, expert interviews and questionnaire surveys were conducted. Through correlation and regression analysis, the quantitative data was subjected to a comprehensive statistical review using SPSS. As a result several Lean tools, such as 5S, Visualization, Just-In-Time (JIT), Total Quality Management (TQM), and Value Based Management (VBM), were found to be appropriate to the Sri Lankan construction industry by the study. Visualization emerged as the most beneficial method of all, greatly improving project quality, time efficiency, and cost control. Nonetheless, the results additionally underscored that notable impediments to the extensive implementation of Lean techniques in Sri Lanka are ignorance and unfamiliarity with them. This emphasizes the need for more instruction and training to spread the advantages and real-world uses of lean construction methods throughout the area.*

***Keywords:*** *Lean construction; Visualization; Quality Management; Sri Lanka; Sustainability.*

## 1. INTRODUCTION

The construction industry plays a vital role in the economic development all around the globe, which is also has a significant influence on infrastructure development, employment generation, and industrial growth (Zhou et al., 2019). Even though, construction industry also faces major challenges such as, delays, cost overruns, material

[1] Quantity Surveyor, Senevirathne Contractors, Sri Lanka, adeesha.senevi@gmail.com
[2] Senior Teaching Fellow, Liverpool John Moores University, United Kingdom, chamaribuddhi@gmail.com
[3] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, kaviniveenadhi1997@gmail.com

waste and inefficient coordination among stakeholders (Nowotarski et al., 2016). Apparently, maintaining a balance between time, cost and quality pillars is a significant challenge in many projects. In order to address this challenge, improving efficiency and minimizing waste within construction processes has become a major concern (Hao et al., 2011).

Consequently, lean construction has identified as an effective approach to address the above said matter through improving efficiency and minimizing waste (Singh, 2025). Lean construction is a project management philosophy that focuses on maximizing value while minimizing waste in construction processes. By emphasizing continuous improvement, efficient workflow, and better collaboration among project stakeholders, lean construction aims to enhance project performance and productivity (Coccolini & Bragadin, 2025). Central to this study is the concept of "pivot strategies" a term used here to describe a deliberate, context-sensitive repositioning of lean implementation approaches. Rather than directly transplanting globally practised lean tools into the Sri Lankan construction environment, pivot strategies reflect an adapted, locally viable approach that acknowledges the unique socio-organisational, cultural, and industry-maturity constraints of the sector. Although lean construction is a widely adopted practice in many developed countries, the level of implementation within the Sri Lankan context remains relatively limited (Kariyawasam & Siriwardana, 2021). Past researchers have also identified that barriers such as; limited awareness, lack of training, resistance to organizational change, and inadequate industry knowledge can reason for this issue. Therefore, it is important to examine the applicability of lean practices in Sri Lankan construction industry (Senevirathne & Wimalasena, 2025). Accordingly, this study aims to examine the application of lean construction principles in Sri Lankan building projects and to identify the most suitable techniques that can improve project efficiency. This aim is achieving through three objectives; firstly, to identify applicable lean construction techniques within the Sri Lankan construction industry, secondly, to analyse the benefits and barriers associated with the implementation of lean principles in the Sri Lankan building construction sector and finally to assess the impact of suitable lean techniques on the efficiency of Sri Lankan building projects. To achieve these objectives, this study adopts a mixed-method research approach, and the findings of this research are expected to provide insights into the current level of lean construction adoption in Sri Lanka and highlight the key factors influencing its implementation.

# 2. LITERATURE REVIEW

## 2.1 OVERVIEW OF LEAN CONSTRUCTION

Lean construction is a project management philosophy derived from lean production principles. The goal of lean construction is to maximize value while minimizing waste in construction operations (Coccolini & Bragadin, 2025). Lean construction places more emphasis on continuous improvement, effective workflow, and improved stakeholder collaboration than traditional construction management techniques, which are largely focused on cost and schedule (Maraqa et al., 2023).

Lean production concept, which were first developed within the Toyota Production System, were adapted and brought to the construction industry. Since its establishment in 1993, the International Group for Lean Construction (IGLC) has been instrumental in advancing lean research and implementation in the architecture, engineering, and

construction (AEC) sector (Chen et al., 2023). According to lean construction, construction should be viewed as a production system with processes that are optimized to enhance flow, get rid of non-value-adding tasks, and boost project efficiency (Bertagnolli, 2022).

As mentioned before, inefficiencies like delays, rework, material waste, and inadequate stakeholder collaboration are frequent problems in construction projects (Moradi & Sormunen, 2023). By increasing cooperation, decreasing waste throughout project phases, and improving process transparency, lean construction solutions seek to address these problems. Lean construction thereby helps to increase client happiness, project performance, and productivity (Kariyawasam & Siriwardana, 2021).

## 2.2 LEAN CONSTRUCTION PRINCIPLES

Lean construction is based on a number of fundamental concepts that emphasize maximizing customer value while reducing waste in project operation (Rosli et al., 2023). Construction projects are planned, managed, and carried out according to these principles.

Accordingly, the fundamental principles can be identified as below in table 1.

*Table 1: Fundamental principles of lean construction*

| Key Principle | Explanation |
|---|---|
| Value identification | Establishing the project's worth in accordance with the requirements and expectations of the client. |
| Value stream mapping | Identifying every task necessary to complete the project and removing those that don't provide value. |
| Flow optimization | Making sure that all project operations are carried out continuously and smoothly. |
| Pull-based manufacturing | Producing work based on actual demand rather than forecasts. |
| Continuous improvement | Enhancing procedures over time to increase productivity and quality |

By putting these principles into practice, construction companies may minimize delays, enhance stakeholder cooperation, and maximize resource use (Maraqa et al., 2023).

## 2.3 LEAN TECHNIQUES USED IN CONSTRUCTION PROJECTS

With the requirement of approaching improved work efficiency and reduced construction waste along with enhanced communication with the project stakeholders, various lean techniques have been adopted in the construction industry (Aslam et al., 2022).

One widely used technique is 5S, which focuses on maintaining an organized and efficient workplace. The flow of operations that create value for the client is the main emphasis of lean construction. There are five levels of housekeeping in the 5S process, which is also called the Visual Work Place and is used to get rid of unnecessary resources. Sort, Set in Order (Section), Shine, Standardize (Seiketsu), and Sustain (Shitsuke) are the five major stages in this concept (Chen et al., 2024). The five stages; Sort, Set in Order, Shine, Standardize, and Sustain help improve site organization, increase productivity, and reduce unnecessary movement and material waste on construction sites. On Construction sites, the 5S housekeeping technique is frequently employed in relation with lean

construction. Enhanced productivity, quality, set-up times, space creation, lower lead times, higher machine uptime, enhanced morale, teamwork, and continual development are all advantages of applying through 5S. On a construction site, the material layout is frequently employed to implement the 5S methodology (Salem et al., 2006).

Another important technique is Just-in-Time (JIT), which aims to deliver materials and resources exactly when they are required in the construction process. This approach helps minimize inventory costs, reduce storage requirements, and improve workflow efficiency (Garcés & Peña, 2023).

Moreover, visual management is also commonly used in lean construction (Ibrahim et al., 2025). The main objectives of visual management are to encourage the extensive exchange of information in the workplace and to lessen barriers to the information's dissemination (Garcés et al., 2025). It involves using visual tools such as information boards, charts, and progress indicators to enhance communication and transparency among project stakeholders. These tools help teams quickly identify problems and make timely decisions (Hasan et al., 2024).

In addition, Total Quality Management (TQM) supports lean construction by promoting continuous quality improvement through collaboration, training, and stakeholder involvement. To increase performance, TQM is a global endeavour involving all organizations (Nowotarski et al., 2016). It affects every part of an organization and elevates quality to a strategic aim. TQM is attained by staff members at all levels working together to continually improve performance to raise customer satisfaction (Marhani et al., 2013). TQM aims to promote customer happiness, cost-effectiveness, and defect-free work by emphasizing process improvement, customer and supplier interaction, cooperation, and training and education. TQM offers the environment and culture necessary for technological advancement and innovation (Moradi & Sormunen, 2023).

Furthermore, building project briefs usually include a definition of values, along with needs, goals, and expectations. Achieving these standards specified by the building customer and users is the primary objective. Market value and utility value are the two types of values. The impact on human behaviour is the central idea of VBM (Hartanti et al., 2022). The actions required to construct are linked to human behaviour in the construction industry. These consist of managerial work and workmanship. In essence, VBM can be understood as a synthesis of values-based management. Since building is not a new field, the main focus of this research is management by values. As a result, it is acknowledged that value management in today's building is far from ideal (Singh, 2025). The building process primarily involves employees working on construction sites, who are primarily concerned with process values such as good cooperation, agreement, discipline, communication, etc. in addition to their pay. Because they will be residing or working in the built structure, the end users are primarily concerned with the product values, such as brick type, roof light, flexibility, economy, architecture, etc (Ibrahim et al., 2025).

Among the lean tools applied in the construction sector, the Last Planner System (LPS) stands out as the most widely researched and operationally implemented scheduling methodology globally (Ballard, 2000; Jayanetti et al., 2024). Originally developed by Glenn Ballard and Greg Howell in the 1990s, the LPS was conceived as a collaborative production planning and control approach designed to address the chronic unreliability of construction schedules (Ballard, 2000). Its theoretical foundation is rooted in lean

production principles, specifically the concepts of pull scheduling, workflow reliability, and continuous improvement.

The LPS operates through a hierarchical planning structure comprising three interrelated components:

1. The Master Schedule, which defines the overall project milestones and sequencing;
2. The Look-Ahead Schedule, a three-to-six-week rolling plan that identifies and removes workflow constraints in advance; and
3. The Weekly Work Plan (WWP), which formalises commitments made by the "last planners"

Those directly responsible for executing work on site (Ballard, 2000; Parameswaran et al., 2024). The performance of the LPS is measured using the Percent Plan Complete (PPC) metric, which tracks the proportion of planned tasks completed as committed, thereby providing a quantitative indicator of workflow reliability.

Empirical evidence from international studies confirms the effectiveness of the LPS in improving schedule predictability, reducing waste, and enhancing team collaboration on construction projects (Moradi & Sormunen, 2023; Garces et al., 2025). Within the Sri Lankan context, Jayanetti et al. (2024) and Parameswaran et al. (2024) have identified the LPS as a promising lean tool, noting its alignment with the collaborative and relationship-driven nature of construction project teams in the region. However, broader adoption of the LPS in Sri Lanka remains limited due to the same barriers prevalent across other lean techniques, particularly low awareness, lack of structured training programmes, and resistance to changing established planning routines (Kariyawasam & Siriwardana, 2021; Senevirathne & Wimalasena, 2025).

In the context of the present study, the LPS represents a significant lean scheduling technique that complements the tools analysed in the quantitative phase such as 5S, JIT, Visualization, TQM, and VBM. Its omission from the original study was a recognised limitation; future research should specifically investigate the applicability and effectiveness of the LPS as a pivot strategy for lean implementation in the Sri Lankan construction sector.

## 2.4 LEAN CONSTRUCTION IN THE SRI LANKAN CONSTRUCTION INDUSTRY

As per the past researchers, Sri Lankan construction industry has been playing a crucial role in the perspective of economic growth, by fostering the development of infrastructure, the creation of jobs, and the expansion of industry, etc (Parameswaran et al., 2024). Regardless of that fact, low productivity, project delays, material waste, and ineffective stakeholder collaboration are some of the industry's problems identifies in past literature (Hettiaarachchige et al., 2022). Evidently, lean construction practices can support positively on overcoming the above said issues simply by, improved project planning, improved communication, and waste reduction throughout the construction process (Perera et al., 2024). By emphasizing on value creation and effective workflow lean construction can enhance project delivery performance, lower costs, and boost customer satisfaction (Senevirathne & Wimalasena, 2025).

As mentioned in the beginning of the study, Sri Lanka is in its earliest phase of adopting lean construction practices. While some organizations have started implementing lean techniques, widespread adoption remains limited due to several barriers such as lack of awareness, insufficient training, resistance to change, and inadequate organizational support (Parameswaran et al., 2024).

## 2.5 BENEFITS OF USING THE LEAN CONCEPT IN SRI LANKAN PROJECT

Although the construction industries worldwide encountered numerous challenges whilst implementing the Lean Concept, a few industries have recognized the possibility of including enhancements through lean implementation.(Senevirathne & Wimalasena, 2025) Various methods and benefits have been known by using the researchers. The maximum vital benefit of using the Lean Concept in corporations is the reduction of waste (Fernando et al., 2024). By putting off waste inside the creation, Lean Concept encourages the following: Minimise double handling and movement of system and employees, Balance team, coordinate flows, Take off fabric constraints, Minimise variance in input, Minimise changeovers and hard setups and Reduce interpersonal dynamics (Kalubovila et al., 2023).

Three primary benefits of lean practices as economic (price, quality, and time), social (courting and satisfaction), and environmental in terms of production tasks. Under monetary advantages reduction in time and fee, improvement of satisfaction, higher stock control and hazard minimization were some of the benefits identified (Senevirathne & Wimalasena, 2025). Social worker satisfaction, worker health and safety, and better cooperation among stakeholders were some of the blessings. Under environmental advantages, reduction of waste and achieving green construction have been recognized. There are challenges to overcome in the construction industry's lean implementation (Jayanetti et al., 2024). The global construction sector is seeing difficulties in implementing lean due to many obstacles, regardless of the specific economic standing of the nation. A significant amount of research papers in many developed, developing, and underdeveloped nations worldwide (Hettiaarachchige et al., 2022).

## 2.6 BARRIERS TO USING LEAN CONCEPT IN SRI LANKA

Given that the Sri Lankan construction industry has brought attention to the need for improving the technical know-how and lean knowledge of implementing lean construction, introducing enough training programs on lean practices, and upholding a proper organizational culture as strategies to overcome the difficulties in implementing lean construction in SMEs (Jayanetti et al., 2024). Studies have also highlighted several tactics for overcoming the difficulties associated with implementing lean, including integrating policies to support cultural shifts, decentralizing top management, and guaranteeing training and growth inside the organizations (Moradi & Sormunen, 2023). The results of the literature review above indicate that there is a lack of research on methods for resolving human-related lean implementation difficulties in Sri Lanka's large-scale contractors.

According to (Kariyawasam & Siriwardana, 2021), under their research findings, they identified key barriers to creating a sustainable lean culture in Sri Lanka.

*Table 1: Key barriers to creating a lean culture in SL*

| Number | Key Barrier |
|---|---|
| 1 | Difficulty in convincing the need for change. |
| 2 | The dearth of learning experts. |
| 3 | Cultural and human attitudes of employees. |
| 4 | Construction fragmentations. |
| 5 | A long time is required for lean transformation. |
| 6 | Employer issues. |
| 7 | The difficulty of changing employee attitudes towards a production system view of construction. |
| 8 | Lack of team spirit. |
| 9 | Improper department proceedings. |
| 10 | Poor involvement of employees during change. |
| 11 | Unexpected and sudden disturbances created to existing processes. |
| 12 | Inability to review lean as a continuous process. |
| 13 | Difficulty of maintaining a consistent workflow. |
| 14 | Reluctance to follow orders from superiors. |
| 15 | Consultant and supplier-related issues. |
| 16 | Low attention is given to the acquisition of soft skills by employers. |
| 17 | Blame culture. |
| 18 | Multiple definitions are given to lean. |
| 19 | More barriers and specific barriers which are suggested by respondents discussed in the upcoming sections. |

## 3. RESEARCH METHODOLOGY

The research is firmly grounded in a mixed research methodology by adopting both qualitative and quantitative techniques, seeking to identify the primary Lean Technique for the Sri Lankan construction industry. The choice of a mixed method approach was made to address the study's research question, offering an explanatory analysis of the key Lean Techniques and the primary barriers to implementing these techniques in the Sri Lankan construction industry. To accomplish the research objectives, a comprehensive literature review and semi-structured interviews were utilized as data collection techniques. Nine interviews were conducted with construction experts possessing at least a Bachelor of Science qualification along with relevant professional credentials and over five years of experience. The data obtained from the interviews were categorized into six distinct groups, which encompass awareness of the lean concept and Lean Techniques, prior utilization of Lean Techniques in their respective firms, the most comprehensible Lean Technique, the most easily applicable Lean Technique, the most effective Lean Technique post-implementation, and the key barriers to applying these techniques within the Sri Lankan Construction industry. The collected data were analyzed using both manual calculations and the SPSS (Statistical Package for the Social Sciences) data analysis tool.

## 3.1 DATA COLLECTION METHODS

A designated questionnaire was circulated among the expert professionals in the Sri Lankan construction sector. A questionnaire was designed and shared via email and social media amongst construction industry professionals actively employed in the industry. The questionnaire was not distributed openly to the general public. It was circulated through targeted professional networks and directed to pre-identified individuals meeting the inclusion criteria: construction industry professionals actively employed in the sector with relevant professional qualifications. Email was the primary distribution channel to contact these pre-screened individuals; social media (LinkedIn) served only as a supplementary means to reach known professional contacts within the same network. Only respondents with verifiable professional credentials and industry experience were included in the final analysis. The respondents were requested to rank the extraordinary viewpoints in keeping with a "Likert Scale". The questionnaire changed into disbursed amongst 30 wide variety of specialists (decided on via stratified random sampling technique) from diverse disciplines along with Project Managers, Construction Managers, Engineers, Quantity Surveyors, and Architects due to the fact primarily based on differences in thought processes, backgrounds, and work experiences, people's replies to the questions may differ. Stratified random sampling was selected because the target population consists of distinctly defined sub-groups based on professional role. Ensuring proportional representation across these subgroups was critical to capturing diverse professional perspectives that would not have been reliably achieved through simple random sampling. Each stratum was defined by professional designation, and respondents were proportionally drawn from each group. To fulfil the aim of this study semi-structured interviews were conducted with the professionals who were selected using purposive sampling.

## 3.2 CONCEPTUAL FRAMEWORK

The overall research methodology of this study is based on below conceptual framework below.

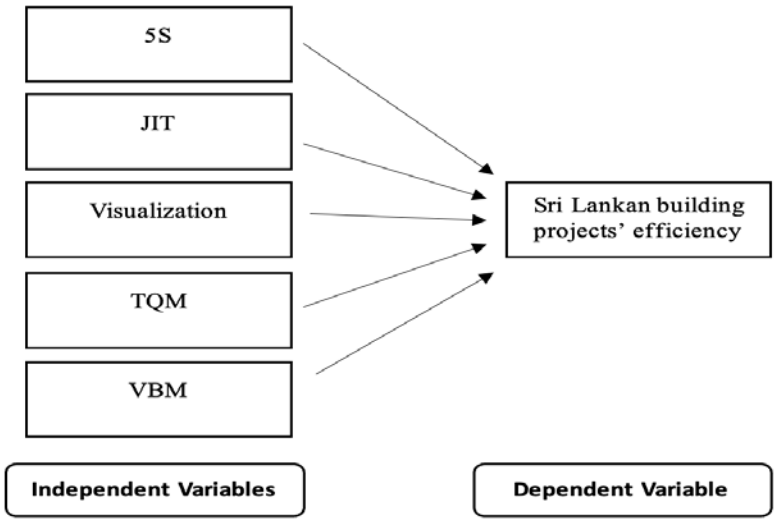



*Figure 1: Conceptual framework*

Independent Variables are identified to describe the lean techniques and the dependent variable describes how lean techniques affect Sri Lankan building projects. The hypotheses were developed as follows,

*Table 2: Hypotheses of the study*

| Identification | Hypotheses |
|---|---|
| $HA_1$ | There is a relationship between 5S and Sri Lankan building projects' efficiency. |
| $HB_1$ | There is a relationship between JIT and Sri Lankan building projects' efficiency. |
| $HC_1$ | There is a relationship between visualization and Sri Lankan building projects' efficiency. |
| $HD_1$ | There is a relationship between TQM and Sri Lankan building projects; efficiency. |
| $HE_1$ | There is a relationship between VBM and Sri Lankan building projects; efficiency. |

### 3.3 DATA ANALYSIS METHODS

Qualitative data provide background information and direction for the literature review. Following that, statistical techniques such as regression analysis and correlation were utilized to observe quantitatively the links between Lean Construction techniques and challenge performance criteria. When controlling for other relevant variables, regression analysis enables us to evaluate the predictive power of precise Lean techniques on cost reduction, time performance, and quality improvement. Correlation analysis also helps to determine the strength and direction of the associations between variables. The implementation of this blended-strategies approach will guarantee a comprehensive and robust comprehension of the efficacy of Lean Construction techniques inside the Sri Lankan construction sector.

## 4. RESULTS

### 4.1 DEMOGRAPHICAL DATA

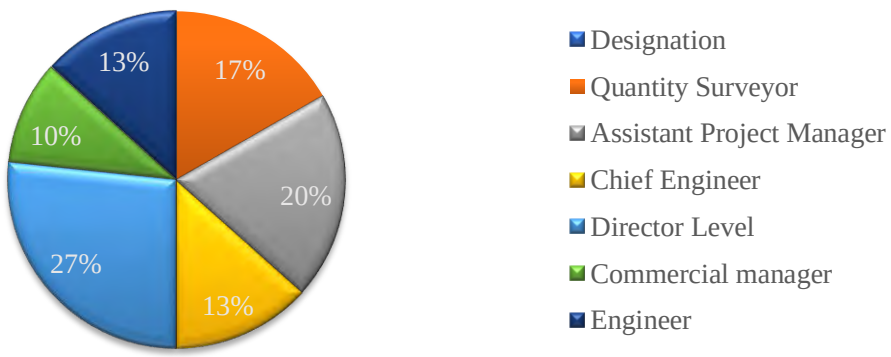



*Figure 2: Respondents' profile*

The above figure certified that the professionals of the construction industry who have an idea regarding the lean concept helped to achieve the objectives of this study via a questionnaire survey. The majority of the respondents were Director - level Professionals in the construction industry. It is 27% and the lowest respondents were commercial managers, it is 10%.

## 4.2 CORRELATION ANALYSIS

The data gained from the questionnaire survey were analysed through SPSS software to examine the above-mentioned hypothesis between independent and dependent variables. Because the "Pearson Correlation Coefficient" indicates linear correlations between two variables, it was utilized in this study using the SPSS software. variables having a -1 to +1 range. A positive correlation between two variables indicates that when the value of one grows, so does the value of the other. When there is a negative correlation between two variables, it means that when one variable increases, the other variable's value decreases. The significance value (P) will determine whether or not the correlation coefficient is met. If P is less than 0.05, there is a relationship between the DV and the specific IV; if P is greater than 0.05, there is no association.

*Table 3: Correlations analysis of the independent & dependent variables*

**Correlations**

| | | AIV | AJIT | AVZ | ATQM | AVBM | ADV |
|---|---|---|---|---|---|---|---|
| AIV | Pearson Correlation | 1 | .933** | .370* | .439* | 0.357 | .433* |
| | Sig. (2-tailed) | | 0.000 | 0.044 | 0.015 | 0.052 | 0.017 |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |
| AJIT | Pearson Correlation | .933** | 1 | 0.331 | .466** | 0.333 | .402* |
| | Sig. (2-tailed) | 0.000 | | 0.074 | 0.009 | 0.072 | 0.027 |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |
| AVZ | Pearson Correlation | .370* | 0.331 | 1 | .702** | .966** | .886** |
| | Sig. (2-tailed) | 0.044 | 0.074 | | 0.000 | 0.000 | 0.000 |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |
| ATQM | Pearson Correlation | .439* | .466** | .702** | 1 | .730** | .721** |
| | Sig. (2-tailed) | 0.015 | 0.009 | 0.000 | | 0.000 | 0.000 |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |
| AVBM | Pearson Correlation | 0.357 | 0.333 | .966** | .730** | 1 | .879** |
| | Sig. (2-tailed) | 0.052 | 0.072 | 0.000 | 0.000 | | 0.000 |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |
| ADV | Pearson Correlation | .433* | .402* | .886** | .721** | .879** | 1 |
| | Sig. (2-tailed) | 0.017 | 0.027 | 0.000 | 0.000 | 0.000 | |
| | N | 30 | 30 | 30 | 30 | 30 | 30 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

*Where; N = Number of Respondents, AIV = Average of 5S, AJIT= Average of JIT, AVZ = Average of Visualization, AVBM = Average of Value-based Management (VBM), ADV= Average of Dependent Variable.*

According to the above table all variables' Pearson correlations range from -1 to +1 and $P < 0.05$, it may be concluded that every independent variable and dependent variable are related.

## 4.3 REGRESSION ANALYSIS

The purpose of this study was to identify the independent variable that had the maximum impact on the dependent variable. The same set of information was obtained by using SPSS software, and regression analysis was conducted on the questionnaire used for the correlation analysis.

*Table 4: Regression analysis of the independent & dependent variables*

| **Coefficients[a]** | | | | | | |
|---|---|---|---|---|---|---|
| Model | | Unstandardized Coefficients | | standardized Coefficients | t | Sig. |
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | -1.214 | 0.829 | | -1.465 | 0.156 |
| | AIV | 0.213 | 0.513 | 0.105 | 0.415 | 0.681 |
| | AJIT | -0.030 | 0.585 | -0.013 | -0.052 | 0.959 |
| | AVZ | 0.631 | 0.409 | 0.530 | 1.541 | 0.136 |
| | ATQM | 0.217 | 0.213 | 0.140 | 1.016 | 0.320 |
| | AVBM | 0.293 | 0.448 | 0.232 | 0.654 | 0.519 |
| a. Dependent Variable: ADV | | | | | | |

The regression's unstandardized β value or coefficients show how much of the building project's efficiency (DV) is reflected by tools for lean construction (IV). According to the above table, there is a 29.3% variance in between Vale based management system lean technique and the Sri Lankan building projects' efficiency. With the increase of properly implemented 5S lean tool building projects efficiency increases by 21.3%. With the proper visualization lean technique, the building projects' efficiency can be increased by 63.1% and the properly implemented JIT technique can delay the projects' efficiency by 3%.

conducting education efforts for lean construction, testing the tools on a brief project with specialists, and increasing, working together and pushing the company's upper management to apply lean construction tools across the board are two short-term solutions to problems with lean construction tool implementation. Long-term recommendations for the effective application of lean construction tools in Sri Lanka include creating a government institute for lean construction, encouraging the construction sector to adopt new technologies, creating an appropriate framework for implementation, carrying out a case study to determine the advantages of lean construction, and offering appropriate lean construction education and training.

## 5. DISCUSSION

The correlation analysis confirmed statistically significant positive relationships between all five lean techniques and building project efficiency ($p < 0.05$), with VBM approaching significance ($r = 0.879$, $p = 0.052$). This aligns with international evidence consistently linking lean tool adoption to improved project performance (Garces & Peña, 2023; Moradi & Sormunen, 2023; Ibrahim et al., 2025). The strong correlation for Visualization ($r = 0.886$, $p < 0.001$) corroborates Kariyawasam and Siriwardana (2021), while the high Visualization–VBM correlation ($r = 0.966$) suggests these techniques tend to be adopted in tandem, reflecting the complementary nature of visual transparency and value-driven decision-making.

The regression analysis identified Visualization as the most influential predictor of project efficiency ($\beta = 0.530$), followed by VBM ($\beta = 0.232$), TQM ($\beta = 0.140$), and 5S ($\beta = 0.105$). Despite a significant bivariate correlation ($r = 0.402$, $p = 0.027$), JIT yielded a negative, non-significant regression coefficient ($\beta = -0.013$, $p = 0.959$), suggesting its effect is largely mediated by other techniques, particularly 5S ($r = 0.933$). The primacy of Visualization is further reinforced by the expert interview findings, where visual management tools were consistently rated as the most comprehensible and readily applicable lean practices. This convergence of quantitative and qualitative evidence aligns with Garces et al. (2025) and Coccolini and Bragadin (2025), who identify visual management as an accessible entry point for lean adoption in organisations with limited lean exposure. The predominance of awareness and knowledge deficits as implementation barriers is consistent with the international literature (Moradi & Sormunen, 2023; Nowotarski et al., 2016) and Sri Lankan-specific findings (Kariyawasam & Siriwardana, 2021; Senevirathne & Wimalasena, 2025). The present study advances beyond barrier identification by proposing context-sensitive pivot strategies, addressing a gap noted by Jayanetti et al. (2024) and Perera et al. (2024). Visualization and 5S are recommended as first-phase priorities; TQM and VBM as second-phase strategies following foundational lean literacy development. The cautious treatment of JIT reflects the well-documented supply chain fragmentation in Sri Lanka, underscoring that lean tools must be sequenced and locally adapted rather than transplanted wholesale from higher-maturity environments.

## 6. CONCLUSIONS

This research explored the adaptability and effectiveness of lean construction methods in the Sri Lankan construction industry, focusing specifically on identifying appropriate lean tools and assessing their influence on project efficiency. This study carried out in mixed method approach utilizing both expert interviews and questionnaire surveys.

The results of the research reveal that various lean construction techniques, such as 5S, JIT, Visualization, Total TQM, and VBM, are relevant to the construction sector in Sri Lanka. The correlation analysis demonstrated that all selected lean techniques show a positive relationship with building project efficiency, suggesting that the adoption of lean practices can contribute to improving project performance in terms of time management, cost control, and quality improvement.

Moreover, among the identified techniques, Visualization has figured out as the most influential lean practice in Sri Lankan construction industry. Collected data through both the methods, expert interviews and the questionnaire surveys indicate that visualization

techniques have significant contribution to improve communication, coordination and transparency among the project stakeholders. By enabling clear information sharing and faster decision-making, visualization tools help reduce misunderstandings, delays, and inefficiencies during project execution. Furthermore, study reveals that, during the procedures of improving workplace organization, workflow efficiency, and stakeholder alignment with project objectives; 5S and VBM also has positively influence the project efficiency. Additionally, study also reveals that though the JIT is a widely used and adopted lean technique globally in Sri Lankan context it has a relatively limited influence on project efficiency. The reason for the limitation has identified as due to the complexity of construction supply chains and the uncertainties associated with project environments.

Apart from the potential benefits, study also identified several barriers which impacts on widespread adoption within the Sri Lankan construction industry. The main barriers are a lack of understanding and familiarity with lean concepts, a lack of training opportunities, organisational change resistance, disjointed project structures, and inadequate stakeholder participation.

Therefore, a number of strategic initiatives are suggested to improve the adoption of lean construction principles in Sri Lanka. Improving industry knowledge and acceptance of lean processes requires raising awareness and offering professional training on lean methodologies. Additionally, construction companies should encourage supportive organisational cultures that enable ongoing improvement and encourage cooperation among project participants. The adoption of lean practices in the industry may be further stimulated by the establishment of institutional support mechanisms, such as industry guidelines or government-backed lean construction programs.

In conclusion, providing actual data on the efficacy of lean construction methods in the Sri Lankan setting, this study adds to the body of knowledge already in existence. The findings of this study carry several practical implications for construction industry stakeholders in Sri Lanka. For construction firms and project managers, the most immediate recommendation is the prioritisation of Visualization tools as the primary entry-point lean strategy. Visual management practices, including site layout boards, task tracking displays, daily stand-up boards, and colour-coded progress indicators, can be introduced with minimal capital investment and without requiring deep organisational restructuring. Their demonstrated impact on project quality, time efficiency, and cost control makes them the most compelling first pivot for organisations beginning their lean journey.

For industry bodies and professional associations, the findings highlight the critical need for structured lean construction awareness and training programmes. The expert interviews consistently identified ignorance and unfamiliarity as the foremost barriers to lean adoption; therefore, targeted capacity-building initiatives, including workshops, certified short courses, and pilot project demonstrations, are essential to building the lean literacy necessary for broader industry-wide adoption.

For government and policy stakeholders, the study recommends the establishment of a dedicated lean construction institute or centre of excellence, modelled on similar bodies in Singapore and the United Kingdom, to provide a national focal point for lean research, training, and implementation support. Policy incentives, such as procurement requirements favouring contractors who demonstrate lean construction competency, could further accelerate adoption across the industry.

This study opens several avenues for future research. First, longitudinal investigations tracking lean adoption and its impact on project efficiency over multiple years would provide stronger causal evidence than the cross-sectional design employed here. Second, future studies should seek to incorporate the Last Planner System (LPS) as an explicit research variable, given its global prominence and the current gap in Sri Lankan-specific empirical evidence on its applicability. Third, qualitative case study investigations of organisations that have successfully implemented lean practices in Sri Lanka would generate rich, contextual insights into the enabling conditions and implementation pathways that quantitative surveys cannot fully capture. Fourth, comparative studies examining lean adoption across different construction sub-sectors, including infrastructure, industrial, and housing projects, would extend the generalisability of the present findings. Finally, research investigating the integration of lean construction with emerging digital technologies, including Building Information Modelling (BIM) and prefabrication practices, represents a particularly promising direction given the growing interest in construction digitalisation within Sri Lanka.

Notwithstanding the contributions outlined above, this study is subject to several methodological limitations that should be considered when interpreting the findings. First, the quantitative phase of the study was based on a sample of 30 construction industry professionals. While this sample size is appropriate for an exploratory mixed-methods study and is consistent with comparable studies in the lean construction literature within developing country contexts (Senevirathne & Wimalasena, 2025; Kariyawasam & Siriwardana, 2021), it nonetheless limits the statistical robustness of the regression model and restricts the generalisability of the quantitative findings beyond the Sri Lankan context. Larger, nationally representative samples would be required to yield more definitive conclusions regarding the relative predictive power of each lean technique. Second, the study was conducted exclusively within Sri Lanka and may not fully capture the diversity of conditions across different project types, organisational sizes, and regional sub-contexts within the country. Third, the cross-sectional nature of the data collection means that the directionality of relationships between lean techniques and project efficiency cannot be conclusively established; longitudinal designs would be better suited to examine causal mechanisms. Future research should seek to address these limitations through expanded sampling, longitudinal designs, and geographically diverse case study investigations.

## 7. REFERENCES

Aslam, M., Gao, Z., & Smith, G. (2022). Framework for selection of lean construction tools based on lean objectives and functionalities. *International Journal of Construction Management*, *22*(8), 1559–1570. https://doi.org/10.1080/15623599.2020.1729933

Ballard, H. G. (2000). The last planner system of production control (unpublished dissertation). University of Birmingham. http://www.leanconstruction.org/media/docs/Ballard2000-Dissertation.pdf

Bertagnolli, F. (2022). *Lean management: Introduction and in-depth study of Japanese management philosophy.* Springer Nature. https://link.springer.com/book/10.1007/978-3-658-36087-0

Chen, X., Kurdve, M., Johansson, B., & Despeisse, M. (2023). Enabling the twin transitions: Digital technologies support environmental sustainability through lean principles. *Sustainable Production and Consumption*, *38*, 13–27. https://doi.org/10.1016/j.spc.2023.03.020

Chen, Y., Qiu, D., & Chen, X. (2024). Integrating lean construction with sustainable construction: Drivers, dilemmas and countermeasures. *Sustainability*, *16*(21), 9387. https://doi.org/10.3390/su16219387

Coccolini, D., & Bragadin, M. A. (2025). History and overview of lean construction fundamentals. In R. Albatici, M. Dalprà, M.P. Gatti, G. Maracchini & S. Torresin (Eds.), *International Conference of Ar.*

*Tec.(Scientific Society of Architectural Engineering* (766, pp. 197-207). Springer, https://doi.org/10.1007/978-3-032-06993-1_12

Fernando, M. H. V., Costa, D. D., Malsha Nadeetharu, B. K., & Kulatunga, U. (2024). Application of lean principles for building refurbishment projects in Sri Lanka. Built Environment Project and Asset Management, 14(2), 244–259. https://doi.org/10.1108/BEPAM-02-2023-0047

Garcés, G., Forcael, E., Osorio, C., Castañeda, K., & Sánchez, O. (2025). Systematic review of Lean Construction: Aan approach to sustainability and efficiency in construction management. *Journal of Infrastructure Preservation and Resilience, 6*(1), 1–28. https://doi.org/10.1186/s43065-025-00119-1

Garcés, G., & Peña, C. (2023). A review on lean construction for construction project management. *Revista Ingeniería De Construcción, 38*(1), 43-60. https://doi.org/10.7764/RIC.00051.21

Hao, J. L., Tam, V. W. Y., Yuan, H. P., & Wang, J. Y. (2011). Construction waste challenges in Hong Kong and Pearl river delta region. *International Journal of Construction Management, 11*(1), 37–47. https://doi.org/10.1080/15623599.2011.10773160

Hartanti, L. P. S., Gunawan, I., Mulyana, I. J., & Herwinarso, H. (2022). Identification of waste based on lean principles as the way towards sustainability of a higher education institution: A case study from Indonesia. *Sustainability, 14*(7), 4348. https://doi.org/10.3390/su14074348

Hasan, S., Işık, Z., & Demirdöğen, G. (2024). Evaluating the contribution of lean construction to achieving sustainable development goals. *Sustainability, 16*(8), 3502. https://doi.org/10.3390/su16083502

Hettiaarachchige, N., Rathnasinghe, A., Ranadewa, K., & Thurairajah, N. (2022). Lean integrated project delivery for construction procurement: the case of Sri Lanka. *Buildings, 12*(5), 524. https://doi.org/10.3390/buildings12050524

Ibrahim, A., Zayed, T., & Lafhaj, Z. (2025). Trends and gaps in lean construction practices for construction of megaprojects: A critical review. *Alexandria Engineering Journal, 118*, 174–193. https://doi.org/10.1016/j.aej.2025.01.046

Jayanetti, J., Perera, B., & Waidyasekara, K. (2024). AS Key parameters of lean construction maturity: A Delphi study. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, and H. Chandanie (eds). *Proceedings the 12th World Construction Symposium* (pp. 712-726), CIOB. https://doi.org/10.31705/WCS.2024.56.

Kalubovila, K., Kawmudi, W., & Lakmal, A. (2023). The impact of lean construction tools on reduction of contractor related causes of delay in Sri Lankan construction industry. *KDU Journal of Multidisciplinary Studies, 5*(2), 84-92, https://doi.org/10.4038/kjms.v5i2.79

Kariyawasam, D., & Siriwardana, C. (2021). Feasibility study on, enablers and barriers for the implementation of lean construction and the applicability of visual management practices through forms of digital communication in the Sri Lankan industry. *2021 Moratuwa Engineering Research Conference (MERCon),* (pp. 1-6). IEEE, https://doi.org 10.1109/MERCon52712.2021.9525758.

Maraqa, M. J., Sacks, R., & Spatari, S. (2023). Strategies for reducing construction waste using lean principles. *Resources, Conservation & Recycling Advances, 19,* 200180. https://doi.org/10.1016/j.rcradv.2023.200180

Marhani, M. A., Jaapar, A., Bari, N. A. A., & Zawawi, M. (2013). Sustainability through lean construction approach: A literature review. *Procedia-Social and Behavioral Sciences, 101*, 90–99. https://doi.org/10.1016/j.sbspro.2013.07.182

Moradi, S., & Sormunen, P. (2023). Implementing lean construction: A literature study of barriers, enablers, and implications. *Buildings, 13*(2), 556. https://doi.org/10.1016/j.sbspro.2013.07.182

Nowotarski, P., Pasławski, J., & Matyja, J. (2016). Improving construction processes using lean management methodologies: Cost case study. *Procedia Engineering, 161,* 1037–1042. https://doi.org/10.1016/j.proeng.2016.08.845

Parameswaran, A., Ranadewa, K., Rajini, P., & Jayanetti, J. (2024). State-of-the-art lean learning practices in construction: A case study in Sri Lanka. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, K.A.T.O. Ranadewa, & H. Chandanie (Eds.), *Proceedings the 12th World Construction Symposium* (pp. 947-960) CIOB. https://doi.org/10.31705/WCS.2024.75

Perera, L., Kajewski, S., & Coffey, V. (2024). A review of developed lean construction frameworks in the Sri Lankan context. *Proceedings - 8th international research symposium of University of Vocational Technology 2024* (pp. 751-758). https://eprints.qut.edu.au/262395/

Rosli, M. F., Muhammad Tamyez, P. F., & Zahari, A. R. (2023). The effects of suitability and acceptability of lean principles in the flow of waste management on construction project performance. *International Journal of Construction Management*, *23*(1), 114–125. https://doi.org/10.1080/15623599.2020.1853006

Salem, O., Solomon, J., Genaidy, A., & Minkarah, I. (2006). Lean construction: From theory to implementation. *Journal of Management in Engineering*, *22*(4), 168–175. https://doi.org/10.1061/(ASCE)0742-597X(2006)22:4(168)

Senevirathne, H., & Wimalasena, B. (2025). Implementation of lean principles in building construction industry, Sri Lanka. *Advances in Technology*, *5*(1), 27-31. https://www.researchgate.net/publication/392575365_Implementation_of_Lean_Principles_in_Building_Construction_Industry_Sri_Lanka

Singh, J. (2025). Lean construction principles and practices. In D. Bajaj (Ed.), *Handbook of Construction Project Management* (1st ed, pp. 941–968). Springer. https://doi.org/10.1007/978-981-96-7631-6_30

Zhou, Z., Wu, J., & Zhang, W. (2019). Construction resource allocation for industrial solid waste treatment centers in cities of Anhui province, China. *Management of Environmental Quality: An International Journal*, *30*(5), 1190–1202. https://doi.org/10.1108/MEQ-01-2019-0001

Premasinghe, B.G.H.N. and Eranga, B.A.I., 2026. Planning net-zero energy communities: Housing strategies for post-disaster resettlement in Sri Lanka - a narrative review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1344-1358. DOI: https://doi.org/10.31705/WCS.2026.98. Available from: https://ciobwcs.com/papers/

# PLANNING NET-ZERO ENERGY COMMUNITIES: HOUSING STRATEGIES FOR POST-DISASTER RESETTLEMENT IN SRI LANKA - A NARRATIVE REVIEW

**B.G.H.N. Premasinghe[1] and B.A.I. Eranga[2]**

## *ABSTRACT*

*Construction industry is a major contributor to global energy consumption and greenhouse gas emissions, while simultaneously being core of post-disaster recovery processes. Net Zero Energy Buildings (NZEB) have become as a key strategy for minimizing environmental impact of this sector, and the concept has increasingly expanded to the community scale as Net Zero Energy Communities (NZEC). Despite the significant potential of NZEC principles for addressing sustainability, resilience, and energy poverty, their application in post-disaster resettlement (PDR) contexts in developing countries remains largely unexplored. PDR communities provide a unique greenfield opportunity in Sri Lanka to integrate community-scale Net Zero Energy Housing (NZEH) at the earliest planning stages. However, there is no comprehensive framework exists to guide this integration. Through a narrative literature review, this paper explores the concepts and principles of NZEH and NZEC, analyses the socio-economic characteristics, climatic conditions, and energy requirements of Sri Lankan PDR communities, and identifies appropriate passive design strategies and renewable energy technologies for tropical community-scale NZE housing. Findings show significant synergies between NZEC principles and PDR housing requirements, including community orientation, shared resources, and local climate adaptation. The paper proposes a conceptual framework incorporating technical, social, and policy aspects for the implementation of community-scale NZEH in PDR context in Sri Lanka, contributing to national sustainability goals and disaster resilience.*

***Keywords:*** *Net Zero Energy Community; Passive Design; Post-disaster Resettlement; Renewable Energy; Sri Lanka.*

## 1. INTRODUCTION

The construction sector faces significant global pressure from climate changes, rising energy demands, and escalating environmental degradation (Ali et al., 2020; Lim et al., 2021). Globally, buildings consume approximately 40% of total global energy and emit approximately 36% of global greenhouse gas emissions (Xiaoxiang et al., 2024; Sajid et al., 2024). These figures reveal the necessity of the transition to the energy-efficient low-carbon models of building (Diliban et al., 2023). The urgency has intensified dramatically

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, premasinghebghn.21@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurue@uom.lk

in the current geopolitical climate: constant Middle East crises and related oil supply chain shocks have led to a constant rise in fuel and electricity prices which have a disproportionate impact on energy-dependent developing economies (Shi, 2025; Sun et al., 2024). This aspect particularly exposes Sri Lanka, where the national electricity generation mix is heavily reliant on hydropower, which historically accounts for approximately 40-50% of total generation, while the remaining share is supplied predominantly through fossil fuels, including oil-fired thermal plants and coal, which together constitute around 45-55% of installed capacity (Fernando et al., 2017; Koswatte et al., 2024). The structural dependence on both hydropower and imported fossil fuels creates a dual vulnerability: first, a hydrological vulnerability, whereby reduced rainfall during dry seasons substantially diminishes hydropower output, triggering rolling power curtailments; and second, a fiscal and supply chain vulnerability, whereby increased reliance on imported fossil fuels exposes the national economy to global price shocks and foreign exchange pressures. During dry seasons, hydropower generation reduces substantially, forcing the country to rely even more heavily on costly fuel imports for power generation, and this reduction directly translates into rolling curtailments that directly affect household welfare and economic activity (Withanaarachchi et al., 2014; Fernando et al., 2017) The power cuts and subsequent rise in fuel prices remained in households in Sri Lanka at the start of 2026, which empowers the national significance of substituting built environments in the nation with energy-sustainable systems (Ananda & Thennakoon, 2026).

As a response to this global and national crisis, the notion of Net Zero Energy Building (NZEB) has become a leading holistic solution, whereby buildings have an annual balance of equal amounts of energy consumed and energy produced by renewable sources, and where the end result is zero net energy used (Jaysawal et al., 2022; Ibrahim et al., 2024). Building upon this, this idea has been extended to the community level as Net Zero Energy Communities (NZEC) where energy management and shared infrastructure produce economies of scale and greater resilience than a single building can provide separately (Carlisle et al., 2009; Moghaddasi et al., 2021). Globally, NZEC pilot projects have demonstrated compelling results. The '*Historic Green Village'* in Florida, USA, achieved its net-zero energy goal through shared solar PV, heat pumps, and community-scale energy management (Huang et al., 2021). The '*West Village Campus'* in California proved that mass production of solar PV arrays and bio-digester generation was able to cover majority of the community energy demands (Huang et al., 2021). All these examples prove that NZECs are technically viable and cost-effective, with lower per-unit costs and enhanced resiliency and co-benefits such as local employment and microclimate improvement (Isaac et al., 2020; (Mavrigiannaki et al., 2021).

The transition from NZEB to NZEC, and from NZEC to construction industry implementation, is an orderly and practically compelling process (Godin et al., 2021). The defining characteristic of NZEC namely the simultaneous, coordinated, green-field development of several buildings under a single planning authority is precisely the condition that PDR housing reconstruction provides (Shrestha et al., 2025; Sulzakimin et al., 2020). Sri Lanka is often exposed to natural disasters such as floods, cyclones and landslides that require massive housing reconstructions (Vijekumara, 2015). Most recently, cyclone '*Ditwah*', which occurred in November 2025, resulted in catastrophic damage to all 25 districts, leading to the largest reconstruction program in Sri Lanka,

providing the timeliest opportunity to pilot community-scale NZEH on a national scale (Amaratunga & Kodituwakku, 2026).

However, past projects of Sri Lankan PDR have been more concerned with speed and quantity, not with sustainability, which has led to houses with low climate-responsiveness, high electricity bills, and poor levels of resident satisfaction (Mannakkara & Wilkinson, 2013). There is no existing comprehensive framework that would integrate the Net Zero Energy (NZE) principles with community-scale Post-disaster Resettlement Housing (PDRH) planning in Sri Lanka. This paper addresses this gap with the following scope and objective: to conduct a narrative literature review that synthesises the concepts and principles of NZEB and NZEC; analyses the socio-economic, climatic, and energy access characteristics of Sri Lankan PDR communities; identifies passive design and renewable energy strategies appropriate for tropical community-scale NZE housing; and proposes an original conceptual framework integrating NZEC principles with PDR housing planning in Sri Lanka. The paper concludes by proposing a conceptual framework that synthesizes finding. It is further suggested that a pilot project can be initiated within Sri Lanka's current cyclone Ditwah reconstruction programme. The benefits of lower household energy bills, better thermal comfort, stronger grid resilience, and faster development towards net-zero by 2050 could extend across country and serve as an incentive to others to adopt renewable energy.

## 2. RESEARCH METHODOLOGY

The study adopts a narrative literature review (NLR) methodology. The NLR methodology can be used when the aim is to synthesize a wide and heterogeneous body of knowledge in multiple, but related, domains and to develop a conceptual argument (Snyder, 2019). Unlike a systematic review, which follows a predetermined protocol in selecting studies, an NLR methodology gives the researcher more freedom to make interpretive judgments in selecting and synthesizing the studies, which is important in bridging the gaps in the related but distinct domains of energy engineering, sustainable construction, and disaster studies (Grant & Booth, 2009)..

Shandiz et al. (2021) employed a narrative review to map the state of the art in energy master planning for net-zero communities, and Gupta and Deb (2023) used the same approach to synthesize envelope design strategies for low-energy buildings in tropical climates. The NLR is particularly appropriate for emerging interdisciplinary fields where the evidence base is distributed across disciplines and where a heterogeneous body of literature needs to be brought together into a coherent conceptual argument, rather than subjected to quantitative meta-analysis (Snyder, 2019). The methodological choice is further justified by the fact that this study aims to develop a first-generation conceptual framework, which is an inherently interpretive and integrative task that precedes and informs subsequent empirical phases such as expert interviews or Delphi studies (Grant & Booth, 2009).

The literature was gathered from peer-reviewed journal articles, conference papers, books, government reports, and institutional publications, which were obtained via databases. The key search terms included combinations of: "*Net Zero Energy Building*", "*Net Zero Energy Community*", "*Post-disaster Resettlement*", "*Passive Design Tropical Climate*", "*Renewable Energy Sri Lanka*", and "*Community-scale Energy*". To make more practical, grey literature of the government agencies in Sri Lanka and reputable

industry bodies of the United Nations were also included. The inclusion criteria prioritized studies that were published after 2010, but there were exceptions in the case of seminal foundational studies. The review was organized thematically and synthesized to discover the principles, gaps, synergies, and integration prospects.

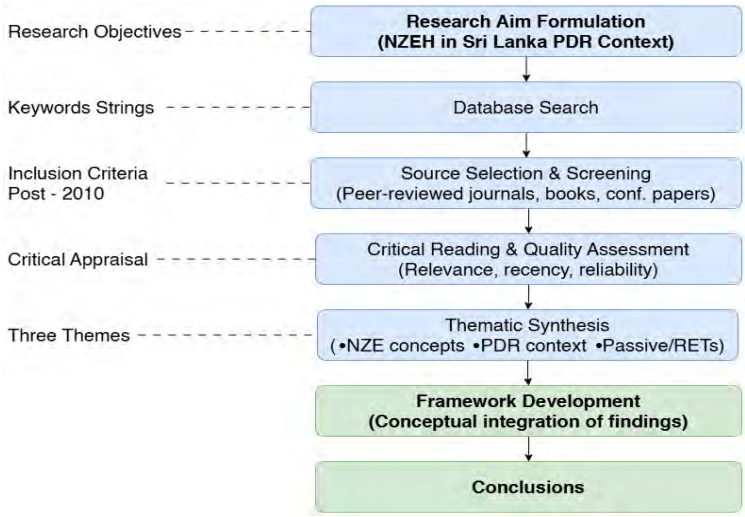



*Figure 1: Research process flowchart*

# 3. NET ZERO ENERGY CONCEPTS: FROM BUILDINGS TO COMMUNITIES

## 3.1 DEFINITION AND EVOLUTION OF NZEB

Net Zero Energy Buildings have emerged as the foundation of sustainable development in the built environment. An NZEB is defined as a building with an annual balance in which the energy consumption equals renewable energy production from on-site or off-site sources, resulting in zero net energy use (Jaysawal et al., 2022; Sartori et al., 2012). The initial systematic NZEB concept emerged in North America during the 1970s, gained traction in Europe through Germany's Passive House Institute in the 1990s, and was formalised when the International Energy Agency introduced the term "net zero energy" in 2008 (Attia, 2018). In 2010, the European Union subsequently proposed the "nearly zero energy building" (nZEB) standard, characterising buildings with extremely high energy efficiency whose minimal remaining needs are supplied by on-site renewable sources (Borowski et al., 2025). Nowadays, NZEB construction is increasingly feasible due to continuous developments of building technologies and renewable energy systems (Jaysawal et al., 2022).

The NZEB concept is based on two complementary strategies: ‘Energy Efficiency Measures’ (EEM) and ‘Renewable Energy Technologies’ (RET). EEM focus on reducing demand by building envelope optimisation, passive design, and efficient appliances and high-performance buildings targeting up to 70% energy reduction compared to national standards (Katipamula et al., 2015). RET then fulfil the reduced remaining demand through solar photovoltaic systems, solar thermal, wind, and biomass technologies (Lim et al., 2021).

## 3.2 TRANSITION FROM NZEB TO NZEC

The NZE concept has gradually extended beyond the individual building to encompass neighbourhood and community scales. A NZEC is defined as a set of buildings and related infrastructure within a defined area whose total annual energy consumption is balanced by renewable generation within or associated with the community (Alaifan & Azar, 2023; Carlisle et al., 2009). This scale change necessitates incorporating holistic planning policies related to grid management, transportation systems, and space planning coordination (Shandiz et al., 2021). Table 1 presents a comparative analysis.

*Table 1: Comparative analysis of NZEB vs. NZEC*

| Dimension | NZEB (Building Scale) | NZEC (Community Scale) | Sources |
|---|---|---|---|
| Operational boundary | Individual building | Multiple buildings + infrastructure | Carlisle et al., 2009; Moghaddasi et al., 2021 |
| Planning integration | Building-level design | Holistic spatial/grid/mobility planning | Shandiz et al., 2021 |
| Technology options | Limited to building-appropriate systems | Wider range including shared solar farms, district heating | Shandiz et al., 2021; Mudgal et al., 2019 |
| Economic efficiency | Higher per-unit costs | 16% lower average initial investment | Isaac et al., 2020 |
| Grid interaction | Individual bidirectional flow | Coordinated community-level management | Moghaddasi et al., 2021 |

Community-scale aggregation is useful in complex building typologies with diverse energy demand spaces to attain net-zero state where individual buildings with high energy demand did not achieve net-zero performance (Polly et al., 2016). The implementation of NZEC also has several co-benefits such as a better microclimate environment, increased compliance with energy-saving regulations, increased energy conservation, local employment creation, and economic growth (Mavrigiannaki et al., 2021; Ahmed et al., 2024). These broad advantages make NZECs particularly appropriate in the context of PDR where comprehensive community planning allows integrated sustainability from the earliest stages of development (Sulzakimin et al., 2020).

## 3.3 SOCIAL AND BEHAVIOURAL DIMENSIONS

The social and behavioural aspects are critical to NZEC adoption's success. In operational NZEH, performance is significantly affected by human-building interactions, often exceeding the impact of weather fluctuations (Nikdel et al., 2022). Community ownership and participation in the actual design of energy projects are critical to improve not only its acceptability but also operational engagement (Piselli et al., 2021). For PDR communities, this is not a choice, and community participation in the actual design of energy-efficient homes is a structural requirement, a condition under which communities always end up with culturally inappropriate homes, leading to low satisfaction and abandonment rates (Mannakkara & Wilkinson, 2013; Vijekumara, 2015).

# 4. POST-DISASTER RESETTLEMENT COMMUNITIES IN SRI LANKA

## 4.1 DEFINITION AND CONTEXT

PDR is defined as a process of planned, assisted, and permanent relocation of populations who have been displaced due to disaster events (Shrestha et al., 2025). PDRH includes initiatives to offer permanent homes to displaced populations, including on-site reconstruction or moving to new resettlement locations (Wijegunarathna et al., 2018). The concept of "Build Back Better" (BBB) implies that the reconstruction cannot be a mere restoration of pre-disaster conditions; instead, the community should be created by creating safer and more sustainable and resilient (Mannakkara & Wilkinson, 2013).

Sri Lanka is prone to natural disasters including floods, cyclones, and landslides that repeatedly destroy housing stock, necessitating massive reconstruction. Even though the most documented disaster of Sri Lanka in the literature is the Indian Ocean tsunami of 2004 that resulted in the death of above 35,000 people and displacement of an estimated of 516,000 people, with approximately 100,000 houses destroyed and approximately 100,000 partially affected (Mannakkara & Wilkinson, 2013; Lunuvila & Kulatunga, 2022), Cyclone Ditwah has fundamentally redefined the magnitude and covered an area of about a fifth of the land of Sri Lanka, over 2.3 million people in all 25 districts were affected, 646 people died, 209,000 displaced, more than 6,000 houses destroyed, and nearly 100,000 partially damaged (DMC, 2025). The total direct damages amount to USD 4.1 billion, which is about 4% of the Sri Lankan GDP in 2024. The timeliest and strategically significant opportunity to integrate NZE in the history of NZE integration in Sri Lanka is, the ongoing ‘Presidential Task Force’ reconstruction programme that is currently under monitoring by UN and World Bank and is projected to last through early 2026 (Amaratunga & Kodituwakku, 2026).

## 4.2 SOCIO-ECONOMIC AND CLIMATIC CHARACTERISTICS

Marginalised groups in society are disproportionately impacted by disasters, and vulnerability closely relates to poverty (Sridarran et al., 2018). Post-tsunami surveys show this pattern that 65% of affected households earned SLR 5,000 or less monthly, with livelihoods concentrated in fishing, trade, and manufacturing (Arunatilake, 2018). A fundamental problem identified in Sri Lankan PDR efforts is the failure to incorporate socio-economic conditions and cultural habits in housing design, which has resulted in people finding these homes alienating, leading to a high level of dissatisfaction, abandonment, and social conflicts (Mannakkara & Wilkinson, 2013; Vijekumara, 2015). These socio-economic characteristics are directly relevant to NZEC planning because the affordability constraints of PDR communities mean that energy cost savings and the reduction of energy poverty must be foregrounded as primary justifications for integrating NZE principles, rather than treating them as secondary sustainability co-benefits. The community-scale model of NZEC is particularly suited to low-income PDR contexts because shared infrastructure, cooperative energy ownership, and collective governance reduce per-household capital costs and maintenance burdens that would be prohibitive if borne individually (Isaac et al., 2020; Mavrigiannaki et al., 2021). Moreover, the cultural factors and livelihood patterns identified in the literature inform the social pillar of the NZEC implementation framework developed later in this paper.

Sri Lanka experiences a tropical climate with two monsoon seasons of great spatial variability. The Southwest monsoon (May–September) affects the Southern and Sabaragamuwa provinces most severely, while the Northeast monsoon (December–February) affects eastern, Northern, and North-central provinces (UNDRR, 2019). Climate change is intensifying these hazards, with flooding identified as the most critical and increasing threat in Sri Lanka. Another glaring weakness in Sri Lanka's PDR efforts is the failure to incorporate climate responsive designs, which has resulted in overheating and a need for mechanical air conditioning, which is unaffordable for low-income residents (Coorey et al., 2017).

### 4.3 ENERGY ACCESS AND PLANNING DEFICIENCIES

Energy poverty is an especially critical problem in PDRs. In Sri Lanka, it was identified that 67.8% of surveyed energy-poor households were not income-poor, thus reinforcing the fact that income poverty alone is not a cause of multidimensional energy poverty (Jayasinghe et al., 2021). Several tsunami-affected households relocated to resettlement programs lacked electricity connections entirely (Arunatilake, 2018). Inadequate thermal design creates a vicious cycle where housing is overheated, and people respond by purchasing cooling devices they cannot afford to run, thus creating energy poverty. (Coorey et al., 2017). There was an emphasis on speed over quality in PDR projects, with inadequate funding and poor planning further contributing to inadequate thermal and energy performance (Lunuvila & Kulatunga, 2022). In the backdrop of high and rising global energy costs in 2026, resettlement housing that does not incorporate passive thermal and on-site power generation technologies will perpetuate energy poverty on the very community's disaster recovery is meant to uplift. This directly validates the application of NZEC principles in PDR contexts: the community microgrid, shared solar generation, and passive design strategies that define a NZEC are precisely the tools required to break this vicious cycle of energy poverty in PDR communities. The energy access deficiencies documented here therefore constitute a core evidence base for the NZEC-PDR integration framework proposed in Section 6.

## 5. PASSIVE DESIGN AND RENEWABLE ENERGY TECHNOLOGIES FOR TROPICAL COMMUNITY-SCALE NZE HOUSING

### 5.1 PASSIVE DESIGN STRATEGIES FOR TROPICAL CLIMATES

In tropical climates such as in Sri Lanka, passive design strategies are found to be the primary and most cost-effective solution to reduce energy demands before any renewable technology is employed, which is an application of the hierarchy of Energy Efficiency Measures (EEM) first, as recommended by Gupta and Deb (2023) and Feng et al. (2019). At the community level, these strategies must be applied universally to all dwelling units to avoid mutual shading and wind obstruction. Table 2 summarises key passive design strategies for the Sri Lankan PDR context.

*Table 2: Passive design strategies for tropical climate NZE housing in Sri Lanka*

| Strategy | Application | Expected Benefits | Sri Lanka Considerations | Sources |
|---|---|---|---|---|
| Building orientation | East-west longitudinal axis | 20–40% cooling load reduction | Minimise east-west façade exposure | Hyde et al., 2012; Gupta & Deb, 2023 |
| Natural ventilation | Cross-ventilation; stack effect design | Mechanical cooling avoidance | Utilise monsoon wind patterns | Coorey et al., 2017; |
| Roof insulation | Reflective coatings; insulation layers | 30–50% heat gain reduction | Cost-effective local materials | Rathnasiri et al., 2023 |
| Solar shading | Extended overhangs (1–1.5 m) | 25–35% cooling load reduction | Balance shading with daylighting | Feng et al., 2019 |
| Daylighting design | Optimised window-to-wall ratio; light shelves; clerestory windows | 20–40% reduction in artificial lighting energy demand | Balance solar heat gain and glare control in tropical conditions | Gupta & Deb, 2023; Feng et al., 2019 |
| Raised floor levels | Elevated above grade | Flood protection; improved under-floor ventilation | Essential given cyclone flood risk | (Coorey et al., 2017) |

## 5.2 RENEWABLE ENERGY TECHNOLOGIES FOR THE SRI LANKAN CONTEXT

Sri Lanka has an ambitious goal of reaching net zero by 2050 with 100% renewable electricity (Fernando et al., 2023). As noted by Koswatte et al. (2024), the country receives 4.5-6.0 kWh/m²/day solar irradiance, giving solar PV a strong resource base. Hybrid systems that integrate solar, wind, and biomass are the most resilient for off-grid or semi-grid PDR communities, and this is confirmed through techno-economic analysis for the communities (Aberilla et al., 2020; Mudgal et al., 2019). Table 3 summarises key RETs applicable in the Sri Lankan NZE community context.

*Table 3: Renewable energy technologies for Sri Lankan NZE communities*

| Technology | Resource Availability | Capacity Range | Implementation Considerations |
|---|---|---|---|
| Solar PV | Excellent nationwide (4.5–6.0 kWh/m²/day) | 1–10 kW per household | Roof area requirements; grid connection; falling costs |
| Solar thermal | Excellent for water heating | 100–300 L per household | Simple technology; low maintenance; high reliability |
| Biomass gasification | Good in agricultural regions | 5–50 kW community systems | Fuel supply logistics; emissions control; community waste streams |
| Micro-wind | Variable (coastal/elevated areas) | 50 W–50 kW | Site-specific wind assessment required; noise considerations |

| Technology | Resource Availability | Capacity Range | Implementation Considerations |
|---|---|---|---|
| Hybrid systems | Excellent (combining sources) | 50–500 kW community scale | Complex design; energy management systems; optimal for off-grid PDR |
| Micro/mini hydro | Good in hill country and riverine areas (Sabaragamuwa, Uva, Central provinces) | 5–100 kW community systems | Site-specific hydrology assessment required; not applicable to coastal/flat PDR sites; high baseload reliability where available (Koswatte et al., 2024; Aberilla et al., 2020) |

The community microgrid is the operational mechanism that transforms individually efficient buildings into a functioning NZEC. Microgrids allow local energy generation, storage, and consumption to be optimised, allow peer-to-peer energy exchange, and provide islanding functionality in case of grid failures (Vindel et al., 2019; Piselli et al., 2021). Islanding capacity is no longer a supporting feature but a core requirement of resilience in PDR communities, where grid infrastructure itself might be damaged.

# 6. SYNERGIES BETWEEN NZEC AND PDR REQUIREMENTS: A CONCEPTUAL FRAMEWORK

## 6.1 MATCHING FEATURES

The preceding sections have established the distinct feature profiles of NZEC and PDRH independently. From the NZEC perspective (Sections 3.1–3.3), the defining features are: community-scale energy boundary with shared infrastructure; democratic and cooperative energy ownership models; integrated passive design and RET portfolios; community microgrid with islanding capability for resilience; and economies of scale that reduce per-unit initial investment by an average of 16% (Isaac et al., 2020). From the PDR context (Sections 4.1–4.3), the defining requirements are: rapid greenfield housing delivery at community scale; affordable construction and operating costs for low-income households; climate-responsive and thermally comfortable designs suited to tropical conditions; reliable access to electricity as a basic service; active community participation and social cohesion to prevent abandonment; and resilient infrastructure that can withstand future disaster events. The narrative review demonstrates significant synergies between NZEC principles and PDRH requirements, classified into three matching feature categories as illustrated in Table 4.

*Table 4: Synergies between NZEC features and PDR housing requirements*

| NZEC Feature | Corresponding PDR Requirement | Synergy Description |
|---|---|---|
| Community-scale focus; democratic energy ownership | Active community participation and social cohesion | NZECs foster collective welfare and shared goals, directly addressing PDR needs for robust social integration |

| NZEC Feature | Corresponding PDR Requirement | Synergy Description |
|---|---|---|
| Shared resources; distributed generation and storage | Reliable basic infrastructure (electricity, water) | NZECs leverage battery storage systems and microgrids for efficient power management, ensuring reliable essential amenities |
| Energy Efficiency Measures; passive design | Adaptable, climate-responsive, resilient housing | NZECs passive strategies tailored to local microclimates, supporting PDR requirements for resilient and affordable designs |

## 6.2 CONCEPTUAL FRAMEWORK

Figure 1 illustrates the conceptual framework developed through synthesis of the narrative literature review. It is presented in the form of a top-down causal flow chart comprising six layers that are interconnected: global and national context drivers, the conceptual evolution and application pathway, flanking barriers and enablers columns that simultaneously act on the implementation zone, the three-pillar implementation framework itself, the NZEC-PDR synergy band, and the NZE-housing outcomes. The feedback loop on the right side of the diagram connects the outcomes back to the context layer, signifying the cyclical and repetitive nature of the framework throughout the future PDR programmes.

The chart reflects interconnections and interrelationships between NZEB, NZEC, construction industry, and the PDR context, illustrating that these areas are not isolated, unrelated fields but a coherent, mutually reinforcing progression. Four global and national context drivers (climate crisis, energy insecurity, disaster frequency and policy imperative) that influence the system downwards. The conceptual evolution row directly plots the NZEB-to-NZEC-to-Construction Industry-to-PDR route, with Cyclone Ditwah reconstruction identified as the immediate entry point. Flanking the implementation zone, the barriers and enablers play the role of opposing forces on the implementation pillars. The three pillars have seven sub-elements each, representing the specific implementation requirements. The synergy band results to four measurable outcome categories: energy self-sufficiency, thermal comfort, disaster resiliency, and sustainability. The inclusion of the policy pillar within the three-pillar implementation framework is grounded in the evidence reviewed in Sections 4 and 5: the failure of past Sri Lankan PDR programmes to adopt energy-efficient designs was not merely a technical shortcoming but was driven by institutional prioritisation of speed over quality, inadequate funding mechanisms, and the absence of sustainability mandates in housing reconstruction policy (Lunuvila & Kulatunga, 2022; Mannakkara & Wilkinson, 2013). Similarly, the inclusion of financial incentives as a sub-element is grounded in the literature's consistent findings that the long-term economic benefits of NZE systems including energy cost savings and reduced utility expenditure are not immediately visible to low-income disaster affected households at the point of reconstruction. Policy instruments such as subsidies, green reconstruction grants, and community energy ownership schemes are therefore necessary enablers to bridge this gap between long-term NZE benefits and short-term recovery priorities (Godin et al., 2021; Mavrigiannaki et al., 2021).

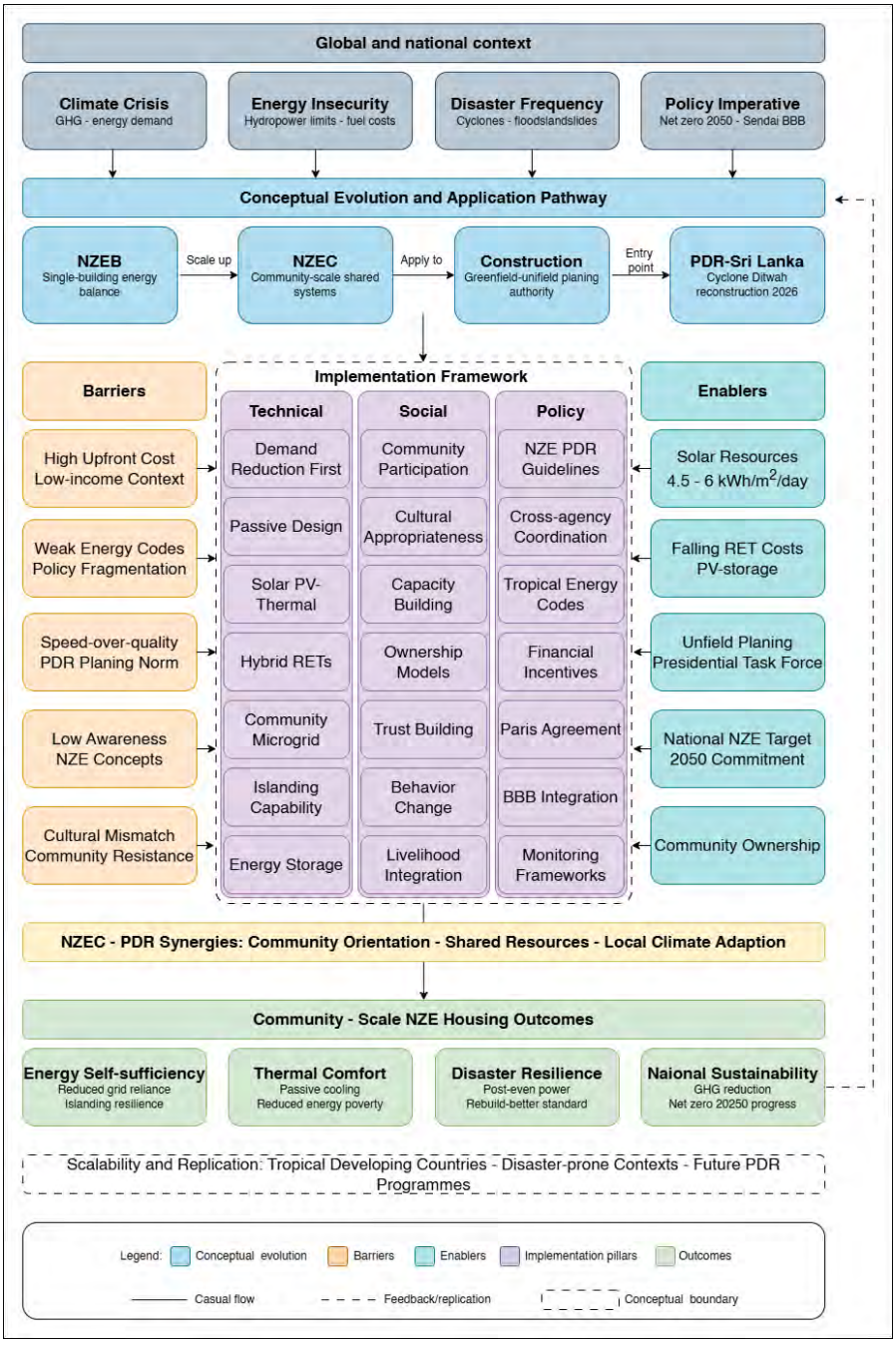



*Figure 2: Conceptual framework for community-scale NZEH in PDR communities in Sri Lanka*

## 7. CONCLUSIONS

The paper has analysed the convergence of concepts under NZE passive design, renewable energy, and post-disaster resettlement housing in Sri Lanka through a narrative literature review and synthesised the findings into an original conceptual framework.

The main contribution of this work is the framework illustrated in Figure 1. It maps, first of its kind, the logical and practical connections between NZEB and NZEC and the construction industry and the PDR context as forming a coherent progression of each level making possible the next, and not as an independent set of inquiry. Key findings confirm that the NZEC principles have certain tangible benefits that outweigh the

individual NZEB strategies, including the economies of scale reducing the initial investment by 16% on average, resiliency imposed by community microgrids with islanding capability, and energy management imposed by distributed peer-to-peer systems, which directly counter the failures recorded in previous Sri Lankan PDR designs. Cyclone Ditwah reconstruction programme is the most strategically important and timely opportunity ever to pilot community-scale NZEH at national scale in Sri Lanka, against the background of global energy price shocks and the national vulnerability of hydropower.

The passive design strategies and RETs identified, building orientation, natural ventilation, roof insulation, solar shading, solar PV, solar thermal, and hybrid energy systems constitute a technically feasible and contextually appropriate toolkit for Sri Lanka's tropical climate and socio-economic conditions. The three-dimensional implementation framework (technical, social, policy) offers a novel and evidence-based framework to further empirical studies. Future research ought to consider this framework by validating and refining it using expert interviews and delphi-based consensus building, the development of quantitative energy performance models within Sri Lankan climatic regions and propose the framework as the foundation of a pilot NZE community in the current Cyclone Ditwah reconstruction programme. When successfully deployed, the positive outcomes, which include lower household energy bills, better thermal comfort, more resilient post-disaster grid, and faster deployment toward national Net Zero by 2050 will be demonstrable, quantifiable, and reproducible in future PDR programmes in Sri Lanka and other developing countries vulnerable to disasters.

## 8. REFERENCES

Aberilla, J. M., Gallego-Schmid, A., Stamford, L., & Azapagic, A. (2020). Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities. *Applied Energy*, *258*, 114004. https://doi.org/10.1016/j.apenergy.2019.114004

Ahmed, S., Ali, A., & D'Angola, A. (2024). A review of renewable energy communities: Concepts, scope, progress, challenges, and recommendations. *Sustainability*, *16*(5), 1749. https://doi.org/10.3390/su16051749

Alaifan, B., & Azar, E. (2023). Potential for net-zero energy communities in Kuwait: An empirical techno-economic modeling and optimization approach. *Buildings*, *13*(8), 2096. https://doi.org/10.3390/buildings13082096

Ali, K. A., Ahmad, M. I., & Yusup, Y. (2020). Issues, impacts, and mitigations of carbon dioxide emissions in the building sector. *Sustainability*, *12*(18), 7427. https://doi.org/10.3390/SU12187427

Amaratunga, D., & Kodituwakku, L. (2026). Cyclone Ditwah: What next for Sri Lanka beyond the storm. *Progress in Disaster Science*, *29*, 100518. https://doi.org/10.1016/j.pdisas.2026.100518

Ananda, T., & Thennakoon, T. M. S. P. K. (2026). Beyond the debris: Why Cyclone Ditwah demands a post-disaster anthropology for Sri Lanka. *Vidyodaya Journal of Humanities and Social Sciences*, *11*(01), Article 2. https://doi.org/10.31357/fhss/vjhss.v11i01.02

Arunatilake, N. (2018). Post-disaster housing: Lessons learnt from the 2004 tsunami of Sri Lanka. In *The Asian Tsunami and post-disaster aid*. https://doi.org/10.1007/978-981-13-0182-7_11

Attia, S. (2018). Evolution of definitions and approaches. In *Net Zero Energy Buildings (NZEB)*. https://doi.org/10.1016/b978-0-12-812461-1.00002-2

Borowski, M., Rathnayake, C. M., & Zwolińska-Glądys, K. (2025). Nearly zero-energy buildings (NZEBs): A systematic review of the current status of single-family houses in the EU. *Energies, 18(12)*, 3215. https://doi.org/10.3390/en18123215

Carlisle, N., Van Geet, O., & Pless, S. (2009). Definition of a "Zero Net Energy" community. *National Renewable Energy Laboratory*, (November). https://www.nrel.gov/docs/fy10osti/47458.pdf

Coorey, S. B. A., Perera, N. G. R., Giridharan, R., & Emmanuel, R. (2017). *Thermal comfort study in post disaster housing in the southern coast of Sri Lanka*. Final Report for SRC Short Term Grant. https://kar.kent.ac.uk/62323/23/FINAL%20SENT-Thermal%20comfort%20in%20Tsunami%20housing-Sri%20Lanka-%20Paper-05-05-17_RE.pdf

Diliban, N. P., Singh, M. K., & Mahapatra, S. (2023). Improving Sri Lankan buildings' energy efficiency through bioclimatic classification and potential assessment. *E3S Web of Conferences*, *396*. https://doi.org/10.1051/e3sconf/202339601038

Disaster Management Centre. (2025). *Daily situation report: Cyclone Ditwah (December 12, 2025)*. https://www.dmc.gov.lk/images/dmcreports/Situation_Report_at_1800hrs_on_2025__1765544355.pdf

Feng, W., Zhang, Q., Ji, H., Wang, R., Zhou, N., Ye, Q., Hao, B., Li, Y., Luo, D., & Lau, S. S. Y. (2019). A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings. *Renewable and Sustainable Energy Reviews*, *114*. https://doi.org/10.1016/j.rser.2019.109303

Fernando, G. L., Liyanage, M. H., Anandarajah, G., Attalage, R. A., & Karunaratne, S. (2023). Achieving near-zero carbon dioxide emissions from energy use: The case of Sri Lanka. *Sustainable Production and Consumption*, *40*. https://doi.org/10.1016/j.spc.2023.06.024

Fernando, W., Gupta, N., & Ozveren, C. S. (2017). The electricity infrastructure in Sri Lanka then, now and hereafter. *2017 52nd International Universities Power Engineering Conference, UPEC 2017*, *2017-January*. https://doi.org/10.1109/UPEC.2017.8231986

Godin, K., Sapinski, J. P., & Dupuis, S. (2021). The transition to net zero energy (NZE) housing: An integrated approach to market, state, and other barriers. *Cleaner and Responsible Consumption*, *3*. https://doi.org/10.1016/j.clrc.2021.100043

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal* 26(2), 91-108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Gupta, V., & Deb, C. (2023). Envelope design for low-energy buildings in the tropics: A review. *Renewable and Sustainable Energy Reviews*, 186, 113650. https://doi.org/10.1016/j.rser.2023.113650

Huang, S., Wang, J., Fu, Y., Zuo, W., Hinkelman, K., Kaiser, R. M., He, D., & Vrabie, D. (2021). An open-source virtual testbed for a real Net-Zero energy community. *Sustainable Cities and Society*, *75*. https://doi.org/10.1016/j.scs.2021.103255

Hyde, R., Rajapaksha, U., Rajapaksha, I., Riain, M. O., & Silva, F. (2012). A design framework for achieving net-zero energy commercial buildings. *Buildings and Energy: 46th Annual International Conference of Architectural Science Association*, 1–10. https://archscience.org/wp-content/uploads/2014/08/p91.pdf

Ibrahim, M., Harkouss, F., Biwole, P., Fardoun, F., & Ouldboukhitine, S. (2024). Building retrofitting towards net zero energy: A review. *Energy and Buildings*, *322*, 114707. https://doi.org/10.1016/j.enbuild.2024.114707

Isaac, S., Shubin, S., & Rabinowitz, G. (2020). Cost-optimal net zero energy communities. *Sustainability*, *12*(6), 2432. https://doi.org/10.3390/su12062432

Jayasinghe, M., Selvanathan, E. A., & Selvanathan, S. (2021). Energy poverty in Sri Lanka. *Energy Economics*, 101, 105450. https://doi.org/10.1016/j.eneco.2021.105450

Jaysawal, R. K., Chakraborty, S., Elangovan, D., & Padmanaban, S. (2022). Concept of net zero energy buildings (NZEB) - A literature review. *Cleaner Engineering and Technology*, *11*. https://doi.org/10.1016/j.clet.2022.100582

Katipamula, S., Brambley, M., & Reddy, A. (2015). Building scale vs. community scale net-zero energy performance. *ACEEE Summer Study on Energy Efficiency in Buildings*, 151-168 https://www.aceee.org/files/proceedings/2010/data/papers/1951.pdf

Koswatte, I., Iddawala, J., Kulasekara, R., Ranaweera, P., Dasanayaka, C. H., & Abeykoon, C. (2024). Can Sri Lanka be a net-zero nation by 2050? Current renewable energy profile, opportunities, challenges, and recommendations. *Cleaner Energy Systems*, 8, 100126. https://doi.org/10.1016/j.cles.2024.100126

Lim, H. W., Kim, J. H., Lee, H. S., & Shin, U. C. (2021). Case study of load matching and energy cost for net-zero energy houses in Korea. *Energies*, *14*(19). https://doi.org/10.3390/en14196407

Lunuvila, H. L. J. M., & Kulatunga, U. (2022). Development of post-disaster resettlement strategies for Sri Lanka. *World Construction Symposium*. https://doi.org/10.31705/WCS.2022.29

Mannakkara, S., & Wilkinson, S. (2013). Build Back Better principles for post-disaster structural improvements. *Structural Survey*, *31*(4). https://doi.org/10.1108/SS-12-2012-0044

Mavrigiannaki, A., Pignatta, G., Assimakopoulos, M., Isaac, M., Gupta, R., Kolokotsa, D., Laskari, M., Saliari, M., Meir, I. A., & Isaac, S. (2021). Examining the benefits and barriers for the implementation of net zero energy settlements. *Energy and Buildings*, 230, 110564. https://doi.org/10.1016/j.enbuild.2020.110564

Moghaddasi, H., Culp, C., & Vanegas, J. (2021). Net zero energy communities: Integrated power system, building and transport sectors. *Energies*, *14*(21), 7065. https://doi.org/10.3390/en14217065

Mudgal, V., Reddy, K. S., & Mallick, T. K. (2019). Techno-economic analysis of standalone solar photovoltaic-wind-biogas hybrid renewable energy system for community energy requirement. *Future Cities and Environment*, *5(1).* https://doi.org/10.5334/fce.72

Nikdel, L., Agee, P., Reichard, G., & McCoy, A. (2022). Net zero energy housing: An empirical analysis from measured data. *Energy and Buildings*, 270, 112275. https://doi.org/10.1016/j.enbuild.2022.112275

Piselli, C., Salvadori, G., Diciotti, L., Fantozzi, F., & Pisello, A. L. (2021). Assessing users' willingness-to-engagement towards Net Zero Energy communities in Italy. *Renewable and Sustainable Energy Reviews*, 152, 111627. https://doi.org/10.1016/j.rser.2021.111627

Polly, B., Kutscher, C., Macumber, D., Schott, M., Pless, S., Livingood, B., & Van Geet, O. (2016). From zero energy buildings to zero energy districts. *2016 ACEEE Summer Study on Energy Efficiency in Buildings* (pp. 1–16). American Council for an Energy-Efficient Economy. http://aceee.org/files/proceedings/2016/data/papers/10_566.pdf

Rathnasiri, K. K. E. A. S. K., Gamage, I. S., & Lingasabesan, V. (2023). *Adapting sustainable energy features to existing condominium building stock in Sri Lanka*. https://doi.org/10.31705/faru.2023.14

Sajid, Z. W., Ullah, F., Qayyum, S., & Masood, R. (2024). Climate change mitigation through modular construction. In *Smart Cities, 7(1),* 394-423. https://doi.org/10.3390/smartcities7010023

Sartori, I., Napolitano, A., & Voss, K. (2012). Net zero energy buildings: A consistent definition framework. *Energy and Buildings*, *48*. https://doi.org/10.1016/j.enbuild.2012.01.032

Shandiz, C. S., Rismanchi, B., & Foliente, G. (2021). Energy master planning for net-zero emission communities: State of the art and research challenges. *Renewable and Sustainable Energy Reviews* 137, 110600. https://doi.org/10.1016/j.rser.2020.110600

Shi, Q. (2025). The impact of political conflicts in the Middle East on the global crude oil market. *Advances in Economics, Management and Political Sciences*, *211*(1). https://doi.org/10.54254/2754-1169/2025.cau26341

Shrestha, B., Uprety, S., & Keitsch, M. M. (2025). A longitudinal study of post-disaster resettlement in Nepal: Insights into building back better. *Architecture*, *5(1).* https://doi.org/10.3390/architecture5010017

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

Sridarran, P., Keraminiyage, K., & Amaratunga, D. (2018). Enablers and barriers of adapting post-disaster resettlements. *Procedia Engineering*, *212*, 125–132. https://doi.org/10.1016/j.proeng.2018.01.017

Sulzakimin, M., Adaji, A. A., Roy Hazli, A., Mohammad Syabilee, N. L., Roshartini, O., Indera Syahrul, M. R., Rozlin, Z., & Ebenehi, I. Y. (2020). Assessing the level of community involvement in post-disaster housing reconstruction and current green design practices towards net-zero energy buildings. *IOP Conference Series: Materials Science and Engineering*, *713*(1). https://doi.org/10.1088/1757-899X/713/1/012044

Sun, M., Cao, X., Liu, X., Cao, T., & Zhu, Q. (2024). The Russia-Ukraine conflict, soaring international energy prices, and implications for global economic policies. *Heliyon*, *10*(16). https://doi.org/10.1016/j.heliyon.2024.e34712

UNDRR. (2019). Disaster risk reduction in Sri Lanka. *UN Disaster Risk Reduction*. https://www.undrr.org/publication/disaster-risk-reduction-sri-lanka

Vijekumara, P. A. (2015). A study on the resettlement planning process applied in post-landslide disaster resettlement projects in Sri Lanka. In *Proceedings of the NBRO Symposium* (pp. 1–9). National Building Research Organisation. https://nbro.gov.lk/images/content_image/pdf/symposia/4.pdf

Vindel, E., Berges, M., & Akinci, B. (2019). Energy sharing through shared storage in net zero energy communities. *Journal of Physics: Conference Series*, *1343*(1). https://doi.org/10.1088/1742-6596/1343/1/012107

Wijegunarathna, E. E., Wedawatta, G., Prasanna, L. J., & Ingirige, B. (2018). Long-term satisfaction of resettled communities: An assessment of physical performance of post-disaster housing. *Procedia Engineering*, *212*. https://doi.org/10.1016/j.proeng.2018.01.148

Withanaarachchi A. S., Nanayakkara L. D. J. F, & Pushpakumara C. (2014). The progress of Sri Lanka's renewable energy sector developments in mitigating the GHG emission. *Energy and Environmental Engineering*, *2*(5). https://doi.org/10.13189/eee.2014.020502

Xiaoxiang, Q., Junjia, Y., Haron, N. A., Alias, A. H., Law, T. H., & Abu Bakar, N. (2024). Status, challenges and future directions in the evaluation of net-zero energy building retrofits: A bibliometrics-based systematic review. *Energies*, *17*(15). https://doi.org/10.3390/en17153826

De Abrew, K.D.S., Chandanie, H. and Ranasinghe, P.H.G.M.A., 2026. Prioritising construction procurement decision factors for achieving sustainable development. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1359-1372. DOI: https://doi.org/10.31705/WCS.2026.99. Available from: https://ciobwcs.com/papers/

# PRIORITISING CONSTRUCTION PROCUREMENT DECISION FACTORS FOR ACHIEVING SUSTAINABLE DEVELOPMENT

**K.D.S. de Abrew[1], H. Chandanie[2] and P.H.G.M.A. Ranasinghe[3]**

## *ABSTRACT*

*The construction industry plays a critical role in advancing sustainable development due to its significant environmental, economic, and social impacts. However, procurement decisions in construction are still frequently driven by cost considerations rather than sustainability objectives. Therefore, this study investigates and prioritises construction procurement decision factors that significantly influence the achievement of sustainable development in construction projects. The main objectives were to prioritise existing procurement decision factors that support sustainability attainment and synthesise sustainability-sensitive procurement decision factors. The study utilises a quantitative research approach. The identification of thirty procurement decision factors was divided into five categories which are selection of the procurement method, construction materials, equipment acquisition, decision regarding labour, and selection of suppliers. A survey was conducted targeting construction professionals and academics using a structured questionnaire. Several statistical tests were performed on collected data including the Shapiro-Wilk test, Kruskal-Wallis test, and weighted mean ranking. The findings reveal that material related procurement decision factors and equipment acquisition related decision factors are the most significant in achieving sustainable development. Furthermore, study revealed that any of the labour related decision factors are not sustainability sensitive. The second most influential cluster were supplier selection and procurement method related decision factors to achieving sustainable development in construction. The implications of the study to offer evidence based guiding principles on how procurement strategies can be designed to incorporate sustainable development for to policymakers, construction professionals.*

***Keywords:*** *Construction Procurement; Construction Projects; Procurement Decision Factors; Sustainable Development.*

## 1. INTRODUCTION

Construction is a global industry that has a substantial influence on economic, social, and environmental development (Chhabra & Grover, 2024). Procurement strategically drives

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, deabrewkds.21@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ranasinghephgma.20@uom.lk

the construction industry and contributes to the long-term success of construction projects (Jayasinghe et al., 2025). According to Bolomope et al. (2022) Construction Procurement (CP) consists of a set of interconnected activities such as project requirements identification, tender document preparation, bid invitation and evaluation, supplier or contractor selection, contract negotiation and award and management of contract performance. Procurement decisions in construction can be defined as the procedure of selecting the most appropriate procedures, contractors, suppliers and resources at projects which are made by multiple stakeholders across different project stages initial planning and design to execution and end (Ruparathna & Hewage, 2015). In addition, effective assessment and consideration of the diverse factors related to procurement decisions will ensure minimisation of cost overruns, delays, and quality problems, which will positively improve its performance (Hassan & Mukarram, 2025). Procurement decisions in construction require considering multiple interconnected factors, and integrating these factors leads to improved overall project performance (Hassan & Mukarram, 2025). Babaeian et al. (2022) explain that most of the fundamental decisions are made during the early stages of a project, however Ruparathna and Hewage (2015) have identified CP activities are effective throughout the entire project lifecycle, such as planning to close of the project, and are critical towards the compliance with quality, cost, and time goals. Together, these studies highlight that procurement decisions are distributed across multiple project stages rather than occurring at one specific point in time.

Procurement in construction much beyond the expectations of the economic effects but as a tool to move environmental and social policy (Naoum & Egbu, 2016). According to Ogunsanya et al. (2023), CP is the value-of-money based on the whole life cycle, with a substantial responsibility of care to ensure that the effects to the environment are minimised at the expense of social benefit to the community. Halwatura and Kodithuwakku (2022) have mentioned CP plays a crucial role in achieving sustainability objectives because it translates environmental social and economic goals into practical project outcomes and serves as a key mechanism for integrating sustainability into construction delivery. Sustainability is an integrated framework that prioritises everyone's quality of life by establishing connections between social and economic factors in addition to environmental factors (Adel et al., 2023). In construction, the goal is to balance environmental sustainability and social equality with economic realities (Halwatura & Kodithuwakku, 2022). Therefore, it can be emphasised that decision-making is not a single, isolated act but a complex and ongoing process in CP (Naoum & Egbu, 2016).

The lowest-price award continues to dominate procurement with minimal regard to life-cycle costs, environmental impacts, or social value (Domingo et al., 2019).In the study of Ershadi et al. (2021) have identified rather than sustainability purpose, implementation of sustainable procurement practices is limited due to financial risks, poor regulatory frameworks, and supply chains, which have a cumulative effect of cost overruns, delays and quality failures that compromise the performance of projects and sustainable development objectives in most cases. Domingo et al. (2019) indicates that existing sustainable procurement measures are excessively focused on the environmental field, and such dimensions as social and economic, including labour standards, rural economic growth, and value innovation are relatively overlooked.

Numerous research has been conducted on various issues related to procurement including the process of selection, performance of projects connected with procurement

approaches and models (Rahmani et al., 2022). Ogunsanya et al. (2023) develop construct-based models and barrier clusters for sustainable procurement. Osuizugbo and Adenuga (2024) identified decisive factors for sustainable procurement on stakeholders' perspectives within the Nigerian context. In line with this, a research gap still exists to study and prioritise the construction procurement decision factors, in various project phases, that have the maximum impact in achieving the goal of sustainability. Specifically, no study has systematically prioritised procurement decision factors across multiple categories spanning procurement method, materials, equipment, labour, and suppliers with explicit reference to all three sustainability dimensions simultaneously. This gap is particularly pronounced in developing-country construction contexts, where sustainability-oriented procurement policy is still emerging. Therefore, the study aims to investigate and prioritise construction procurement decision factors that significantly influence the achievement of sustainable development in construction projects through below objectives.

1. Investigating general procurement decision factors through literature.
2. Prioritising existing procurement decisions that supports attainment of sustainability in construction industry.
3. Synthesising and discussing sustainability sensitive procurement decision factors.

For the purposes of this study, 'sustainability-sensitive procurement decision factors' are defined as those procurement decisions that, when appropriately applied, demonstrably contribute to one or more dimensions of sustainable development namely, environmental protection, economic efficiency, and social equity in construction project delivery.

# 2. LITERATURE REVIEW

## 2.1 PROCUREMENT AND SUSTAINABILITY IN CONSTRUCTION PROJECTS

The successful completion of construction work is positively connected with efficient procurement processes, including clear control requirements and quality assurance, underscoring the significance of methodical and organised procurement activities (Jayasinghe et al., 2025). Effective assessment and consideration of the diverse factors related to procurement decisions will ensure minimisation of cost overruns, delays, and quality problems, which will positively improve its performance (Hassan & Mukarram, 2025). The built environment has a crucial role in determining a sustainable development since constructions are major consumers of natural resources and lead to other problems being climate change, depletion of resources and even the generation of waste (Opoku et al., 2022). Therefore, there is growing expectation that the construction sector applies sustainable practices that will encourage effective utilisation of resources, protection of the environment, and both economic and social gains in the long run (Ajayi & Oyedele, 2018). Beyond environmental performance, procurement decisions also carry significant economic and social implications. Economically, procurement strategies influence whole-life value, cost efficiency, and local economic development through supplier and labour sourcing decisions (Ogunsanya et al., 2023). Socially, procurement provides a mechanism for advancing labour rights, community benefit, and inclusive participation of marginalised groups in the construction supply chain (Loosemore et al., 2023). Sustainable construction seeks to achieve a balance of these three aspects of sustainability through the reduction of environmental degradation and generation of economic value

and enhancement of social well-being (Opoku et al., 2022). Construction industry is required to integrate sustainability considerations into its project planning, design, and implementation processes to ensure responsible development and long-term project performance (Halwatura & Kodithuwakku, 2022).

Procurement activities define the decision of materials, technologies, suppliers and construction methods over the course of construction (Bolomope et al., 2022). Procurement in construction projects entails the planning, contracting, and management of contracts involved in the supply and maintenance of construction works and hence plays a major role in determining the efficiency of resources, waste management, and environmental performance (Opoku et al., 2022). Sustainable procurement strategies that include the adoption of energy-saving technologies, facilitating material reuse, introducing waste segregation, and the use of the whole-life costing strategies may help to minimise environmental impacts and enhance the project value and performance over time (Halwatura & Kodithuwakku, 2022). Therefore, effective assessment and of procurement decision factors are essential to support sustainability objectives, minimise cost overruns and delays, and improve overall project performance.

## 2.2 PROCUREMENT DECISION FACTORS

Project success is largely dependent on the procurement method selected, such as design-bid-build, design-build, integrated project delivery, public-private partnerships, and construction management (Zhong et al., 2023). There is not a single best approach; instead, the choice is influenced by contextual circumstances, customer objectives, and project complexity (Bolomope et al., 2022; Naoum & Egbu, 2016). Ajayi and Oyedele (2018) indicates the need to adopt high quality, durable, and reusable materials to minimise replacement and pre-mature replacement, improve the lifecycle performance and reduce the amount of waste. Furthermore, Waris et al. (2019) discloses a strong model of equipment selection that encompassed important factors, such as life cycle cost, performance, system capability, operational convenience, environmental impact, and social benefits. sustainable procurement focuses on using equipment that are less harmful to the environment, have greater operational efficiencies and extended life cycles (Islam et al., 2020).Moreover the selection between direct and contracted labour is a key procurement decision; although overall cost overruns are generally similar, direct labour can reduce unit costs by eliminating contractor profit but is more prone to time overruns and is therefore mainly used for maintenance works (Osei-Asibey, 2021).In addition qualification assessment of suppliers is usually, environmental performance, social responsibility practices, economic stability and adherence to labour and industry standards (Tosa-Williamsa & Nsikan, 2024). According to Hoseini et al. (2021) procurement managers are also keen on suppliers who can guarantee the material to be of international quality and safety because high quality of the inputs is directly linked with successful project outcome. According to the above factors the below Table 1 illustrates the general procurement decision factors under the categories of decision factors related to selection of procurement method, construction materials, Equipment acquisition, labour and supplier selection.

*Table 1:Procurement decision factors*

| Category | Decision factor | Source |
|---|---|---|
| Selection of procurement method | Selection of contract type | [1] |
| | Decision on contract award criteria | [2] |
| | Prequalification for contractors | [2] |
| | Timing of contractor involvement | [3] |
| | Design changes requirement during project execution | [4],[5] |
| | Project schedule and speed | [4],[6] |
| | Scope of the work for respective parties | [6] |
| Construction materials | Select high-quality, durable, and reusable materials | [7],[8] |
| | Conduct precise materials estimation to prevent over/under ordering | [7],[8],[12], [9] |
| | Implement just-in-time delivery systems | [7],[8], [9], |
| | Ensure effective protection during transportation, loading, and unloading | [7],[8],[12] |
| | Minimise packaging materials | [7],[8] |
| | Collaborate with suppliers to facilitate small quantity supply | [7],[8],[9] |
| | Establish mutual agreements for take-back schemes | [7],[8],[9] |
| | Reduce the waste allowance | [7],[8] |
| Equipment acquisition | Environmental impact assessment | [12],[13],[10] |
| | Worker health and safety considerations when acquiring equipment | [15] |
| | Integration of LCA in procurement | [12],[13],[14] |
| | Equipment acquisition method | [10],[11] |
| | Social benefits evaluation | [13] |
| Supplier selection | Supplier location | [22] |
| | Required supplier qualifications | [22],[23],[24],[25] |
| | Decisions on time duration on delivery | [24],[25],[32] |
| | Delivery cost | [22],[24],[25] |
| | Required material or equipment qualification | [22],[23],[32] |
| Decision on labour | Skilled and unskilled labour composition | [20],[19] |
| | Social procurement practices in labour procurement | [21] |
| | Direct labour and contracting labour | [16] |
| | Local vs. foreign labour decisions | [20] |
| | Labour-only procurement | [17],[18] |

[1] Niriella & Gamage (2022);[2] Almuhannadi & Ghareeb (2024);[3] Osuizugbo et al. (2024);[4] Agbaxode et al. (2024);[5] Eriksson (2017);[6] Naoum and Egbu (2016); [7] Ajayi & Oyedele (2018); [8] Ajayi et al. (2017);[9] Chidiobi et al. (2024); [10] Polavarapu & Rao (2023));[11] Polavarapu & Rao (2023);[12] Scherz et al. (2023);[13] Waris et al. (2019);[14] Petroutsatou et al. (2023),[15] Zuraidi et al. (2025);[16] Osei-Asibey (2021);[17] Akinkunmi et al. (2018);[18] Awodele et al. (2019);[19] Hussain et al. (2020);[20] Juricic et al. (2021);[21]

| Category | Decision factor | Source |
|---|---|---|
| | | Loosemore et al. (2023);[22] Ghafoori & Abdallah (2025);[23] Hoseini et al. (2021);[24] Cengiz et al. (2017);[25] Tosa-Williamsa and Nsikan (2024) |

The above factor categories relate to sustainable development dimensions as follows. Material-related decisions directly support environmental sustainability through resource efficiency and waste reduction, and economic sustainability through whole-life cost optimisation (Ajayi & Oyedele, 2018). Equipment acquisition decisions contribute to environmental sustainability via reduced emissions and lifecycle impact, and to social sustainability through worker health and safety considerations (Waris et al., 2019; Zuraidi et al., 2025). Supplier selection decisions span all three dimensions environmental performance, economic stability, and social responsibility (Hoseini et al., 2021; Tosa-Williamsa & Nsikan, 2024). Procurement method selection influences economic sustainability through cost and risk allocation, and social sustainability through contractor prequalification criteria that may embed sustainability requirements (Naoum & Egbu, 2016; Bolomope et al., 2022). Labour decisions, while primarily associated with social sustainability through fair employment and skills development (Loosemore et al., 2023; Juricic et al., 2021), were found to have a comparatively indirect link to environmental and economic sustainability outcomes in this study.

## 3. RESEARCH METHODOLOGY

The research method is quantitative research since it statistically prioritises procurement decision factors which impact in achieving the goal of sustainability. Consequently, 30 general procurement decision factors were established in five categories as demonstrated in Table 1. The study was then done through a questionnaire survey to gather the data, asking respondents to rank the level of significance of each factor using a five-point Likert scale, ranging from “Not Significant” to “Highly Significant” in determining whether the procurement decision factors have a significant effect on the realisation of sustainable development in construction projects. According to Barella et al. (2024), the quantitative research approach intends to establish relationships, patterns, or trends in the data and extend the findings to a larger population. This approach is directly aligned with the research objectives of ranking and prioritising procurement decision factors across a professional population, as it enables systematic comparison and generalisation of perceived factor significance. Purposive sampling was employed to target professionals with direct knowledge of both construction procurement practices and sustainability objectives, ensuring that responses were grounded in practical experience. The sample size of 75 was determined based on established guidelines for quantitative survey studies in the construction field (Barella et al., 2024).

Initially, the collected data were evaluated for normality using the Shapiro-Wilk test, as it is more sensitive than other normality tests in identifying deviations from a normal distribution and is suitable for large sample sizes (Khatun, 2021). Based on the results, since the p-value was $\leq 0.05$ (indicating that the data were not normally distributed), the Kruskal-Wallis test was applied. Specifically, the Kruskal-Wallis test was applied to verify that the significance ratings of procurement factors were not systematically influenced by respondents' professional designation, thereby confirming that the aggregated rankings are representative of the broader professional population rather than reflecting the bias of any single occupational group. All statistical analyses were carried

out using IBM SPSS statistics 26 software. Subsequently, quantitative data collected through the questionnaire survey were analysed using descriptive analysis.

The mean of any data set is the average rate of response in the application of Likert scale of analysis of a data, the mean value reveals the rating of the opinion of the statements under analysis (Yaska & Nuhu, 2024). Accordingly, the following formula was used for the calculation of mean.

$$Mean = \frac{\sum_{i=1}^{5} x_i \times f_i}{n} \qquad (01)$$

Where, $f_i$= is the total response of a statements (ranging from 1 to 5), n=total number of respondents and X$i$ is the Likert scale value (weight).

Standard deviation is a convenient measure of dispersion that is often applied to estimate the extent to which the data deviates or disperses around the mean by taking the positive square root of the variance is the expected value of the standard deviation (Yaska & Nuhu, 202). Thuss, it was used in this study to determine the spread of the findings on the participant's opinion on the sustainability sensitive construction procurement decisions factors. Accordingly, the following formula was used.

$$Standard\ deviation = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}} \qquad (02)$$

where, xi=Weight assigned to each response based on the level of agreement, $\bar{x}$= Mean of the dataset and $n$= Number of respondents.

In line with the threshold utilised by Hussain et al. (2025) to identify factors with highest importance level in that study, the weighted mean rating greater than 4.00 was used as the benchmark to identify the most influential decision factors. The standard deviation was also determined to ascertain the amount of deviation of the rating of the respondents with a lower value showing more agreement between the respondents.

## 4. FINDINGS AND ANALYSIS

The questionnaire was distributed as an online survey via Google form targeting 75 industry professionals and academic researchers with familiarity regarding construction procurement and sustainable development. The survey yielded a response rate of 77.33% (58 responses), successfully achieving the required sample size for the study. First section of the questionnaire survey collected the background data of the respondents such as experience, designation, awareness of the sustainability and the construction procurement. Figure 1 illustrates the background of the respondents.

Accordingly, the inner layer of the chart represents the professional designation of the respondents, and the outer layer represents the highest education qualification of the professionals. The composition of this sample reflects the diverse group of construction professionals indicating that the data is representative and reliable for drawing meaningful conclusions. Experience levels among respondents with the largest group having more than 10 years of experience (38%). While 19% of respondents have 1–5 years of experience, the remaining 81% have more than 5 years of experience, indicating that the questionnaire responses are reliable and gather from well-experienced professionals.

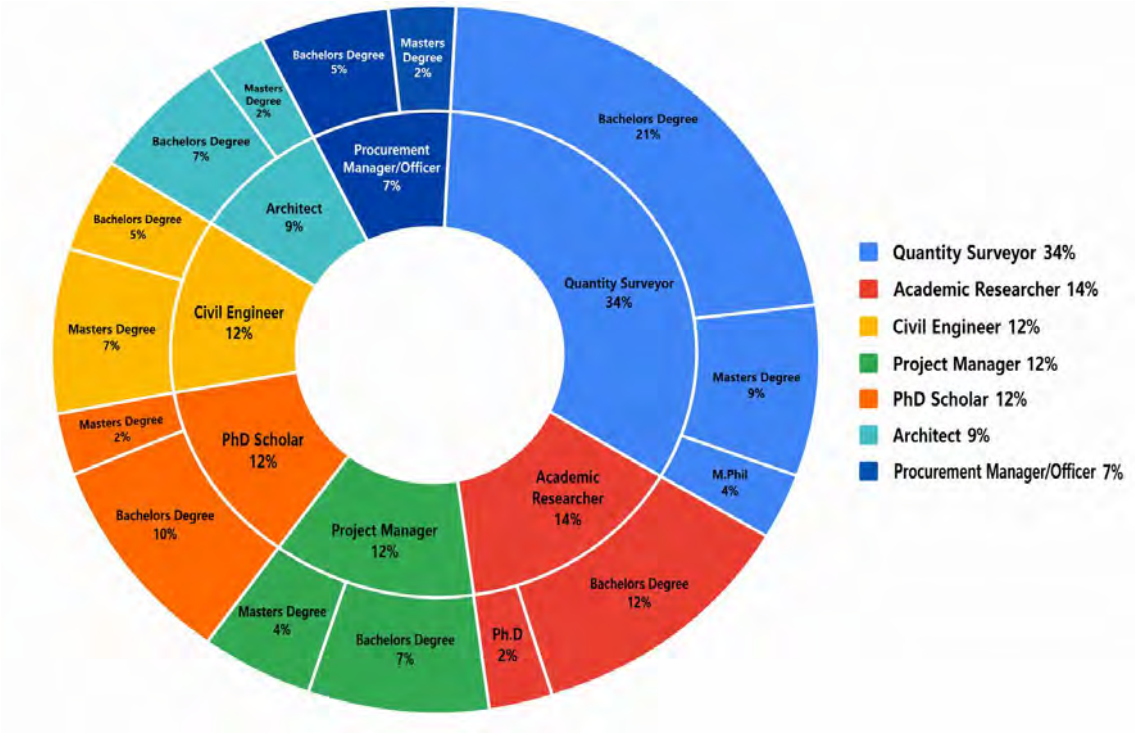



*Figure 1:Profile of the Sample*

## 4.1 SUSTAINABILITY SENSITIVE CONSTRUCTION PROCUREMENT DECISIONS FACTORS

The Shapiro-Wilk test was employed to assess the normality of the data distribution using SPSS software. The null hypothesis ($H_0$) stated that "The data sample from the questions follow a normal distribution". the P value $\leq 0.05$ for all questions rejecting the null hypothesis ($H_0$). This indicated that the data were not normally distributed. As a result, the Kruskal-Wallis test was used as a non-parametric test to identify the correlation between the professional designation of the respondents and their responses. Kruskal-Wallis test was performed for all questions. For this test null hypothesis ($H_0$) stated as "the distribution of the sample same across categories of professional designation". The P value > 0.05, retaining the null hypothesis ($H_0$) for all the questions. This proved that all the answers which are provided by the respondents are not dependent on their professional designation category. Therefore, an equal sample size from each professional group is not required. Subsequently, the weighted mean rating method was applied to evaluate the relative rankings of each decision factors, in descending order of significance, with the results summarised in Figure 2.

These decision factors range from "Select high-quality, durable, and reusable materials" under the materials category, which was ranked the highest, to "Labour-only procurement," under the labour decision category which was ranked the lowest. In line with the threshold, the weighted mean rating greater than 4.00 was used as the benchmark to identify the most influential decision factors. Accordingly, 14 of the 30 factors surpassed this threshold and were considered highly significant in attainment of sustainability through procurement decision factors as illustrates in Table 2.

*Table 2:Sustainability sensitive procurement decision factors*

| Decision factor | Mean | SD | Rank |
|---|---|---|---|
| Select high-quality, durable, and reusable materials | 4.50 | 0.884 | 1 |
| Environmental impact assessment | 4.43 | 0.84 | 2 |
| Worker health and safety considerations when acquiring equipment | 4.33 | 1.033 | 3 |
| Prequalification for contractors | 4.29 | 0.955 | 4 |
| Required material or equipment qualification | 4.29 | 0.859 | 5 |
| Reduce the waste allowance | 4.24 | 0.844 | 6 |
| Integration of LCA in procurement | 4.21 | 0.874 | 7 |
| Conduct precise materials estimation to prevent over/under ordering | 4.12 | 1.01 | 8 |
| Minimise packaging materials | 4.07 | 1.024 | 9 |
| Required supplier qualifications | 4.07 | 0.953 | 10 |
| Social benefits evaluation | 4.05 | 0.907 | 11 |
| Supplier location | 4.05 | 0.999 | 12 |
| Decision on contract award criteria | 4.03 | 1.025 | 13 |
| Timing of contractor involvement | 4.02 | 1.017 | 14 |
| Ensure effective protection during transportation, loading, and unloading | 4.00 | 1.009 | 15 |
| Skilled and unskilled labour composition | 4.00 | 0.991 | 16 |
| Project schedule and speed | 3.98 | 1.1 | 17 |
| Decisions on time duration on delivery | 3.98 | 1.017 | 18 |
| Implement just-in-time delivery systems | 3.95 | 1.016 | 19 |
| Delivery cost | 3.95 | 1.05 | 20 |
| Establish mutual agreements for take-back schemes | 3.91 | 0.904 | 21 |
| Design changes requirement during project execution | 3.90 | 1.021 | 22 |
| Equipment acquisition method | 3.79 | 1.104 | 23 |
| Selection of contract type | 3.72 | 1.24 | 24 |
| Social procurement practices in labour procurement | 3.62 | 1.006 | 25 |
| Scope of the work for respective parties | 3.60 | 0.917 | 26 |
| Collaborate with suppliers to facilitate small quantity supply | 3.59 | 0.918 | 27 |
| Direct labour and contracting labour | 3.55 | 1.062 | 28 |
| Local vs. foreign labour decisions | 3.43 | 0.957 | 29 |
| Labour-only procurement | 3.36 | 1.055 | 30 |

"Selecting high-quality, durable, and reusable materials" was identified as the most significant factor in this study, and together with the other three material-related factors that surpassed the threshold (as shown in Figure 2), this demonstrates the substantial impact of material-related procurement decisions on achieving sustainable development. Conversely, all the decision factors that are related to labour were below the threshold

which verifies their relatively lower importance in attaining sustainability. This indicates that, despite labour considerations being still significant in the delivery of the project they are seen to have a less direct influence on sustainable development. Moreover, equipment acquisition–related factors, such as "Worker health and safety considerations when acquiring equipment" and "Environmental impact assessment," were ranked as the second and third most significant factors, highlighting the critical role of responsible equipment selection in promoting environmental protection and social well-being. Within the supplier selection category, the factor that was determined to be the most important was the required material or equipment qualification with highest mean (4.29). This further confirms that material- and equipment-related considerations are highly relevant in supplier selection and reinforces that the highest-ranked factors play a critical role in achieving sustainable development in construction projects. Moreover, the current study has identified the prequalification of the contractors as the most important factor within the procurement method selection category which is strategically crucial in ensuring that sustainability outcomes are achieved. In contrast least important factors that affect sustainable development are under the category of labour decisions. These factors are ranked low, potentially because on sustainability performance of labour-related procurement concerns are more indirect than the other categories. Furthermore, the analysis of significant decision factors to achieve sustainable development, were clustered according to the categories identified in the literature, as illustrated in Figure 2 below.

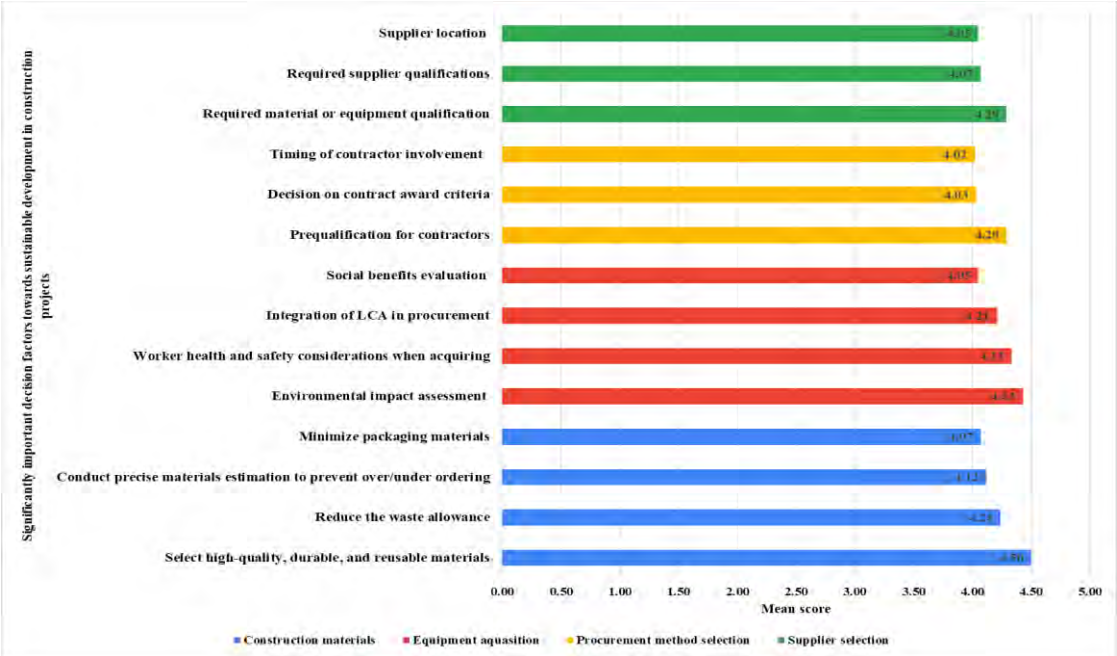



*Figure 2: Categories of sustainability sensitive procurement decision factors*

## 5. DISCUSSION

The study identified 14 out of 30 construction procurement decision factors as highly significant for achieving sustainable development, reinforcing that procurement is a key mechanism for translating environmental, social, and economic goals into project outcome. Moreover, the empirical findings of the study align closely with the literature. Findings are showing that materials and equipment choices are perceived as the primary

levers for improving environmental performance, while social and labour aspects often receive less attention. According to Opoku et al. (2022), the provided factors such as material reuse, sustainable design, fuel-efficient machinery, low emission technology and low-carbon production technology, waste segregation are aligned with the above analysed material and equipment related categories. Ajayi and Oyedele (2018), emphasised that reusing materials and recycling help to optimisation of resources and cutting down on carbon emissions. Therefore, it is further findings are closely aligned with literatures. Further it is aligned with important factors, such as life cycle cost, environmental impact, and social benefits are important factors under supplier selection (Waris et al., 2019). In line with Gurgun and Koc (2020), contractor prequalification has progressively integrated the concerns of sustainability and life-cycle costs to make sure that the targeted environmental goals are realised after the procurement method selection. According to Akinkunmi et al. (2018), the lowest factor (mean=3.36) can be interpreted as an opinion that the labour-based procurement systems are commonly implemented to attain short-term cost-effectiveness rather than pursue the goals of sustainability. Together, these results prove that the empirical knowledge produced in this study is not isolated and part of a consistent trend in modern construction literature. More broadly, the lower ranking of labour-related factors may reflect a prevailing short-term cost-focus culture in construction procurement, where social sustainability levers are perceived as peripheral rather than integral to procurement decisions (Akinkunmi et al., 2018). In the Sri Lankan construction context specifically, labour decisions are often governed by informal industry norms and subcontractor relationships rather than formal procurement criteria, which may further explain their comparatively lower perceived sustainability sensitivity (Osei-Asibey, 2021). Addressing these social dimensions through policy intervention and formal procurement frameworks represents an important avenue for future practice development.

This research has implications for policy makers, project managers and procurement professionals in that it offers evidence-based advice on how to integrate sustainability into the procurement strategies to answer the key question of why such procurement decisions that are sensitive to sustainability are important. Simultaneously, the study is limited because it is based on perception-based quantitative data collected through a questionnaire survey. This means the results reflect the opinions and judgments of respondents rather than actual observations of real project practices. Future research might establish more procurement factors than those analysed in the current research and applies the case study research methods to examine how such decisions are applied in actual construction projects.

Furthermore, while the study targeted construction professionals and academics, it did not separately stratify or collect data from distinct stakeholder roles such as clients, main contractors, subcontractors, material suppliers, and regulatory bodies. The differing priorities and procurement responsibilities of these groups may yield varied perceptions of factor significance, and future research should explicitly include multi-stakeholder sampling to capture these perspectives.

## 6. CONCLUSIONS

The present study set out to examine prioritising existing procurement decisions that supports attainment of sustainability in construction industry and synthesising and discussing sustainability sensitive procurement decision factors. This was achieved

through a literature review and the questionnaire survey. The findings indicated that, demonstrating that construction material related procurement decision factors are the most significant to achieving sustainable development and moreover the equipment acquisition related factor also similarly influenced to the attainment of sustainability. further it was revealed that as second most significant factors have come from the clusters of supplier selection and the procurement method selection related decision factors. These findings are significant as they offer insights that can be used to enhance construction procurement sustainability through the relative significance of factors of material related, equipment procurement, supplier selection and procurement method decision.

## 7. REFERENCES


Adel, G., Othman, A. A. E., & Harinarain, N. (2023). Integrated Project Delivery (IPD): An Innovative Approach for Achieving Sustainability in Construction Projects. *Lecture Notes in Civil Engineering*, *245*, 195–209. https://doi.org/10.1007/978-3-030-97748-1_16

Agbaxode, P. D. K., Saghatforoush, E., Dlamini, S., & Korsah, J. K. (2024). Integrated project delivery enablers to enhance conventional project delivery toward improving design documentation quality. *Built Environment Project and Asset Management*, *14*(6), 817–834. https://doi.org/10.1108/BEPAM-09-2023-0158

Ajayi, S. O., & Oyedele, L. O. (2018). Waste-efficient materials procurement for construction projects: A structural equation modelling of critical success factors. *Waste Management*, *75*, 60–69. https://doi.org/10.1016/j.wasman.2018.01.025

Ajayi, S. O., Oyedele, L. O., Bilal, M., Alaka, H. A., & Owolabi, H. A. (2017). Optimising material procurement for construction waste minimization: An exploration of success factors. *Sustainable Materials and Technologies*, *11*, 38–46. https://doi.org/10.1016/j.susmat.2017.01.001

Akinkunmi, O. G., Aghimien, D. O., & Awodele, O. A. (2018). Appraising the use of labour-only procurement system for building construction in Nigeria. *Organization, Technology and Management in Construction: An International Journal*, *10*(1), 1719–1726. https://doi.org/10.2478/otmcj-2018-0003

Almuhannadi, M. A., & Ghareeb, A. S. (2024). Enhancing design-bid-build project delivery: A comprehensive review and framework for contractor selection and project optimisation in the construction industry. *Organization, Technology and Management in Construction*, *16*(1), 63–80. https://doi.org/10.2478/otmcj-2024-0005

Awodele, O. A., Aghimien, D. O., Akinkunmi, O. G., & Aigbavboa, C. O. (2019). Labour-only procurement. *Journal of Engineering, Design and Technology*, *17*(2), 347–361. https://doi.org/10.1108/JEDT-06-2017-0060

Babaeian, J., Wilkinson, S., Kalatehjari, R., & Zou, Y. (2022). Designing for construction procurement: An integrated decision support System for Building Information Modelling. *Built Environment Project and Asset Management*, *12*(1), 111–127. https://doi.org/10.1108/BEPAM-07-2020-0132

Barella, Y., Fergina, A., Mustami, M. K., Rahman, U., & Alajaili, H. M. A. (2024). Quantitative methods in scientific research. *Jurnal Pendidikan Sosiologi Dan Humaniora*, *15*(1), 281. https://doi.org/10.26418/j-psh.v15i1.71528

Bolomope, M., Amidu, A., Ajayi, S., & Javed, A. (2022). Decision-Making framework for construction clients in selecting appropriate procurement route. *Buildings*, *12*(12), 2192. https://doi.org/10.3390/buildings12122192

Cengiz, A. E., Aytekin, O., Ozdemir, I., Kusan, H., & Cabuk, A. (2017). A multi-criteria decision model for construction material supplier selection. *Procedia Engineering*, *196*, 294–301. https://doi.org/10.1016/j.proeng.2017.07.202

Chhabra, P., & Grover, S. (2024). Navigating the path to sustainability: The construction industry's crucial role. *The Genesis*, *11*(2), 31–40. https://doi.org/10.47211/tg.2024.v11i02.007

Chidiobi, C. C., Booth, C. A., & Lamond, J. E. (2024). Prioritising materials procurement and construction waste management attributes. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management*, *177*(1), 29–43. https://doi.org/10.1680/jwarm.22.00013

Domingo, L. M., García-Segura, T., Amalia Sanz, M., & Pellicer, E. (2018). Social sustainability in delivery and procurement of public construction contracts. *Journal of Management in Engineering*, *35*(2). https://doi.org/10.1061/(asce)me.1943-5479.0000674

Eriksson, P. E. (2017). Procurement strategies for enhancing exploration and exploitation in construction projects. *Journal of Financial Management of Property and Construction*, 22(2), 211–230. https://doi.org/10.1108/JFMPC-05-2016-0018

Ershadi, M., Jeffereis, M., Davis, P., & Mojtahedi, M. (2021). Achieving sustainable procurement in construction projects: The pivotal role of a project management office. *Construction Economics and Building*, *21*(1), 35–53. https://doi.org/10.5130/AJCEB.v21i1.7170

Ghafoori, M., & Abdallah, M. (2025). Multi-criteria decision support model for material and supplier selection in the construction industry. *International Journal of Construction Management*, *25*(4), 409–418. https://doi.org/10.1080/15623599.2024.2327251

Gurgun, A. P., & Koc, K. (2020). Contractor prequalification for green buildings—Evidence from Turkey. *Engineering, Construction and Architectural Management*, *27*(6), 1377–1400. https://doi.org/10.1108/ECAM-10-2019-0543

Halwatura, R. U., & Kodithuwakku, K. A. B. P. (2022). Incorporating sustainable procurement practices in the construction industry in Sri Lanka: Benefits and challenges. *PM World Journal*, *11*(10), 1–15.

Hassan, & Mukarram, M. (2025). Evaluating the effect of procurement performance evaluation variables on successful project delivery in north-western Nigeria. *International Journal of Environmental Design and Construction Management*, *8*(4). https://doi.org/10.70382/hijedcm.v08i4.044

Hoseini, S. A., Fallahpour, A., Wong, K. Y., Mahdiyar, A., Saberi, M., & Durdyev, S. (2021). Sustainable Supplier Selection in Construction Industry through Hybrid Fuzzy-Based Approaches. *Sustainability*, *13*(3), 1413. https://doi.org/10.3390/su13031413

Hussain, S., Hasmori, M. F., Balasbaneh, A. T., Khan, M. W., & Sohu, S. (2025). Contributing factors to key performance indicators of Saudi Arabian construction project success. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *50*(1), 151–167. https://doi.org/10.37934/araset.50.1.151167

Hussain, S., Xuetong, W., & Hussain, T. (2020). Impact of skilled and unskilled labor on project performance using structural equation modeling approach. *SAGE Open*, *10*(1). https://doi.org/10.1177/2158244020914590

Islam, M. H., Chavez, Z., & Bellgran, M. (2020). *An exploratory study on integrating sustainability aspects during the acquisition of production equipment*. https://doi.org/10.3233/atde200143

Jayasinghe, I. D., Domingo, N., & Le, A. (2025). The evolving landscape of procurement methods in the construction industry: A literature review. *CIB Conferences*, *1*(1). https://doi.org/10.7771/3067-4883.2031

Juricic, B. B., Galic, M., & Marenjak, S. (2021). Review of the construction labour demand and shortages in the EU. *Buildings*, *11*(1), 1–17. https://doi.org/10.3390/buildings11010017

Khatun, N. (2021). Applications of normality test in statistical analysis. *Open Journal of Statistics*, *11*(1), 113–122. https://doi.org/10.4236/ojs.2021.111006

Loosemore, M., Zhang, S., Alkilani, S., & Wang, Z. (2023). Social procurement in the Chinese construction industry: Relevance, drivers and barriers to implementation. *Buildings*, *13*(9), Article 2383. https://doi.org/10.3390/buildings13092383

Naoum, S. G., & Egbu, C. (2016). Modern selection criteria for procurement methods in construction: A state-of-the-art literature review and a survey. *International Journal of Managing Projects in Business*, *9*(2), 309–336. https://doi.org/10.1108/IJMPB-09-2015-0094

Niriella, A., & Gamage, I. (2022). Relationship between procurement systems and payment methods in assuring financial safety in Sri Lankan building projects. *The SLIIT International Conference on Engineering and Technology 2022* (pp. 127-137). https://doi.org/10.54389/IZCF4906

Ogunsanya, O. A., Aigbavboa, C. O., & Thwala, D. W. (2023). Sustainable procurement model for publicly funded construction projects in developing nations–A structural equation modelling approach. *International Journal of Construction Management*, *23*(3), 449–461. https://doi.org/10.1080/15623599.2021.1889087

Opoku, A., Deng, J., Elmualim, A., Ekung, S., Hussien, A. A., & Abdalla, S. B. (2022). Sustainable procurement in construction and the realisation of the sustainable development goal (SDG) 12. *Journal of Cleaner Production, 376*, 134294. https://doi.org/10.1016/j.jclepro.2022.134294

Osei-Asibey, D. (2021). Direct labour as a procurement route for infrastructure delivery within Metropolitan, Municipal and District Assemblies (MMDAs) in Ghana. *Advances in Social Sciences Research Journal, 8*(5), 293–312. https://doi.org/10.14738/assrj.85.10201

Osuizugbo, I. C., & Adenuga, O. A. (2024). Decisive factors for decision-making to achieving sustainable procurement in construction projects. *International Journal of Building Pathology and Adaptation, 42*(6), 1185–1202. https://doi.org/10.1108/IJBPA-04-2022-0065

Osuizugbo, I. C., Omer, M. M., Rahman, R. A., & Oshodi, O. S. (2024). A systematic search and review of early contractor involvement in construction project development. *Built Environment Project and Asset Management, 14*(6), 835–857. https://doi.org/10.1108/BEPAM-01-2024-0012

Petroutsatou, K., Ladopoulos, I., & Nalmpantis, D. (2023). Hierarchizing the criteria of construction equipment procurement decision using the AHP method. *IEEE Transactions on Engineering Management, 70*(9), 3271–3282. https://doi.org/10.1109/TEM.2021.3080117

Polavarapu, S., & Rao, V. N. (2023). Sale of second-hand and remanufactured components of construction equipment: An empirical study of user perception in Andhra Pradesh. *Marginal: Journal of Social, Management and Human Resources, 2*(4). https://ojs.transpublika.com/index.php/MARGINAL/

Rahmani, F., Khalfan, M., & Maqsood, T. (2022). A conceptual model for selecting early contractor involvement (ECI) for a project. *Buildings, 12*(6), 786. https://doi.org/10.3390/buildings12060786

Ruparathna, R., & Hewage, K. (2013). Review of contemporary construction procurement practices. *Journal of Management in Engineering, 31*(3). https://doi.org/10.1061/(asce)me.1943-5479.0000279

Scherz, M., Kreiner, H., Alaux, N., & Passer, A. (2023). Transition of the procurement process to Paris-compatible buildings: Consideration of environmental life cycle costing in tendering and awarding. *International Journal of Life Cycle Assessment, 28*(7), 843–861. https://doi.org/10.1007/s11367-023-02153-1

Tosa-Williamsa, D. E., & Nsikan, J. (2024). Vendor selection criteria and construction project performance in Rivers Nigeria. *Diamond Bridge Economics and Business Journal, 4*(1), 1–34. https://doi.org/10.60089/dbebj.2024.4.1.4

Waris, M., Panigrahi, S., Mengal, A., Soomro, M. I., Mirjat, N. H., Ullah, M., Azlan, Z. S., & Khan, A. (2019). An application of analytic hierarchy process (AHP) for sustainable procurement of construction equipment: Multicriteria-based decision framework for Malaysia. *Mathematical Problems in Engineering, 2019*, 1–20. https://doi.org/10.1155/2019/6391431

Yaska, M., & Nuhu, B. M. (2024). Assessment of measures of central tendency and dispersion using Likert-type scale. *African Journal of Advances in Science and Technology Research, 16*(1), 33–45. https://doi.org/10.62154/ajastr.2024.016.010379

Zhong, Q. P., Tang, H., Chen, C., & Igor, M. (2023). A comprehensive appraisal of the factors impacting construction project delivery method selection: A systematic analysis. *Journal of Asian Architecture and Building Engineering, 22*(2), 802–820. https://doi.org/10.1080/13467581.2022.2060983

Zuraidi, N., Rani, N. I. A., Hadi, A. A. A., & Ghafourian, K. (2025). Safety of workers when dealing with machinery in construction project. *Jurnal Kejuruteraan, 37*(2), 869–881. https://doi.org/10.17576/jkukm-2025-37(2)-25

Thanthirige, T.N.D, Mapa, M.M.I.S. and Chandani, G.G.N., 2026. Prioritisation of BIM-based safety management features using the analytic hierarchy process. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1373-1386. DOI: https://doi.org/10.31705/WCS.2026.100. Available from: https://ciobwcs.com/papers/

# PRIORITISATION OF BIM-BASED SAFETY MANAGEMENT FEATURES USING THE ANALYTIC HIERARCHY PROCESS

**T.N.D Thanthirige[1], M.M.I. S Mapa[2], and G.G.N Chandani[3]**

## *ABSTRACT*

*The construction industry is widely recognised as one of the most hazardous sectors due to its dynamic environment, complex processes, and high exposure to safety risks. Improving safety performance, therefore, requires effective management strategies supported by advanced technologies. Building Information Modelling (BIM) has emerged as a valuable tool for enhancing safety management throughout the building lifecycle. This study aims to prioritise key BIM-based safety management features using the Analytic Hierarchy Process (AHP). Three evaluation criteria, i.e. (i) importance, (ii) effectiveness, and (iii) ease of implementation, were used to assess three major BIM safety feature, including Prevention through Design (PtD), Automated Hazard Identification (AHI), and Emergency planning and simulation (EPS). Data were collected from ten BIM experts through pairwise comparisons, and the results were analysed using AHP. The findings indicate that importance is the most influential criterion. Among the features, PtD ranked highest, followed by Automated Hazards Identification (AHI), and Emergency Planning Simulation (EPS). The results highlight the significance of proactive design-based safety strategies and guide prioritising BIM-enabled safety interventions in construction safety practices.*

***Keywords:*** *Analytic Hierarchy Process; Automated Hazard Identification; Building Information Modelling; Emergency Planning and Simulation; Prevention through Design.*

## 1. INTRODUCTION

The construction sector is widely recognised as one of the most accident-prone industries due to its inherent complexity, dynamic work environment, and high exposure to occupational risks (Yiu et al., 2018). Construction projects involve multiple stakeholders, heavy machinery, working at heights, and constantly changing site environments, which significantly increase the likelihood of accidents and injuries (Bavafa et al., 2018). According to Rey-Becerra et al. (2021), the construction sector contributes to a substantial

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, nisansala37880@gmal.com

[2] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, isuru.mapa@uom.lk

[3] Lecturer (Temporary), Department of Facilities Management, University of Moratuwa, Sri Lanka, navodag@uom.lk

proportion of workplace accidents worldwide, particularly in developing countries where safety management practices may be less advanced. As a result, improving safety performance has become a critical priority for the construction industry.

Traditional safety management approaches in construction mainly rely on reactive measures, such as inspections, safety training, and incident reporting, after hazards have already emerged (Khosravi et al., 2020). This limitation highlights the need for more proactive safety management approaches that can identify and mitigate hazards during the earlier stages of the project lifecycle. Recent advancements in digital technologies have introduced innovative tools that can enhance construction safety management. Among these technologies, BIM has emerged as a powerful platform for integrating safety considerations into construction planning, design, and project management processes (Hire et al., 2024). BIM enables the creation of digital representations of building components and processes, allowing project stakeholders to visualise construction activities, identify potential hazards, and simulate safety scenarios before actual construction begins (Jaafar et al., 2018). Through capabilities such as hazard visualisation, design coordination, and simulation-based planning, BIM has the potential to significantly improve safety performance across the building lifecycle.

Despite the growing interest in BIM applications for construction safety, existing research has focused on individual BIM tools or specific safety applications, such as hazard visualisation or fall detection. However, limited studies have systematically evaluated and prioritised the most influential BIM-based safety management features that can effectively improve safety features and should receive attention and investment. This lack of prioritisation may lead to inefficient allocation of resources and limited adoption of the most impactful safety interventions. Therefore, there is a need for a systematic decision-making approach that can evaluate multiple BIM-based safety management features and determine their relative importance in improving construction safety performance. Multi-criteria decision-making methods provide a structured way to compare different alternatives based on expert judgement and multiple evaluation criteria. Among these methods, AHP is widely used for prioritising complex decision problems since it allows both qualitative and quantitative evaluation and includes a consistency verification mechanism to ensure reliable results.

This study aims to prioritise key BIM-based safety management features that contribute to improved safety performance in construction projects using the AHP method. To achieve this aim, the study pursues objectives: First, the study identifies key BIM-based safety management features relevant to construction projects through a literature review. Second, a framework for AHP analysis was developed to evaluate these features based on three criteria: importance, effectiveness, and ease of implementation. Third, Expert judgements from BIM professionals are collected and analysed through pairwise comparisons to determine the relative priority of the identified BIM-based safety features. Finally, the study provides practical insights for professionals and decision-makers by identifying the most influential BIM-based safety features that can support improved.

# 2. LITERATURE REVIEW

## 2.1 SIGNIFICANCE OF SAFETY

Safety is the preservation of positive value, “An ability for a system to perform its intended purpose, whilst preventing harm to persons” (Vandeskog, 2024, P.5). On the

other hand, Ball and Frerk (2015), emphasised that, applying risk control across the workplace, individual and system, integrating it into the organisation to reduce risk as much as reasonably practicable to achieve sustainable action, accountability, and potential injury reduction. Improving safety is a continuous process requiring organisational initiatives such as structural safety training and ensuring the application of learned safety skills in daily work activities (Hutchinson et al., 2022). In high-risk work environments, unresolved health and safety issues may lead to reduced productivity, increased medical expenses, and overall strain on employees (Classen et al., 2020). Moreover, sharing safety information and adhering to safety procedures rely heavily on effective interpersonal communication and cooperation (Newnam & Goode, 2019). Some researchers have provided a clear elucidation regarding the significance of safety, as described in Table 1.

*Table 1: Importance of safety*

| Importance | Authors |
|---|---|
| Safety directly influences work performance, enhancing workers' effectiveness and confidence. | Noor Arzahan et al. (2022) |
| Preventing workplace accidents is a core outcome of a strong safety system, and it improves the physical and mental health of workers, minimizing exposure to hazards. | Wachter & Yorio (2014) |
| Effective safety knowledge transmission must align with real working conditions, understanding task-related hazards and developing strategies to reduce risk. | Rémery (2022) |
| Inefficient planning negatively affects both productivity and safety performance, demonstrating that safety is not an isolated function but directly linked to overall project success. | Vinodkumar & Bhasi (2010) |
| Safety integration is critical requirement for construction firms to remain competitive, as high accident rates hinder productivity, quality outcomes, and financial performance. | Rodrigues et al. (2021) |
| Effective safety planning must span the entire project lifecycle from design and planning, through construction, to end-of-life to address hazards evolving over time. | Wetzel & Thabet (2015) |
| Safety directly influences work performance, enhancing workers' effectiveness and confidence. | Noor Arzahan et al. (2022) |

As mentioned above, safety is important to the construction sector, and integration of advanced technologies can be used to enhance safety features and safety culture.

## 2.2 ENHANCING SAFETY FOR BUILDINGS THROUGH BIM

Enhancing safety for buildings through BIM is an advanced digital process that is transforming how construction projects are created, managed, and visualized (Thang Ngoc Nguyen, 2025).The United States National BIM standard for BIM is defined as " a shared knowledge resource, a sharing of information about the facility, to provide a reliable basis for the establishment of the facility from the construction to the demolition of the whole life cycle of the process"(National BIM Standard-United States, 2013, P.5). This definition highlights BIM not merely as a modelling tool, but as an integrated information management process that supports decision-making across the entire building

lifecycle Borkowski (2023). In recent years, the use of BIM has increased significantly, not only in the design management of construction elements (Antwi-Afari et al., 2018), but also in activities related to the life cycle of buildings, such as hazard identification and safety assurance, maintenance of building assets, and their environmental performance (Fargnoli & Lombardi, 2020). The integration of BIM across multiple project stages enables proactive planning, improved visualisation, and early identification of potential design, construction, and operational challenges (Fargnoli & Lombardi, 2020).

## 2.3 PREVENTION THROUGH DESIGN

Prevention through Design is a proactive safety approach that aims to eliminate or reduce construction hazards during the design stage before construction activities begin (Collinge et al., 2022). BIM-based PtD addresses common on-site accidents caused by poor planning and weak risk management by embedding safety considerations into building and construction design (Aladayleh & Aladaileh, 2024). This enables early hazard identification, evaluates safer design alternatives, and improves communication and coordination among project stakeholders (Rodrigues et al., 2021). According to Johansen et al. (2024), PtD is closely related to the hierarchy of controls because it focuses on eliminating hazards at their source through design modifications rather than relying only on protective measures during construction. Furthermore, BIM-supported PtD tools can assist in detecting safety risks, analysing construction sequences, and providing safety-related information during the design stage, which contributes to reducing construction-site accidents and improving overall safety performance (Li et al., 2021).Automated hazard identification Traditional hazard identification requires extensive planning, monitoring, and coordination, which are challenging to maintain consistently across all phases of a construction project (Phinias, 2023). Among emerging technological tools, BIM has gained significant attention for its potential to improve safety outcomes on construction sites (Malik et al., 2021). One of the most valuable capabilities of BIM is its capacity to address safety hazards directly within the digital project environment (Akram et al., 2019). Hence, BIM supports the identification of potential risks by enabling the visualisation of site conditions, construction sequence, and spatial constraints (Kim et al., 2024).

## 2.3 EMERGENCY PLANNING AND SIMULATION

Effective emergency planning in buildings increasingly relies on the integration of BIM and simulation tools to ensure safe evacuation routes, efficient fire response zoning, and well-defined safety zones (Abir et al., 2022). According to Hassanpouret al. (2022), BIM models allow dynamic, agent-based evacuation simulations that account for human movement patterns, response delays, obstacle interactions, and route preferences. This integration is essential for analysing emergency exit performance, identifying congestion points, and assessing alternative evacuation strategies under varying conditions (Gao et al., 2022). The simulation framework incorporates key behavioural mechanisms, such as agents' speed, body radius, perception of nearby obstacles, path weighting, and emergency response activation once alarms are triggered (Makinoshima et al., 2022). Methodology This study aims to prioritise key BIM-based safety management features for improving safety performance in construction practices in the building industry. A literature review was conducted to identify relevant BIM safety features and determine their relative importance using AHP. The selection of BIM features was based on their

relevance to different phases of the building lifecycle. And represent proactive hazard prevention, automated hazard detection, and emergency preparedness, which are considered major dimensions of BIM-enabled safety management in construction projects. AHP provides a structured multi-criteria decision-making approach that accommodates both qualitative and quantitative assessments (Szabo et al., 2021). AHP decomposes complex problems into hierarchical levels, enabling systematic comparison and prioritisation (Wong & Li, 2023). Furthermore, AHP includes a consistency verification mechanism, ensuring the reliability of expert evaluations. Therefore, AHP was considered the most suitable method for prioritising BIM-based safety management features in this study.

## 3. METHODOLOGY

Although BIM supports a wide range of applications in construction safety management, this study focuses on three major BIM-based safety management features: prevention through design supports proactive risk elimination during the design stage and is widely recognised as a fundamental strategy for reducing construction hazards (Chris et al., 2024). Automated hazard identification leverages BIM-based analysis tools to detect and visualise potential hazards, enhancing safety monitoring and decision-making during construction activities. Moreover, emergency planning and simulation were selected since BIM-enabled simulation technologies support evacuation planning, emergency response analysis, and safety preparedness in building operations (Sidani et al., 2023). Together, these three features represent safety prevention, hazard identification, and emergency preparedness across different stages of the building lifecycle.

The AHP method was employed to rank the identified BIM-based features according to their relative contribution to improving building safety performance. The hierarchical structure developed for this study consists of three levels. This study focuses on applying a direct comparison approach among the three primary BIM- based safety features and structures to ensure clarity and focuses on identifying the most influential feature from the BIM experts' perspective. The application of AHP includes the following steps.

**Step 1: Problem definition**

The first step involved clearly defining the decision problem, which is to prioritize the selected BIM-based safety management features in improving overall safety performance.

**Step 2: Construction of pairwise comparison matrix**

Four 3×3 matrices were created,

- One for importance
- One for effectiveness
- One for ease of implementation
- One for identified criteria

Saaty's scale was used to perform pairwise comparisons between features. This scale allows experts to express the relative importance of one feature over another using numerical values ranging from one to nine. The use of Saaty's scale provides a systematic and standardised approach for converting subjective expert judgement into quantitative

values, thereby, enhancing the reliability and consistency of the decision-making process in AHP. Table 2 presents Saaty's scale used for pairwise comparisons.

*Table 2: Saaty's scale*

| Intensity of importance | Definition |
|---|---|
| 1 | Equal Importance |
| 3 | Moderate Importance |
| 5 | Strong Importance |
| 7 | Very Strong Importance |
| 9 | Extreme Importance |

Each matrix satisfies the reciprocity condition:

$$a_{ij} = \frac{1}{a_{ji}} \qquad (01)$$

Where, $a_{ij}$ = importance of element of i compared with element j, $a_{ji}$ = importance of element j compared with element i,1= reciprocal relationship between the two comparisons, i, j= criteria and factors being compared.

**Step 3: Aggregation of Expert Judgements**

The geometric mean method was used to combine expert responses:

$$a_{ij} = \left(\prod_{K=1}^{N} c_{ij}^{(k)}\right)^{1/N} \qquad (02)$$

Where, $a_{ij} =$ the aggregated pairwise comparison value, $c_{ij}^{(k)}$= the pairwise comparison value provided by respondants, K= index of experts, N= total number of experts,1/N= geometrix mean calculation.

**Step 3: Derivation of local weights**

Each matrix was normalized:

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \qquad (03)$$

Where, $n_{ij}$= Normalized value,$a_{ij}$= pairwise comparison value, n= total number of criteria and features being compared.

The row average method was then used to determine the local weight of each feature:

$$w_i = \frac{\sum_{j=1}^{n} n_{ij}}{n} \qquad (04)$$

Where,$w_i$ = priority weight, $n_{ij}$= normalized value, j= index of column, n=total number of criteria and features being compared.

**Step 4: consistency verification**

To verify the consistency of the judgments, the consistency Index (CI) and consistency Ratio (CR) were computed:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (05)$$

Where, CI= Consistency Index,$\lambda_{max}$= the maximum eigenvalue, n= number of criteria and factors, n-1 = adjustment factor.

$$CR = \frac{CI}{RI} \qquad (06)$$

Where, CR=Consistency Ratio, CI=Consistency Index, RI=Random Index.

*Table 3: Random index value*

| **Random index** | **n** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|
| | RI | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

*Forn = 3, RI= 0.58.*

*A CR value below 0.10 indicates acceptable consistency.*

**Step 5: Calculation of Global weights**

The Global weights of each BIM-based safety feature were calculated by multiplying the criterion weight by the local weight of the feature under that criterion:

$$\textit{Global weight} = \textit{Criteria weight} \times \textit{Local weight} \qquad (07)$$

The final ranking of the features was determined based on the calculated global weights.

Data were collected through semi-structured interviews with ten BIM experts who have 5-15 years of experience in BIM-based construction projects across pre-construction, and post construction phases. The summary of the responders is presented in Table 4.

*Table 4: Profile of respondents*

| **Expert** | **Designation** | **Work experience** | **Most familiar building lifecycle** |
|---|---|---|---|
| E1 | BIM Manager | 12 | Pre-construction |
| E2 | BIM Engineer | 5 | Pre-construction |
| E3 | BIM Director | 12 | Pre-construction and construction |
| E4 | BIM Manager | 9 | Pre-construction and construction |
| E5 | BIM Manager | 7 | Pre-construction and post -construction |
| E6 | BIM Architect | 9 | Pre-construction |
| E7 | BIM manager | 10 | Pre-construction |
| E8 | BIM Modeler | 7 | Pre-construction |
| E9 | BIM Manager | 11 | Pre-construction and post-construction |
| E10 | BIM Modeler | 6 | Pre-construction |

## 4. RESULTS AND DISCUSSION

The results of this study are consistent with the literature presented in sections 2.3 to 2.5, which highlights the theoretical and practical importance of Prevention through Design, Automated Hazard Identification, and Emergency Planning and Simulation in BIM-based

safety management. The literature supports AHI as an effective tool for early hazard detection through BIM visualisation and analysis, while EPS is widely recognised for enhancing emergency preparedness and evacuation planning. The findings of this study, therefore, reinforce existing research by empirically prioritising these BIM safety features. The pairwise comparisons were performed by evaluating the relative importance, effectiveness, and ease of implementation of the three BIM-based safety features. Prevention through Design (PtD) was considered more important and effective because it eliminates hazards during the design phase, thereby preventing risks before construction begins. Automated Hazard Identification was ranked next, as it enables early detection of potential hazards through BIM-based visualisation and rule-based analysis. Emergency Planning and Simulation was ranked lower in comparison because it mainly focuses on emergency preparedness rather than hazard prevention. In terms of ease of implementation, Automated Hazard Identification and Emergency Planning and simulation were considered relatively easier to implement than PtD, since PtD requires deeper integration with design processes and may involve design modifications and multidisciplinary coordination.

## 4.1 BIM-BASED SAFETY MANAGEMENT FEATURES IN IMPROVING OVERALL BUILDING SAFETY PERFORMANCE

The pairwise comparisons were performed by evaluating the relative importance, effectiveness, and ease of implementation of the three BIM-based safety features. PtD was considered more important and effective because it eliminates hazards during the design phase, thereby preventing risks before construction begins. Automated Hazard Identification was ranked next, as it enables early detection of potential hazards through BIM-based visualisation and rule-based analysis. Emergency Planning and Simulation was ranked lower in comparison because it mainly focuses Emergency preparedness rather than hazard prevention. In terms of ease of implementation, Automated Hazard Identification and Emergency Planning and simulation were considered relatively easier to implement than PtD, since PtD requires deeper integration with design processes and may involve design modifications and multidisciplinary coordination.

## 4.2 FRAMEWORK TO PRIORITISE BIM-BASED SAFETY MANAGEMENT FEATURES

A conceptual AHP hierarchical model for prioritising BIM-based Safety management features was developed based on the literature review and input from industrial experts. The hierarchical framework consists of three levels. The first level represents the overall goal of the study, which is to prioritise BIM-based safety management features for improving safety performance. The second level includes the evaluation criteria used to assess the identified features. These criteria were selected because they reflect both the practical applicability and the potential impacts of BIM safety features in real environments. The third level consists of the main BIM safety management features identified from the literature. This hierarchical structure enables systematic pairwise comparison among the identified features under each criterion and supports the calculation of relative priorities using AHP. The pairwise comparison results for the evaluation criteria used in this study are presented in Table 5, while the corresponding normalised comparison matrix is shown in Table 6. The calculated local weights and ranking derived from the AHP analysis are summarised in Table 7, and the hierarchical model developed for this study is illustrated in Figure 1. The results obtained from the

calculations indicate the three evaluation criteria for assessing BIM-based safety management features.

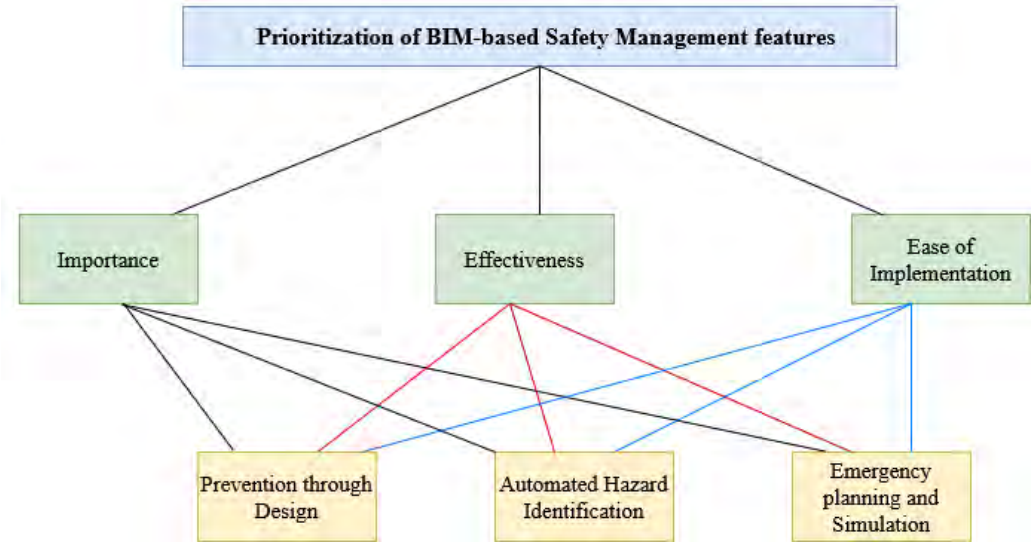



*Figure 1: Hierarchical model of BIM-based features*

Table 5 presents the pairwise comparison matrix of the evaluation criteria. The values in the matrix represent the relative preference of one criterion over another based on expert judgement using the AHP scale. For instance, the value 3.62 indicates that importance is moderately more significant than effectiveness, while 5.57 suggests that importance is strongly preferred over Ease of Implementation. The reciprocal values (0.276 and 0.179) represent the inverse comparisons. This matrix forms the basis for determining the relative priority of the ease evaluation criterion.

*Table 5: Criterion-to-criterion pairwise comparison matrix for evaluation criteria*

| | **Importance** | **Effectiveness** | **Ease of implementation** |
|---|---|---|---|
| **Importance** | 1 | 3.62 | 5.57 |
| **Effectiveness** | 0.276243094 | 1 | 5.8 |
| **Ease of implementation** | 0.179533214 | 0.172413793 | 1 |

Table 6 shows the normalised pairwise comparison matrix, which is obtained by dividing each value in the pairwise comparison matrix by the sum of its respective column. This normalisation process converts the values into comparable proportions, allowing the relative influence of each criterion to be evaluated. The normalised values indicate the contribution of each criterion in relation to the others.

*Table 6: Matrix normalization for evaluation criteria*

| | **Importance** | **Effectiveness** | **Ease of implementation** |
|---|---|---|---|
| **Importance** | 0.686918722 | 0.755360484 | 0.450282943 |
| **Effectiveness** | 0.189756553 | 0.208663117 | 0.468876314 |
| | 0.123324726 | 0.035976399 | 0.080840744 |

| | Importance | Effectiveness | Ease of implementation |
|---|---|---|---|
| **Ease of implementation** | 0.686918722 | 0.755360484 | 0.450282943 |

Table 7 presents the priority weights and ranking of the evaluation criteria derived from the normalised matrix. The results show that importance has the highest weight 0.63085, and is ranked first, followed by effectiveness 0.2891 and Ease of Implementation 0.08005. Additionally, the table includes the consistency evaluation of the AHP matrix, where the Consistency Index (CI) and Consistency Ratio (CR) are calculated. The CR value of 0.021966, which is below the acceptable threshold of 0.1, indicates that the expert judgments are consistent and reliable.

*Table 7: Ranking of the criteria value*

| Criteria | W | Rank | AW | λ | CI | RI | CR |
|---|---|---|---|---|---|---|---|
| **Importance** | 0.63085 | 1 | 3.626787053 | 3.02546645 | 0.012735 | 0.58 | 0.021966 |
| **Effectiveness** | 0.2891 | 2 | 5.57379242 | | | | |
| **Ease of implementation** | 0.08005 | 3 | 5.809061438 | | | | |

*Table 8: Final findings of the criteria and BIM-based features*

| Criteria | Features | LW | Rank | GW | Rank | λ | CI | RI | CR |
|---|---|---|---|---|---|---|---|---|---|
| **Importance** | PtD | 0.618035 | 1 | 0.38987148 | 1 | 3.090141 | 0.045 | 0.58 | 0.077 |
| | AHI | 0.296956 | 2 | 0.18736542 | 2 | | | | |
| | EPS | 0.085009 | 3 | 0.0536231 | 5 | | | | |
| **Effectiveness** | PtD | 0.622502 | 1 | 0.17996475 | 3 | 3.09268494 | 0.046343 | 0.58 | 0.079897 |
| | AHI | 0.300506 | 2 | 0.08687455 | 4 | | | | |
| | EPS | 0.076992 | 3 | 0.00616308 | 9 | | | | |
| **Ease of implementation** | PtD | 0.622521 | 1 | 0.049825 | 6 | 3.02546645 | 0.012735 | 0.58 | 0.021966 |
| | AHI | 0.295365 | 2 | 0.023644 | 7 | | | | |
| | EPS | 0.082114 | 3 | 0.006571 | 8 | | | | |

The AHP analysis evaluates the Local Weights (LW) and Global Weights (GW) of the identified BIM-based safety features under three main criteria i.e. (i) importance, (ii) effectiveness, and (iii) ease of Implementation. The results clearly indicate that PtD is the most influential safety feature across all criteria. Under the importance criterion, PtD obtained the highest local weight (LW=0.618035) and a global weight (GW=0.38987,

ranked 1st), highlighting the critical role of integrating safety considerations during the early design stage of construction projects. Automated Hazard Identification (AHI) ranked second (LW= 0.296956, GW=0.18736542, ranked 2nd), indicating its significance in detecting potential hazards through the BIM visualisation and analysis tool. Meanwhile, Emergency Planning and Simulation (EPS) ranked third with the lowest local weight (LW=0.085009, GW=0.0536231, ranked 5th), suggesting that although it contributes to safety preparedness, its impact is relatively lower compared with the other features.

For the effectiveness criterion, PtD again achieved the highest weight (LW= 0.622502, GW= 0.17996475, ranked 3rd), emphasising that design-stage risk elimination is the most effective strategy for improving construction safety performance.

AHI ranked second (LW=0.300506, GW=0.08687455, ranked 4th), reinforcing the value of automated detection systems in identifying hazards before construction activities commence. EPS remained in the third position (LW=0.076992, GW=0.00616308, ranked 9th), indicating that while simulation tools support safety planning, their effectiveness is comparatively limited when measured against proactive design and hazard detection approaches.

Similarly, under the Ease of Implementation criterion, PtD maintained the highest ranking (LW=0.6225, GW=0.049825, ranked 6th), suggesting that incorporating safety consideration within BIM during the design stage can be readily implemented in project workflows. AHI ranked second (LW=0.295365, GW=0.023644, ranked 7th), demonstrating moderate implementation feasibility due to the technological requirements associated with automated hazard detection systems. EPS ranked third (LW=0.082114, GW=0.006571, ranked 8th), indicating comparatively lower ease of implementation.

Overall, the findings highlight that PtD is the most critical BIM-based safety management feature, followed by AHI, while EPS plays a supportive role in improving construction safety performance. These results emphasise the importance of integrating safety considerations at the early design stage and utilising BIM technologies to proactively identify and manage potential hazards in construction practices in the industry.

## 5. CONCLUSIONS

This study developed a structured framework to prioritise BIM-based safety management features in building construction projects using AHP. The proposed hierarchical model integrates three evaluation criteria i.e. (i) importance, (ii) effectiveness, and (iii) ease of implementation to systematically assess key BIM-based safety features identified from the literature and validated through expert input. The results indicate that importance is the most influential criterion with a weight of 0.63085, followed by effectiveness 0.2891, and ease of implementation. The consistency ratio obtained from the AHP analysis was below 0.1, confirming that the expert judgements used in the pairwise comparisons are reliable and acceptable.

Among the BIM-based safety management features evaluated in this study, PtD achieved the highest priority across all evaluation criteria, highlighting its significant role in integrating safety considerations during the early design stage. Automated Hazard Identification ranked second, demonstrating the importance of BIM technologies in identifying potential hazards through digital visualisation and analysis. Emergency Planning and Simulation received the lowest priority, indicating that although it supports

safety preparedness, it is perceived as less influential compared with proactive design and hazard identification strategies.

Overall, the developed AHP-based framework provides a systematic and transparent approach for prioritising BIM-based safety management features in building projects. This study contributes to the academic field by providing a validated AHP framework to prioritise BIM-based safety features, advancing theoretical understanding of safety management in the building lifecycle. The framework assists decision-makers, project managers, and safety performance during project planning and execution. Emphasising supports improved risk management and contributes to safer construction practices in the building industry.

# 6. REFERENCES

Abeynayake, D.N., Perera, B.A.K.S., & Hadiwattege, C. (2022). A roadmap for business model adaptation in the construction industry: *A structured review of business model research. Construction Innovation, 22(4),* 1122-1137. https://doi.org/10.1108/ci-05-2020-0077

Abir, I. M., Mohd Ibrahim, A., Toha, S. F., & Shafie, A. A. (2022). A review on the hospital evacuation simulation models. *International Journal of Disaster Risk Reduction, 77,* 103083. https://doi.org/10.1016/j.ijdrr.2022.103083

Ajayi, I. A., & Ekundayo, H. T. (2011). Factors Determining the Effectiveness of Secondary Schools in Nigeria. *The Anthropologist, 13(1),* 33–38. https://doi.org/10.1080/09720073.2011.11891174

Akram, R., Thaheem, M. J., Nasir, A. R., Ali, T. H., & Khan, S. (2019). Exploring the role of building information modeling in construction safety through science mapping. *Safety Science, 120,* 456–470. https://doi.org/10.1016/j.ssci.2019.07.036

Ball, D. R., & Frerk, C. (2015). A new view of safety: Safety 2. *British Journal of Anaesthesia, 115(5),* 645–647. https://doi.org/10.1093/bja/aev216

Bavafa, A., Mahdiyar, A., & Marsono, A. K. (2018). Identifying and assessing the critical factors for effective implementation of safety programs in construction projects. *Safety Science, 106,* 47–56. https://doi.org/10.1016/j.ssci.2018.02.025

Chi, S., Han, S., Kim, D. Y., & Shin, Y. (2015). Accident risk identification and its impact analyses for strategic construction safety management. *Journal of Civil Engineering and Management, 21(4),* 524–538. https://doi.org/10.3846/13923730.2014.890662

Classen, D. C., Holmgren, A. J., Co, Z., Newmark, L. P., Seger, D., Danforth, M., & Bates, D. W. (2020). National Trends in the Safety Performance of Electronic Health Record Systems From 2009 to 2018. *JAMA Network Open, 3(5),* e205547. https://doi.org/10.1001/jamanetworkopen.2020.5547

Collinge, W. H., Farghaly, K., Mosleh, M. H., Manu, P., Cheung, C. M., & Osorio-Sandoval, C. A. (2022). BIM-based construction safety risk library. *Automation in Construction, 141*. https://doi.org/10.1016/j.autcon.2022.104391

Gao, D. L., Ming Lee, E. W., & Lee, Y. Y. (2022). Integration of cumulative prospect theory in cellular automata model for building evacuation. *International Journal of Disaster Risk Reduction, 74,* 102904. https://doi.org/10.1016/j.ijdrr.2022.102904

Haadir, S. Al, & Panuwatwanich, K. (2011). Critical Success Factors for Safety Program Implementation among Construction Companies in Saudi Arabia. *Procedia Engineering, 14,* 148–155. https://doi.org/10.1016/j.proeng.2011.07.017

Hassanpour, S., Gonzalez, V., Liu, J., Zou, Y., & Cabrera-Guerrero, G. (2022). A hybrid hierarchical agent-based simulation approach for buildings indoor layout evaluation based on the post-earthquake evacuation. *Advanced Engineering Informatics, 51,* 101531. https://doi.org/10.1016/j.aei.2022.101531

Hire, S., Sandbhor, S., & Ruikar, K. (2024). A Conceptual Framework for BIM-Based Site Safety Practice. *Buildings, 14(1),* 272. https://doi.org/10.3390/buildings14010272

Ho, C., Lee, H. W., & Gambatese, J. A. (2020). Application of Prevention through Design (ptd) to improve the safety of solar installations on small buildings. *Safety Science, 125,* 104633. https://doi.org/10.1016/j.ssci.2020.104633

Hutchinson, D., Luria, G., Pindek, S., & Spector, P. (2022). The effects of industry risk level on safety training outcomes: *A meta-analysis of intervention studies. Safety Science, 152*, 105594. https://doi.org/10.1016/j.ssci.2021.105594

Jaafar, M. H., Arifin, K., Aiyub, K., Razman, M. R., Ishak, M. I. S., & Samsurijan, M. S. (2018). Occupational safety and health management in the construction industry*: a review. International Journal of Occupational Safety and Ergonomics, 24(4)*, 493–506. https://doi.org/10.1080/10803548.2017.1366129

Johansen, K. W., Teizer, J., & Schultz, C. (2024). Automated rule-based safety inspection and compliance checking of temporary guardrail systems in construction. *Automation in Construction, 168*, 105849. https://doi.org/10.1016/j.autcon.2024.105849

Khosravi, Y., Asilian-Mahabadi, H., Hajizadeh, E., Hassanzadeh-Rangi, N., Bastani, H., & Behzadan, A. H. (2014). Factors Influencing Unsafe Behaviors and Accidents on Construction Sites: A Review. *International Journal of Occupational Safety and Ergonomics, 20(1)*, 111–125. https://doi.org/10.1080/10803548.2014.11077023

Li, C. T., Cheng, J. C. P., & Chen, K. (2021). Top 10 technologies for indoor positioning on construction sites. *Automation in Construction, 118*, 103309. https://doi.org/10.1016/j.autcon.2020.103309

Makinoshima, F., Oishi, Y., & Imamura, F. (2022). Mechanism of an evacuation cascade during the 2011 Tohoku tsunami inferred from an evacuation simulation incorporating communications in social networks. *International Journal of Disaster Risk Reduction, 71*, 102810. https://doi.org/10.1016/j.ijdrr.2022.102810

Malik, Q., Nasir, A. R., Muhammad, R., Thaheem, M. J., Ullah, F., Khan, K. I. A., & Hassan, M. U. (2021). Bimp-Chart—A Global Decision Support System for Measuring BIM Implementation Level in Construction Organizations. *Sustainability, 13(16)*, 9270. https://doi.org/10.3390/su13169270

Manzoor, B., Othman, I., & Waheed, A. (2022). Accidental safety factors and prevention techniques for high-rise building projects – A review. *Ain Shams Engineering Journal, 13(5)*, 101723. https://doi.org/10.1016/j.asej.2022.101723

Marefat, A., Toosi, H., & Mahmoudi Hasankhanlo, R. (2019). A BIM approach for construction safety: applications, barriers and solutions. *Engineering, Construction and Architectural Management, 26(9)*, 1855–1877. https://doi.org/10.1108/ECAM-01-2017-0011

Newnam, S., & Goode, N. (2019). Communication in the workplace: Defining the conversations of supervisors. *Journal of Safety Research, 70*, 19–23. https://doi.org/10.1016/j.jsr.2019.04.009

Noor Arzahan, I. S., Ismail, Z., & Yasin, S. M. (2022). Safety culture, safety climate, and safety performance in healthcare facilities: *A systematic review. Safety Science, 147*, 105624. https://doi.org/10.1016/j.ssci.2021.105624

Phinias, R. N. (2023). Benefits and challenges relating to the implementation of health and safety leading indicators in the construction industry: *A systematic review. Safety Science, 163*, 106131. https://doi.org/10.1016/j.ssci.2023.106131

Rémery, V. (2022). The transmission of prudent knowledge in a work collective: *Issues and perspectives on an enabling intervention for the preservation of health at work. Safety Science, 151*, 105650. https://doi.org/10.1016/j.ssci.2021.105650

Rey-Becerra, E., Barrero, L. H., Ellegast, R., & Kluge, A. (2021). The effectiveness of virtual safety training in work at heights: *A literature review. Applied Ergonomics, 94*, 103419. https://doi.org/10.1016/j.apergo.2021.103419

Rodrigues, F., Antunes, F., & Matos, R. (2021). Safety plugins for risks prevention through design resourcing BIM. *Construction Innovation, 21(2)*, 244–258. https://doi.org/10.1108/CI-12-2019-0147

Sidani, A., Poças Martins, J., & Soeiro, A. (2023). Examining BIM-based automated rule-checking techniques in construction. https://orcid.org/0000-0003-4784-959

Szabo, Z. K., Szádoczki, Z., Bozóki, S., Stănciulescu, G. C., & Szabo, D. (2021). An Analytic Hierarchy Process Approach for Prioritisation of Strategic Objectives of Sustainable Development. *Sustainability, 13(4)*, 2254. https://doi.org/10.3390/su13042254

Thang Ngoc Nguyen. (2025). BIM in Construction: Benefits, Challenges, and Development Trends. International Journal of Scientific Research in Science, Engineering and Technology, 12(2), 160–165. https://doi.org/10.32628/IJSRSET25122140

Vandeskog, B. (2024). Safety is the preservation of value. Journal of Safety Research, 89, 105–115. https://doi.org/10.1016/j.jsr.2024.02.004

Vinodkumar, M. N., & Bhasi, M. (2010). Safety management practices and safety behaviour: *Assessing the mediating role of safety knowledge and motivation. Accident Analysis & Prevention, 42(6)*, 2082–2093. https://doi.org/10.1016/j.aap.2010.06.021

Wachter, J. K., & Yorio, P. L. (2014). A system of safety management practices and worker engagement for reducing and preventing accidents*: An empirical and theoretical investigation. Accident Analysis & Prevention, 68*, 117–130. https://doi.org/10.1016/j.aap.2013.07.029

Wetzel, E. M., & Thabet, W. Y. (2015). The use of a BIM-based framework to support safe facility management processes. *Automation in Construction, 60*, 12–24. https://doi.org/10.1016/j.autcon.2015.09.004

Wong, J. K. W., & Li, H. (2008). Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems. *Building and Environment, 43(1)*, 108–125. https://doi.org/10.1016/j.buildenv.2006.11.019

Yiu, N. S. N., Sze, N. N., & Chan, D. W. M. (2018). Implementation of safety management systems in Hong Kong construction industry – A safety practitioner's perspective. *Journal of Safety Research, 64*, 1–9. https://doi.org/10.1016/j.jsr.2017.12.011

Yuan, J., Li, X., Xiahou, X., Tymvios, N., Zhou, Z., & Li, Q. (2019). Accident prevention through design (ptd): Integration of building information modeling and ptd knowledge base. *Automation in Construction, 102*, 86–104. https://doi.org/10.1016/j.autcon.2019.02.015

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science, 72*, 31–45. https://doi.org/10.1016/j.ssci.2014.08.001

Shaikh, S. and Garud, A., 2026. PuzzleGlaze: A user-driven window system to maximize user comfort. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1387-1397. DOI: https://doi.org/10.31705/WCS.2026.101. Available from: https://ciobwcs.com/papers/

# PUZZLEGLAZE: A USER-DRIVEN WINDOW SYSTEM TO MAXIMIZE USER COMFORT

**S. Shaikh[1] and A. Garud[2]**

## *ABSTRACT*

*Not everyone can afford an air conditioning system for their home, thus requiring a manual flexible window system that helps household stay comfortable without using expensive automated systems. This study aims to conceptualize, design and evaluate a low cost, user driven window system where access to mechanical cooling is limited. This study proposes a window system which works like a puzzle named as PuzzleGlaze, with a 3×3 grid of panels in which four panels of clear glass, four panels with sun-film-coated glass, and a ventilation void. Each panel has a lock-and-key mechanism that lets it slide sideways and up and down, so users can adjust the window panel position depending on the sun angle at different times of the day. This exploratory design research based on a physical model prototype evaluates performance of the proposed system for heat, daylight and glare by digital simulation comparative study against a fully clear glass window and a fixed sun film window. The findings show that PuzzleGlaze reduces glare, improves user control of natural light, and uses less film material, making it both practical and cost-effective. This study suggests that simple, hands-on design solutions can offer flexible and sustainable ways to respond to changing sunlight in urban buildings.*

***Keywords:*** *Adaptive window system; Interactive facade systems; Lock-and-key panel mechanism; Low-tech facade innovation; User-centric daylight control.*

## 1. INTRODUCTION

Creating a comfortable indoor environment and reducing heat without compromising light are important aspects in our day-to-day life. But in cities like Pune, where sunlight can be strong and direct, it often creates problems of glare and heat gain. This makes indoor spaces uncomfortable and forces people to depend on artificial cooling or heavy shading, which can feel uncomfortable and can create disturbance and making it expensive. Most conventional solutions, like fixed sun films or static shading devices, don't change with the sun also cause darkness when applied to the whole window. Once installed, they either block too much light or too little, leaving users with limited control. This is where the idea of PuzzleGlaze came into the picture. Inspired by the logic of a puzzle, the system uses a grid of nine small panels, four of clear glass, four with sun film, and one left open for air movement. These panels can move up and down and also sideways through lock and key mechanism i.e. tongue and groove joint where the groove acts as a channel for the panels to slide. This makes the window flexible, interactive, and less wasteful, since sun film is only used where it really matters. For this research, a

[1] Undergraduate, MKSSS's Dr. B.N. College of Architecture, SPPU, India, sofiyashaikh2610@gmail.com
[2] Assistant Professor, MKSSS's Dr. B.N. College of Architecture, SPPU, India, amruta.garud@bnca.ac.in

physical prototype of 1:2 scale named PuzzleGlaze was created and tested under simulated sunlight conditions that mimic Pune's sun path and also simulations are carried out on Revit and Grasshopper-Honeybee software. This study aims to show how adaptive window systems like PuzzleGlaze can be used to control daylight, heat and glare, while also giving users more control over their indoor environment.

## 2. LITERATURE REVIEW

Figure 1 maps insights drawn from the literature study where various discourses in window systems have been categorized based on mode of operation and energy usage. While the passive facades are on the left extreme where the systems are static and non-responsive but are cost effective and built solutions in most of the cases; on the right extreme lies the Kinetic facade which are dynamic and responsive. Research on Kinetic facades shows that they save energy, give better daylight and comfort by responding dynamically to environmental conditions, but a very few real-life examples are seen (Hosseini et al., 2019). Adaptive facades also move or react to weather to cut glare and heat and work best when designed for local climate and user needs (Juaristi et al., 2018a). Parametric studies of sun-responsive facade skins have further demonstrated that such systems can significantly improve daylighting performance and visual comfort when their geometry is tuned to local solar conditions (Tabadkani et al., 2018).

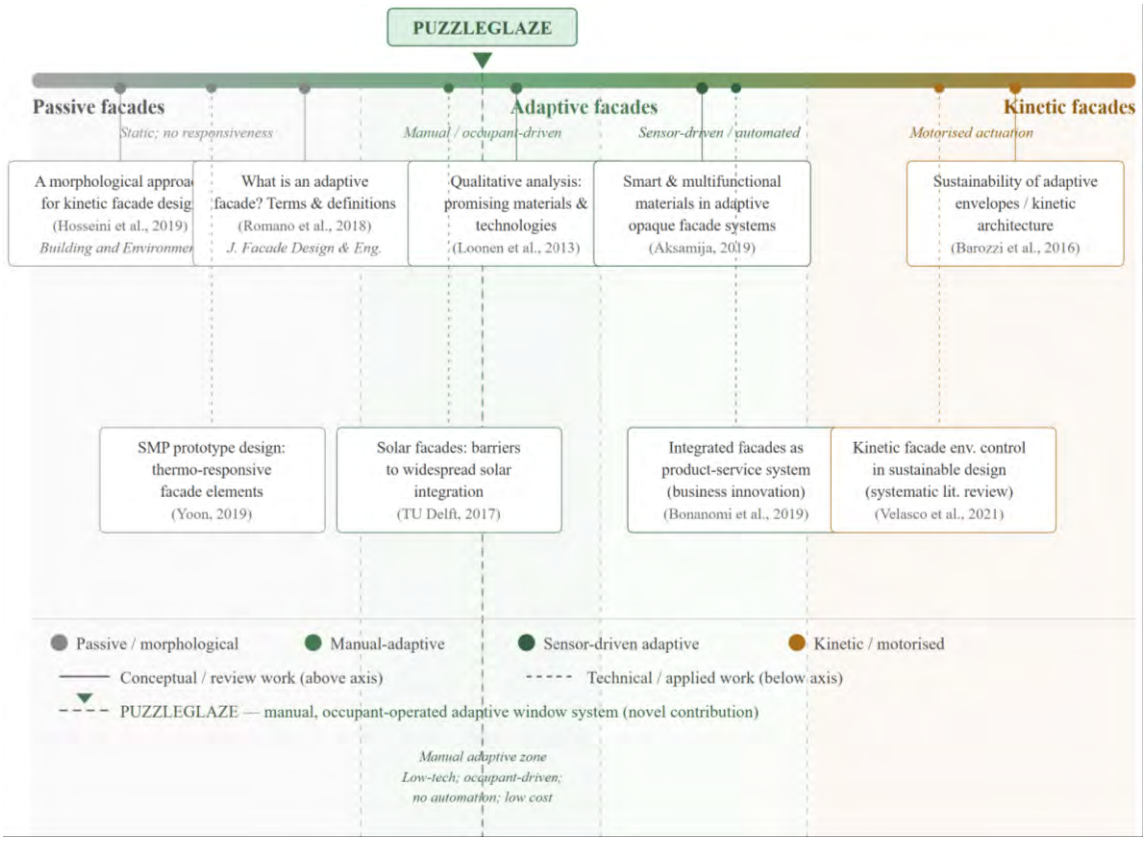



*Figure 1: Facade design research spectrum: From passive to kinetic facades, situating PuzzleGlaze within the manual-adaptive zone*

However, to install, operate and maintain such kinetic and adaptive facades a system is required which might be overwhelming for a layperson. As a product if such facades can be rented or serviced, such advanced designs would become more affordable and

universal (Azcárate-Aguerre et al., 2018). Solar facades do have a potential for universal use but are seen as too costly and slow to adopt (Prieto et al., 2017). Adaptive facades in real projects reduce cooling needs, but most rely on expensive tech; simpler solutions are missing (Barozzi et al., 2016). However, adaptive facades do act like building skins, adjusting to climate and people (Romano et al., 2018), but use of smart materials, sensors-based technologies have become expensive limiting household adoption; thus, highlighting a need for low-cost and simple design solution (Juaristi et al., 2018b). Research also highlighted limitations of kinetic and adaptive facades, which says since it is automated and expensive it is not preferred in households (Hosseini et al., 2019; Juaristi et al., 2018a). This identified a clear research gap that a window system is required that can be manually operated by the user making it user-centric and cheaper, improving indoor thermal comfort and also ensuring sustainable operation and maintenance.

PuzzleGlaze addresses this gap as a novel contribution as a cost-effective solution at the intersection of adaptive façade designs and low-tech driven solutions. The system doesn't require automation, sensors and nor specialist installation. Thus, PuzzleGlaze system situates itself within the adaptive façade spectrum – between the static passive systems and motorised dynamic facades – this study responds to the call in the literature for a simpler and more accessible solution for residential buildings (Barozzi et al., 2016; Hosseini et al., 2019). Simulations were conducted to evaluate performance, focusing on daylight distribution, glare reduction, and solar heat gain, following standard metrics for indoor environmental quality (Hosseini et al., 2019; Juaristi et al., 2018a).

# 3. DATA AND METHOD

This research adopts an exploratory design approach (Groat & Wang, 2013) to evaluate the performance of a partially glazed, adjustable window system referred to as PuzzleGlaze – using sun films for glare control and daylight optimization. The methodology involves three sequential stages- (1) conceptual design, (2) physical prototype construction and observation, and (3) digital simulation to validate PuzzleGlaze performance under user-adjusted puzzle. For simulation study, the window system is evaluated within the Pune India (18.52°N, 73.85°E) context which is categorized as hot semi-arid climate (Köppen climate classification BSh) characterised by high solar radiation, prolonged periods of intense direct sunlight, and limited cloud cover during summer months.

## 3.1 CONCEPTUAL DESIGN OF PUZZLEGLAZE

The foundation of this study is the development of a modular window system inspired by the logic of a puzzle. The window is divided into a 3×3 grid consisting of nine equal-sized panels. The sunfilm panels and clear glass panels are in 50-50 ratio so that it is easy to apply or have a grid pattern in which 4 panels are made of clear glass, 4 panels are glass panels with sunfilm, and one panel is left void with a jali for ventilation. These panels can be moved up and down or sideways with the help of lock and key mechanism which is basically tongue and groove joint in which the tongue part having extruded edge can move in the groove or channel of the same size. This configuration or mechanism allows the panels to be manually adjusted sliding or rotating them based on the changing position of the sun throughout the day. Such as if the sun is at higher angle the sunfilm panels can be moved upwards so that it reduces glare and heat coming inside the room, if the sun angle is at lower horizon the sunfilm panels can be moved downwards and heat

coming inside can be reduced, in such way it is very user - centric that the individual can decide how much heat can be entered and adjust it accordingly. Also, these panels are in grid so are aesthetically appealing and also the pattern can go on changing as per the individual's choice, so different patterns can be seen throughout the day.

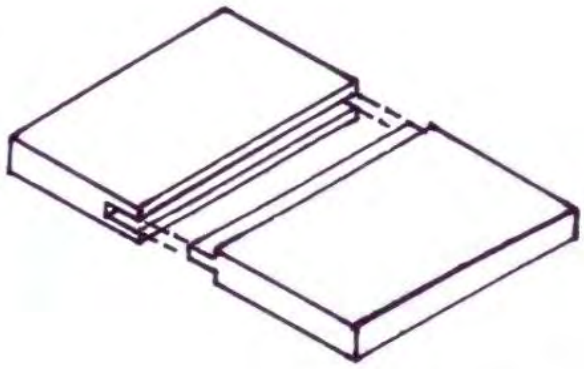


*Figure 2: Tongue and groove joint mechanism in which groove acts as a channel*

*Figure 3: Window panel design with 9 panels, four with sunfilm and 4 as clear glass and corner is void for ventilation.*

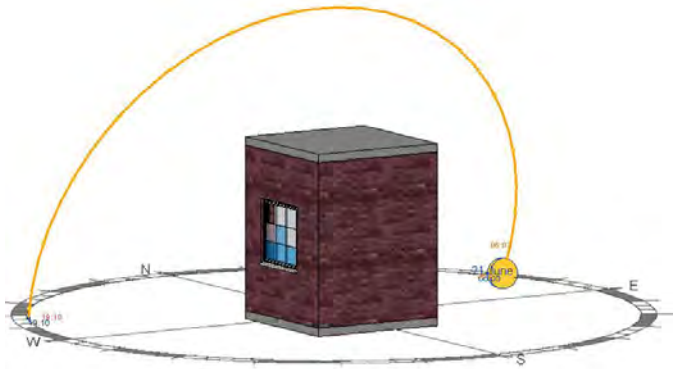



*Figure 4: The digital Revit software model room with the prototype window placed to the west side as heat gain is more towards west.*

## 3.2 PHYSICAL PROTOTYPE CONSTRUCTION AND OBSERVATION

The prototype was built at a scale of 1:2, considering a standard window opening of 1200mm x 1200mm as shown in Figure 5. The window system is divided into 9 equal parts each measuring 400mm X 400mm at 1:1 scale. The scaled prototype panel measured 200mm X 200mm which was fabricated using acrylic sheet which was used as a substitute to glass for the ease of demonstration at lower cost. The material prototype development cost was around INR1200 (USD 14). The tongue and groove joint to facilitate the sliding mechanism was created as shown in Figure 5 with each panel having extruded tongue profiles along two adjacent sides and groove channels along the remaining two sides. The window frame is similarly provided with groove channels along the inner edges allowing smooth sliding mechanism.

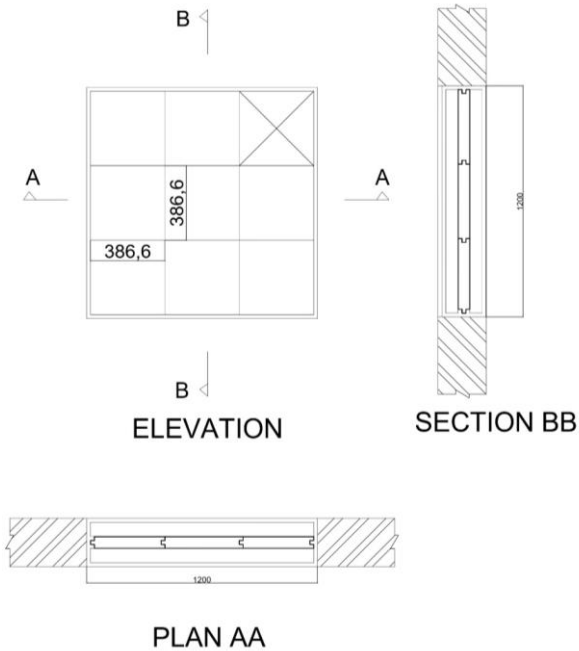



*Figure 5: Technical drawings of PuzzleGlaze prototype, a nine- panel window*

The prototype model consisted of a transparent acrylic sheet of 3mm cut to a panel size of 200mm X200mm at 1:2 scale (see Figure 6) and 3 panels pasted together by an adhesive making effective thickness 9mm thick (see Figure 7) in such a way that it creates tongue and groove by cutting the sides or the middle part, representing standard glass. Sun film is applied to designated panels i.e. four panels. A single panel left open to simulate a ventilated void will have a jali or small net. The window panel mechanism is designed to allow manual adjustment to simulate how users might react to changing glare throughout the day. Each panel operates on a lock-and-key mechanism: two adjacent sides of the panel are designed with extruded parts (keys), while the other two sides have depressions (locks) (see Figure 8). The side frame of the grid is provided with corresponding slots, enabling panels to securely slide, rotate, or fit in place. This ensures both flexibility of movement and structural stability during adjustment.

*Figure 6: Cutting of acrylic sheets to make nine window panels in a wood cutting machine*

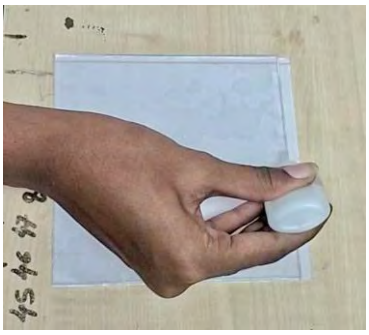


*Figure 7: Pasting the 3 acrylic panels with an adhesive*

*Figure 8: Making tongue by trimming side panels and groove by trimming middle panel*

To make the prototype window, the frame was made of wood to provide both strength and ease of fabrication. The frame also consisted of tongue and groove geometry so as to make panels fit into and slide easily. The window system fabricated consisted of 4 panels with sunfilm applied (see Figure 9), 4 clear glass panels and a void (Figure 10). The clear glass panels used in the PuzzleGlaze system are showing white patches due to the adhesive used while pasting three panels together, as transparent adhesive was not commercially easily available due to probable adverse reaction to health. Figure 11 shows a beam of artificial light falling onto the window system where panels with sunfilm layering are blocking the direct light. In addition to this a backside support was given to make the window stand independently which was also made of wood (see Figure 12).

*Figure 9: Black are panels with sunfilm*

*Figure 10: A void for ventilation is at the corner*

*Figure 11: The striking of glare on the window panel*

*Figure 12: The backside window supports*

## 3.3 DIGITAL SIMULATION TO VALIDATE PUZZLEGLAZE PERFORMANCE

### 3.3.1 Revit Solar Analysis

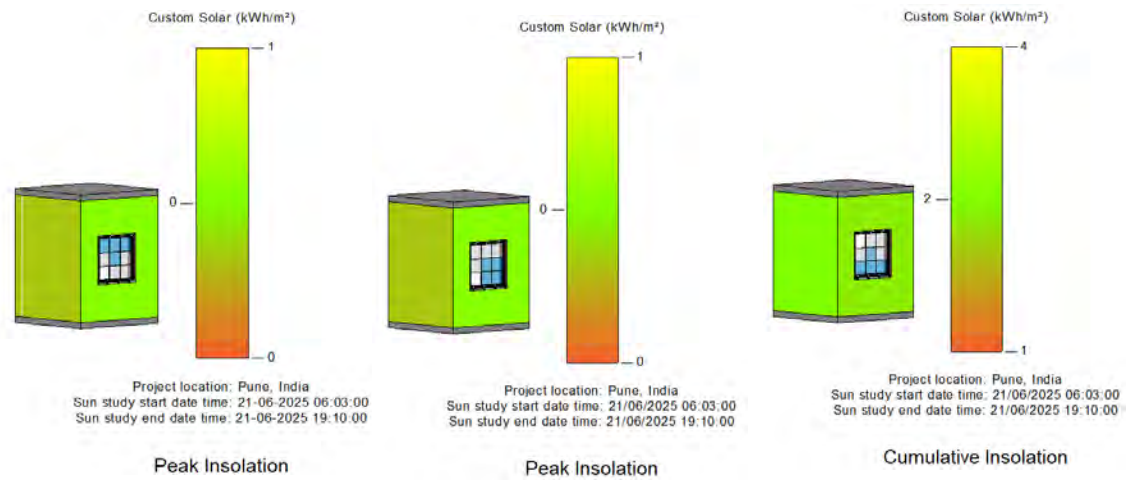



*Figure 13: Simulation of Adaptive Panel Response to Solar Insolation at Different Sun Angles in Revit*

The Figure 13 shows the solar insolation study carried out in Revit software at different sun positions, including higher, middle, and lower horizon angles. As the position of the sun changes throughout the day, the panels also adjust accordingly to control the amount of sunlight entering the space. This helps in reducing heat gain and improving indoor

comfort through a simple passive design approach. The panels with sunfilm can be manually moved at the top when the sun is at higher altitude in the morning, then the panels can be moved to the middle in the afternoon, and the panels can also move to the bottom when the sun is at lower altitude in the evening.

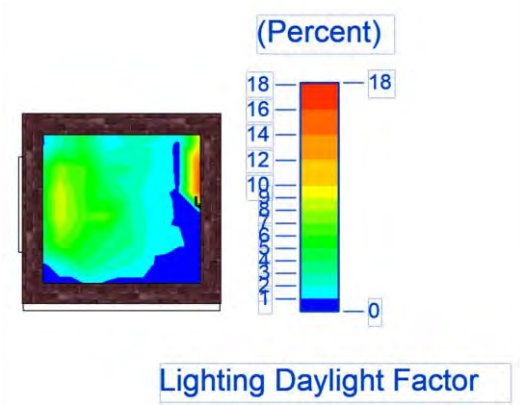



*Figure 14: Daylight simulation showing the effect of sunfilm panels on indoor light control*

The Figure 14 shows that direct sunlight enters the room more intensely through the clear glass surfaces. The simulation study also shows that the sunfilm panels help reduce the intensity of incoming sunlight, creating a more balanced indoor environment and improving visual and thermal comfort within the space.

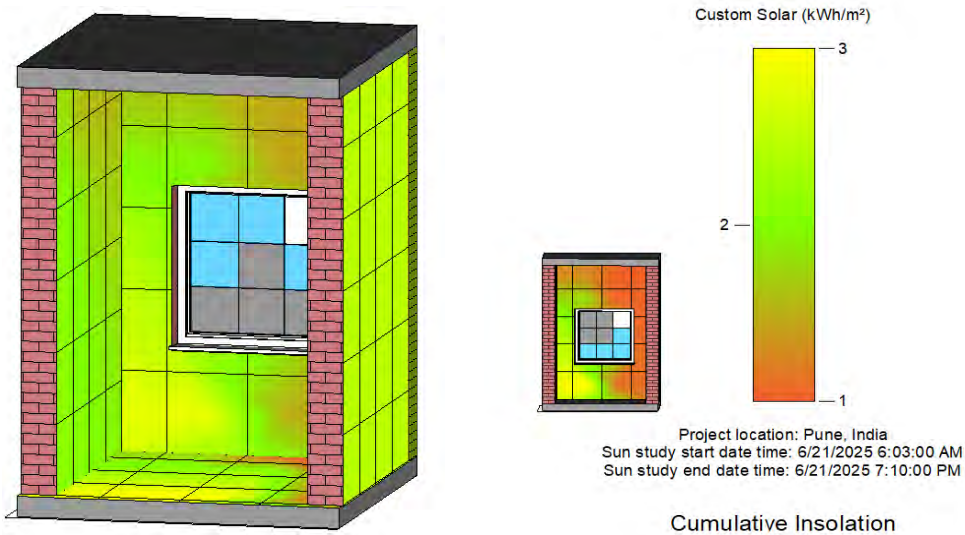



*Figure 15: Comparison of solar heat gain through clear glass and sun-film-coated panels*

The figure compares the solar heat gain through clear glass panels and sun-film-coated panels based on the simulation carried out in Revit software. The clear glass allows a greater amount of sunlight and heat to enter the room, creating brighter and warmer areas near the window. In contrast, the sun-film-coated panels reduce the amount of solar radiation entering the space, helping to maintain lower surface temperatures and improve indoor comfort.

### 3.3.2 Grasshopper-Honeybee with Radiance and OpenStudio Plugins

The prototype model was made in Rhinoceros software, in which the Daylight (Tabadkani et al., 2018) and Heat gain simulations were carried out in Grasshopper using Ladybug, Honeybee (refer Figure 22 in Annexures), Radiance, and Open studio plugins by making a manual script of components referring to various resources available on the internet such as tutorials, blogs related to how to build scripts in grasshopper for simulation studies. All the scripts were built by the author in the Grasshopper and the details are given in the Annexures.

- **DAYLIGHT SIMULATION**

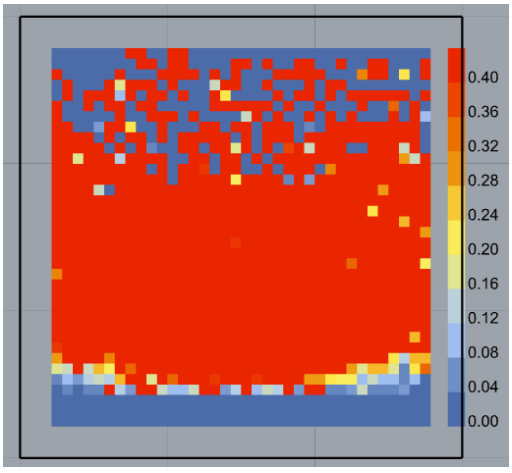



*Figure 16: Daylight simulation results for Clear Glass Window system*

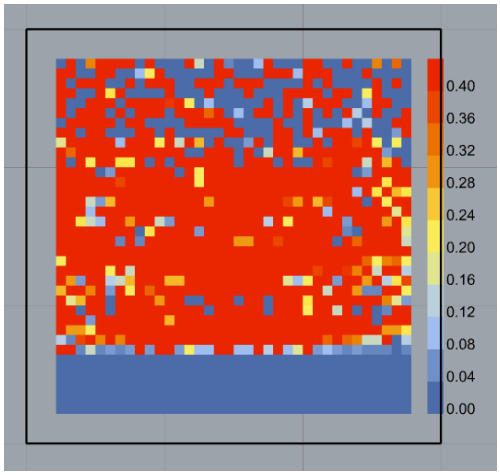



*Figure 17: Daylight simulation results for the proposed PuzzleGlaze Window system*

*Table 1: Legends showing daylight simulation scale*

| DF Scale | Lighting condition |
|---|---|
| 0 - 0.12 | Poor daylight |
| 0.12 - 0.16 | Low daylight |
| 0.16 - 0.24 | Moderate daylight |
| 0.24–0.28 | High daylight |
| 0.28–0.4 | Possible glare |

Figure 16 shows the daylight analysis for a lower-side clear glass window with a light transmittance of 85%. A higher amount of natural light enters through the window and gradually spreads deeper into the room, resulting in increased daylight levels across the interior space. Refer to Table 1 to understand the daylight simulation scale and associated lighting conditions. The corresponding Grasshopper script used to perform the simulation is also presented (refer Figure 22 in Annexures). Whereas Figure 17 shows the daylight analysis for a lower-side sunfilm-coated glass window with a light transmittance of 45%. Due to the reduced transmittance, the amount of daylight entering the room is lower, resulting in more controlled and evenly distributed illumination levels within the space. This indicates the effectiveness of the sunfilm in reducing excessive daylight penetration while still maintaining adequate indoor lighting. The accompanying Grasshopper script

illustrates the simulation workflow (refer Figure 23 in Annexures), and all daylight results are expressed in lux.

- **HEAT RADIATION SIMULATION**

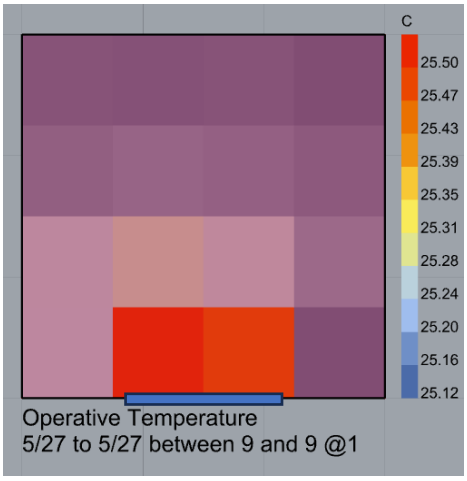



*Figure 18 Operative temperature analysis with clear glass window at 9 am*

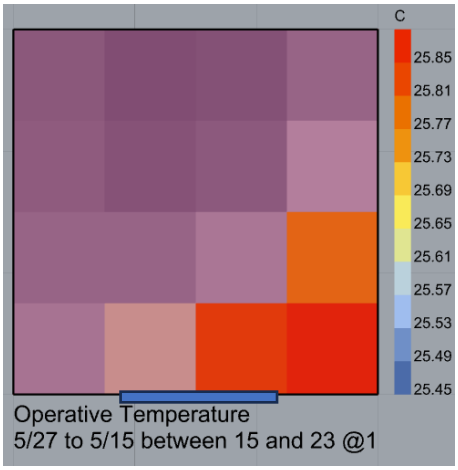



*Figure 19: Operative temperature analysis with clear glass window at 3 pm*

The figure shows the operative temperature simulation carried out on 27 May at 9 AM and 3 PM for a space with a clear glass window located at the bottom. Higher temperatures are observed near the window due to increased solar heat gain through the clear glass surface. The afternoon condition at 3 PM shows slightly higher temperatures compared to the morning at 9 AM, indicating greater heat accumulation during later hours of the day. The simulation results are represented in degrees Celsius (°C), (refer Figure 24 in Annexures).

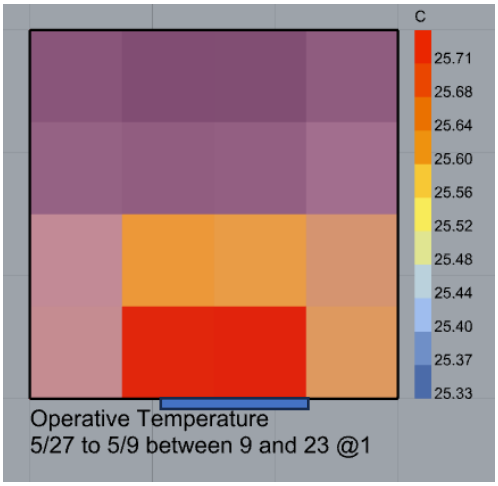



*Figure 20: Operative temperature analysis with sun-film coated glass window at 9 am*

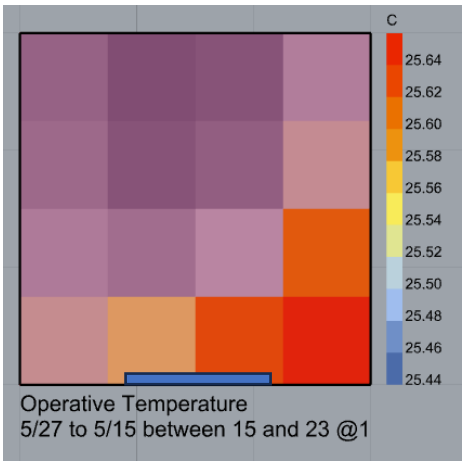



*Figure 21: Operative temperature analysis with sun-film coated glass window at 3 pm*

The figure shows the operative temperature simulation carried out on 27 May at 9 AM and 3 PM for a space with a sunfilm-coated glass window located at the bottom. The sunfilm helps reduce solar heat gain, resulting in more uniform and slightly lower temperatures near the window area. Although the afternoon condition at 3 PM still records slightly higher temperatures than the morning at 9 AM, the overall indoor thermal conditions remain comparatively more comfortable. The simulation results are represented in degrees Celsius (°C), (refer Figure 25 in Annexures).

## 4. CONCLUSIONS

PuzzleGlaze is a window designed using a puzzle system, made of nine panels that can be moved and arranged. Some panels are with clear glass to let in light, some have sun film coating to block glare, and one is left open for fresh air. This simple design gives people the freedom to adjust their windows based on the sun's position, keeping rooms bright, comfortable, and cool without depending too much on electricity. From the simulations, it shows that the clear glass has higher solar heat gain (Figure 18 & Figure 19) that increases indoor temperature, while sunfilm-coated glass reduces heat gain (Figure 20 & Figure 21) and maintains indoor temperature. Therefore, the PuzzleGlaze window prototype is a mixture of both clear glass and sunfilm which helps balance daylight and thermal comfort, allows light to enter with lesser heat gain in the peak sun hours. The novelty lies in three features: first, the tongue-and-groove modular panel mechanism that allows occupant-driven repositioning in response to solar angle; second, the hybrid panel configuration that distributes sun-film and clear glass within a single frame, rather than applying uniform glazing across the entire window; and third, its deliberate design for replicability at low cost, demonstrated through a functional prototype built for approximately INR 1,200. However, a formal performance validation of the PuzzleGlaze through full scale physical set-up and sensor-based data collection for radiation and daylight represents a key limitation of the present study and constitutes the most critical direction for future research. Unlike fixed glass or costly automated systems, PuzzleGlaze is easy to use, affordable, and saves material because sun film is only used where it is really needed. It works well in homes, but it is also especially valuable in Schools, where children can enjoy sliding the panels like a game. By playing with the system, they not only improve their classroom comfort but also learn in a hands-on way how daylight can replace electric lights and how sustainable design can save energy. In this way, PuzzleGlaze is not just a window, it is a simple, low-tech, and educational tool that makes buildings more comfortable while teaching the next generation about the importance of saving energy.

## 5. REFERENCES

Azcárate-Aguerre, J. F., Den Heijer, A., & Klein, T. (2018). Integrated façades as a product-service system: Business process innovation to accelerate integral product implementation. *Journal of Facade Design and Engineering, 6*(1), 41–56. https://doi.org/10.7480/jfde.2018.1.1840

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The sustainability of adaptive envelopes: Developments of kinetic architecture. *Procedia Engineering, 155,* 275–284. https://doi.org/10.1016/j.proeng.2016.08.029

Groat, L. N., & Wang, D. (2013). Architectural research methods (2nd ed.). Wiley.

Hosseini, S. M., Mohammadi, M., Rosemann, A., Schröder, T., & Lichtenberg, J. (2019). A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. *Building and Environment, 153,* 186–204. https://doi.org/10.1016/j.buildenv.2019.02.040

Juaristi, M., Gómez-Acebo, T., & Monge-Barrio, A. (2018a). Qualitative analysis of promising materials and technologies for the design and evaluation of climate adaptive opaque façades. *Building and Environment*, *144*, 482–501. https://doi.org/10.1016/j.buildenv.2018.08.028

Juaristi, M., Monge-Barrio, A., Sánchez-Ostiz, A., & Gómez-Acebo, T. (2018b). Exploring the potential of smart and multifunctional materials in adaptive opaque façade systems. *Journal of Facade Design and Engineering*, *6*(2), 107–117. https://doi.org/10.7480/jfde.2018.2.2216

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017). Solar façades: Main barriers for widespread façade integration of solar technologies. *Journal of Facade Design and Engineering*, *5*(1), 51–62. https://doi.org/10.7480/jfde.2017.1.1398

Romano, R., Aelenei, L., Aelenei, D., & Mazzucchelli, E. S. (2018). What is an adaptive façade? Analysis of recent terms and definitions from an international perspective. *Journal of Facade Design and Engineering*, *6*(3), 65–76. https://doi.org/10.7480/jfde.2018.3.2478

Tabadkani, A., Banihashemi, S., & Hosseini, M. R. (2018). Daylighting and visual comfort of oriental sun-responsive skins: A parametric analysis. *Building Simulation*, *11*(4), 663–676. https://doi.org/10.1007/s12273-018-0433-0

Yoon, J. (2019). SMP prototype design and fabrication for thermo-responsive façade elements. *Journal of Facade Design and Engineering*, *7*(1), 41–61. https://doi.org/10.7480/jfde.2019.1.2662

## 6. ANNEXURES

Following are the Grasshopper scripts developed by the author to conduct Honeybee Radiance analysis.

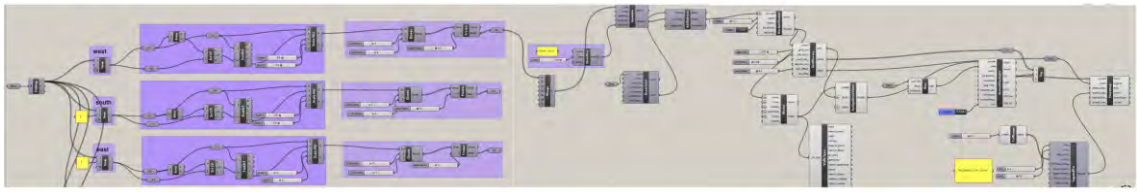


*Figure 22: Daylight distribution analysis and grasshopper simulation script.*

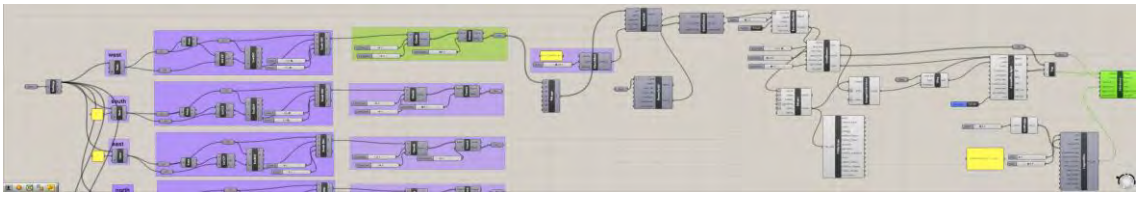


*Figure 23: Daylight distribution analysis of sunfilm-coated glass and grasshopper simulation script.*

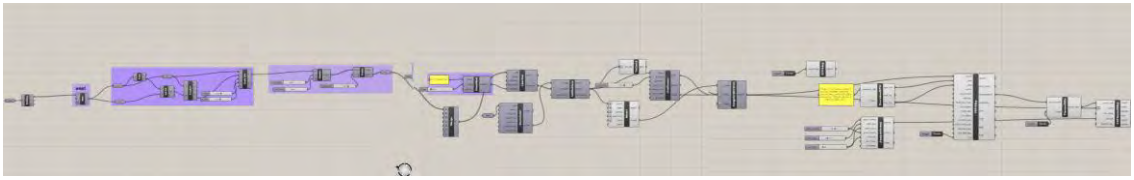


*Figure 24: Operative temperature analysis with clear glass window at 9 am and 3 pm*

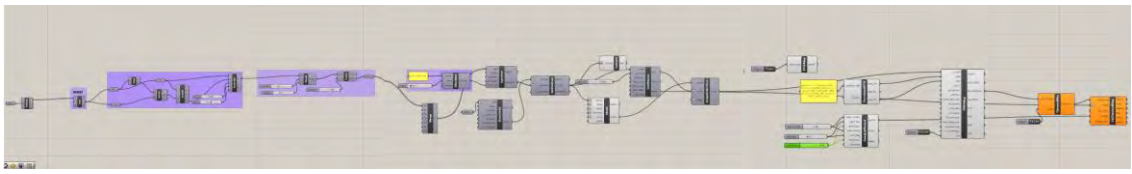


*Figure 25: Operative temperature analysis with sunfilm-coated glass window at 9 am and 3 pm*

Sewwandi, A.I. and Samarawickrama, S., 2026. Reframing the inclusive classroom as a designed learning environment: An integrative literature review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1398-1413. DOI: https://doi.org/10.31705/WCS.2026.102. Available from: https://ciobwcs.com/papers/

# REFRAMING THE INCLUSIVE CLASSROOM AS A DESIGNED LEARNING ENVIRONMENT: AN INTEGRATIVE LITERATURE REVIEW

**A.I. Sewwandi[1] and S. Samarawickrama[2]**

## *ABSTRACT*

*Research on inclusive classrooms has developed across three domains: inclusivity, focusing on belonging and social participation; inclusive education, addressing pedagogy, leadership, and institutional practices; and inclusive design, which considers the spatial, material, and sensory conditions of learning environments. An inclusive learning environment is one in which learners are supported to access educational opportunities, participate meaningfully, and achieve learning outcomes. Although inclusion reflects broader philosophies, policies, and institutional commitments, the inclusive classroom is the site where these principles are enacted, translating inclusion into accessible spaces, equitable learning opportunities, and socially participatory practices. Despite growing scholarship in these areas, limited research integrates these perspectives, constraining the conceptualization of the inclusive classroom as a holistically designed learning environment that simultaneously addresses social, pedagogical, spatial, and institutional dimensions. To address this gap, this study conducts an integrative literature review of 34 studies, synthesizing interdisciplinary knowledge across the three domains. Using a thematic synthesis process involving initial coding, descriptive theme development, and analytical theme generation, the review examined how inclusive classrooms are conceptualised across disciplinary contexts. The analysis identifies four conceptualizations of the inclusive classroom: a value-based environment emphasizing social justice and belonging; a pedagogical and organizational space shaped by teaching practices and curriculum adaptation; a designed physical and sensory environment defined by spatial layout and accessibility; and a design system involving resources, technologies, and institutional supports. Through cross-domain synthesis, these conceptualisations were further integrated into four higher-order analytical framings: the Architecture of Capability, Technologically-Mediated Relationality, Proactive Ecosystemic Design, and Relational Systemic Enactment. The findings reconceptualise the inclusive classroom as a designed learning environment emerging through the dynamic interaction of social, pedagogical, spatial, and institutional dimensions. This integrative perspective contributes a conceptual framework that extends existing understandings of inclusive classrooms and provides a foundation for future research, educational practice, and the design of inclusive learning environments.*

***Keywords:*** *Built Environment; Inclusive Classroom; Inclusive Design; Inclusive Education; Integrative Literature Review; Learning Environments.*

---

[1] Research Assistant, Department of Integrated Design, Faculty of Architecture, University of Moratuwa, Moratuwa, Sri Lanka, imalkasewwandi1805@gmail.com
[2] Senior Lecturer, Department of Integrated Design, Faculty of Architecture, University of Moratuwa, Moratuwa, Sri Lanka, sumanthris@uom.lk

# 1. INTRODUCTION

Inclusion has become a central principle in contemporary educational discourse, reflecting broader societal commitments to equity, participation, and accessibility (Ainscow, 2020; Florian, 2014; Carney, 2022) foundational elements of inclusive educational environments. Within educational contexts, these elements collectively underpin inclusive education by ensuring that all learners, regardless of ability, background, or learning needs, can meaningfully access educational opportunities, participate in learning activities, and achieve desired outcomes (Altakhaineh et al., 2026; Díaz-Boladeras et al., 2025). The inclusive learning environment operationalizes these principles, functioning not only as a physical or pedagogical space but also as a socially, organisationally, and resource-mediated ecosystem that enables learners to engage fully and equitably (Carney, 2022; Florian, 2014). While inclusion encompasses broader philosophies, policies, and institutional structures, the inclusive classroom represents the primary site where these principles are enacted, translating inclusion into accessible spaces, equitable learning opportunities, and socially participatory practices.

Within this perspective, the inclusive classroom becomes a key setting where inclusive education principles are translated into everyday teaching and learning practices. As a localized component of the broader inclusive learning environment, the classroom represents the immediate context in which inclusion is experienced and enacted by learners. Research indicates that simply integrating students with diverse learning needs into mainstream classrooms does not automatically result in inclusive learning experiences (Cade, 2023; Polat et al., 2024). Rather, inclusive classrooms require intentional instructional strategies, adaptive resources, and supportive institutional structures that enable educators to respond effectively to diverse learner needs(Altakhaineh et al., 2026; Curry et al., 2024). As outlined above, inclusive classrooms are embedded within broader inclusive learning environments that influence the availability of resources, teacher preparation, and leadership support. When educational policies, institutional leadership, and classroom practices function cohesively, they create learning environments that support equitable access, meaningful participation, and improved learning outcomes for all students (Curry et al., 2024; Wang et al., 2025).

The concept of the inclusive classroom is frequently explored within existing literature. However, it is frequently explored through specific disciplinary lenses, such as social inclusion, pedagogical practice, and environmental accessibility, which can also be identified as three intersecting domains: inclusivity, inclusive education, and inclusive design, each emphasizing distinct aspects of inclusion (Altakhaineh et al., 2026). As a result, the inclusive classroom is often conceptualized through isolated dimensions rather than as a holistic learning environment shaped by the interaction of social, pedagogical, and spatial factors. This fragmentation creates challenges in understanding how different aspects of inclusion collectively influence learner participation, engagement, and educational outcomes.

Within the inclusivity domain, the inclusive classroom is primarily conceptualized as a social environment that promotes belonging, participation, and supportive learning communities. 'Inclusivity' refers to the broader social and ethical principle of ensuring that all individuals are recognized, respected, and able to participate fully in social,

institutional, and educational contexts (Anđić et al., 2024; Cade, 2023). In education, inclusivity emphasizes social interaction, belonging, and the development of supportive learning communities that accommodate varied identities, abilities, and learning needs. Understanding the inclusive classroom through the lens of inclusivity highlights the social and relational dimensions of learning environments. Inclusion is not achieved solely through structural adjustments or the placement of diverse learners in mainstream settings; rather, it requires cultivating classroom cultures that support interaction, collaboration, and the recognition of diversity. Consequently, examining inclusive classrooms within the domain of inclusivity provides important insights into how equity, participation, and accessibility are enacted through classroom practices, peer interactions, and collaborative learning structures.

Within the inclusive education domain, the inclusive classroom is primarily conceptualized as a pedagogical environment in which teaching practices, curriculum adaptations, and institutional supports facilitate participation and learning (Altakhaineh et al., 2026). "Inclusive education" refers to an educational approach that seeks to ensure that all learners, particularly those with diverse abilities, backgrounds, and learning needs, are able to access, participate in, and benefit from quality education (Altakhaineh et al., 2026; Díaz-Boladeras et al., 2025). It emphasizes the removal of barriers to learning and participation through supportive pedagogical practices, institutional policies, and professional collaboration (Altakhaineh et al., 2026; Florian, 2014).

Within the inclusive design domain, the inclusive classroom is primarily conceptualized as a spatial and material environment that supports accessibility, usability, and engagement. "Inclusive design" refers to the intentional process of designing environments, products, and systems that are accessible, usable, and meaningful for the widest possible range of users, regardless of age, ability, or background (Sewell et al., 2022). Within educational contexts, inclusive design emphasizes the creation of learning environments that remove physical, sensory, and cognitive barriers that may limit participation and engagement in learning activities (Altakhaineh et al., 2026). Rather than adapting spaces after barriers emerge, inclusive design promotes proactive planning in which accessibility and diversity are considered from the outset of the design process (Florian, 2014; Sewell et al., 2022). In this sense, inclusive design aligns closely with principles of universal access and equitable participation, ensuring that educational environments can support diverse learners without requiring extensive individual modifications. Understanding inclusive classrooms through the lens of inclusive design highlights that learning environments are not neutral settings; rather, they actively shape participation, engagement, and learning outcomes. Poorly designed classrooms may unintentionally create barriers that restrict mobility, communication, or access to learning resources. Conversely, thoughtfully designed classrooms can enhance interaction, support diverse learning styles, and promote equitable participation among students (Ntalindwa et al., 2022; Pasenidou, 2026a). Consequently, inclusive design contributes an important spatial and environmental perspective to the understanding of inclusive learning environments.

Although the three domains address the same classroom context, they are frequently examined as separate perspectives within the literature, with research often emphasizing either the social, pedagogical, or spatial dimensions of inclusion. This separation can result in a fragmented understanding of the inclusive classroom, limiting its conceptualisation as a localized component of the broader inclusive learning

environment. From a socio-cultural and relational perspective, inclusion is not a set of discrete features located within pedagogy, physical space, or social relationships, but rather an emergent process shaped through the dynamic interaction of these elements in everyday classroom practice (Booth & Ainscow, 2016; Black-Hawkins, 2014). When these dimensions are considered independently, the interdependent nature of inclusion becomes less visible, obscuring how social relationships, teaching practices, and spatial conditions collectively shape inclusive learning experiences. Consequently, inclusive practice risks being conceptualised in segmented rather than holistic terms, limiting a comprehensive understanding of how inclusive classroom environments are created and sustained (Florian, 2014).

*Table 1: Conceptualization of the inclusive classroom across three domains*

| Domain | Focus | Key Concepts |
|---|---|---|
| Inclusivity | Social/ethical | Belonging, participation, identity |
| Inclusive Education | Pedagogical/institutional | Differentiation, curriculum adaptation |
| Inclusive Design | Spatial/environmental | Accessibility, usability, universal design |

For example, inclusive pedagogical strategies such as differentiation or collaborative learning may be implemented; however, without corresponding attention to spatial arrangements, such practices may still limit participation for learners who require flexible or accessible learning environments. Similarly, even physically accessible classrooms may not fully support inclusion if interactional patterns or classroom cultures reproduce subtle forms of exclusion, such as unequal participation or cultural and linguistic marginalisation. These examples illustrate that access, participation, and belonging are co-constructed across multiple dimensions rather than achieved through any single element in isolation. Socially inclusive classroom cultures may therefore be constrained by inaccessible or inflexible physical environments, while well-designed environments may still fail to support participation if pedagogical practices and classroom relationships remain exclusionary. This highlights Booth and Ainscow's (2016) view of inclusion as a continuing process of identifying and removing barriers to participation and learning. Understanding how these dimensions interact is therefore essential for conceptualising the inclusive classroom as an integrated learning environment rather than as a collection of separate features.

The inclusive classroom therefore represents the point where these three domains, inclusivity, inclusive education, and inclusive design, intersect. Inclusivity provides the ethical and social foundation for recognizing diversity and promoting participation, while inclusive education operationalizes these principles through teaching practices, curriculum adaptation, and institutional support mechanisms (Altakhaineh et al., 2026; Curry et al., 2024). At the same time, inclusive design ensures that the physical and material characteristics of the learning environment support accessibility and engagement for diverse learners (Pasenidou, 2026a; Sewell et al., 2022). When considered together, these domains reveal that inclusive classrooms are not only social or pedagogical environments but also designed systems in which social relationships, teaching practices, and spatial conditions interact to shape learning experiences. While previous studies have examined inclusivity, inclusive education, and inclusive design independently, limited research has synthesized these perspectives to understand how they collectively shape inclusive classroom environments. Consequently, the relationships and

interdependencies between social, pedagogical, and spatial dimensions of inclusion remain insufficiently explored within the literature.

This gap highlights the need for an integrative perspective that examines how inclusivity, inclusive education, and inclusive design collectively shape the inclusive classroom as a localized component of a broader inclusive learning environment. The aim of this study is to examine how these three domains conceptualize the inclusive classroom and to synthesize these perspectives in order to reconceptualize the inclusive classroom as a designed learning environment. Specifically, the study seeks to: (1) examine how inclusive classrooms are conceptualized within the domains of inclusivity, inclusive education, and inclusive design; (2) identify common themes and relationships emerging across these domains; and (3) synthesize these perspectives to develop an integrated conceptualization of the inclusive classroom as a designed learning environment. To achieve this, the study conducts an integrative literature review of 34 peer-reviewed studies, bringing together insights from education and built environment research to develop a more integrated understanding of inclusive classroom environments.

## 2. METHODOLOGY

This study adopts an Integrative Literature Review (ILR) methodology to examine how the concept of the inclusive classroom is understood across the domains of inclusivity, inclusive education, and inclusive design. To support this, the study examines how the inclusive classroom is conceptualised in existing literature, analyses how different domains emphasise distinct dimensions of inclusion within classroom environments, identify common themes and relationships emerging across these domains and synthesises insights across these perspectives in order to develop a more integrated conceptual understanding of inclusive classroom environments.

The integrative literature review (ILR) approach was selected because research on inclusive classrooms spans multiple disciplinary fields, including education, social sciences, design studies, and built environment research. Integrative reviews are particularly suited to synthesising diverse forms of evidence and knowledge across disciplinary boundaries, enabling a more comprehensive understanding of complex phenomena (Whittemore & Knafl, 2005). Accordingly, the ILR methodology provides an appropriate framework for examining how inclusive classroom environments are conceptualised across social, pedagogical, and spatial perspectives.

A comprehensive literature search was conducted across multiple academic databases to ensure broad interdisciplinary coverage of research related to inclusivity, inclusive education, and inclusive learning environments. The databases consulted included ERIC (Education Resources Information Center), Taylor & Francis Online, SpringerLink, ScienceDirect, and Google Scholar. ERIC was prioritised for literature related to inclusive education because of its extensive coverage of educational research, classroom practices, and educational policy. Taylor & Francis Online and SpringerLink were included to capture peer-reviewed scholarship within the social sciences and special education literature. ScienceDirect was used to identify studies related to learning environments and inclusive design, including research within design studies, environmental psychology, architecture, and educational facilities. Google Scholar was used as a complementary search platform to ensure broader interdisciplinary coverage and to identify influential theoretical and policy documents that may not be consistently

indexed across specialised databases. The search focused on literature published between 2016 and 2025 and was limited to sources published in English.

Literature was included in the review based on its relevance to the conceptual focus of the study. Priority was given to peer-reviewed journal articles, foundational theoretical and conceptual scholarship, and key international policy or guidance documents addressing inclusion within educational environments. Studies were considered relevant if they contributed to understanding inclusion in educational contexts, classroom practices related to participation and access, learning environments and spatial considerations, or design principles influencing usability, accessibility, and engagement within classroom environments. Literature from education, social sciences, design studies, and built environment disciplines was included where it contributed to the review objectives. These criteria ensured that the selected literature contributed directly to the study's objective of reconceptualising the inclusive classroom as a designed learning environment. The studies were excluded if they focused exclusively on clinical or medical models of disability, addressed subject-specific pedagogical issues without reference to classroom environments or resources, or lacked relevance to the social, pedagogical, or spatial dimensions of inclusion.

Search terms were developed in relation to the three conceptual domains that frame this study. The search strategy focused on identifying literature that explicitly or implicitly discussed the concept of the inclusive classroom within these three domains. The combinations of search terms used in the literature search are presented in Table 2.

*Table 2: Search terms used for literature retrieval*

| Domain | Keywords |
|---|---|
| Inclusivity | "inclusive classroom" AND inclusivity |
| Inclusive Education | "inclusive classroom" AND "inclusive education" |
| Inclusive Design | "inclusive classroom" AND "inclusive design" & "inclusive classroom" AND "universal design" |

This alignment between the conceptual framework of the study and the search strategy helped ensure that the literature retrieved was relevant to the study's aim of examining how inclusive classrooms are conceptualised across different disciplinary contexts. A structured screening process was applied to identify relevant studies. The initial database search was conducted using predefined filters, including a publication time range (2015–2015), English language restriction, and full-text availability. This search generated 876 records. These records were imported into the screening process, and duplicates were first identified and removed (n = 6), resulting in 870 unique records. The remaining studies were then screened based on their titles and abstracts to assess relevance to inclusivity, inclusive education, inclusive design, and classroom environments. Studies that were clearly unrelated to the review focus were excluded at this stage, leaving 44 studies for full-text assessment. Full-text screening was then conducted, resulting in the exclusion of 8 studies in accordance with the predefined inclusion and exclusion criteria. In addition to database searching, 2 further relevant studies were identified through supplementary Google Scholar searching to enhance coverage of inclusive design literature and address potential limitations in database indexing and retrieval. Following full-text screening and supplementary inclusion, a total of 34 studies were retained for final synthesis in the integrative review.

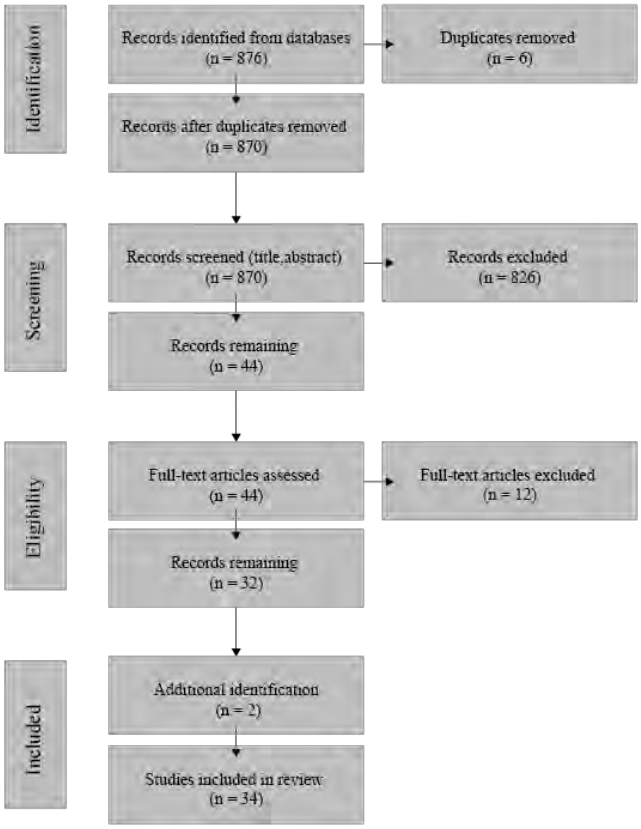



*Figure 1: Flow diagram for the process of article selection*

The selected studies were subsequently analysed using a thematic synthesis approach. The analysis followed an iterative, inductive–deductive coding process involving repeated reading, constant comparison, and cross-domain mapping of concepts across the inclusivity, inclusive education, and inclusive design literature. Codes were progressively refined and clustered to develop higher-order analytical themes that captured convergences and divergences in how inclusive classrooms are conceptualised. Through this process, themes were developed that captured dominant ways in which inclusive classrooms are conceptualised in relation to social participation, pedagogical practice, and spatial or environmental conditions. This thematic synthesis enabled the integration of insights from education and built environment scholarship, culminating in a cross-domain synthesis that informs a more holistic conceptualisation of the inclusive classroom as an interdependent social, pedagogical, and spatial system. The analytical process was conducted in five stages. First, initial coding was undertaken to identify recurring concepts related to inclusion within the selected studies. Second, similar codes were grouped into descriptive themes reflecting common patterns across the literature. Third, these descriptive themes were further synthesised into higher-order analytical themes that captured broader conceptualisations of the inclusive classroom. Fourth, relationships, tensions, and synergies between themes and domains were examined through cross-domain comparison. Finally, insights from these analyses informed the development of an integrated conceptual framework reconceptualising the inclusive classroom as a designed learning environment.

# 3. RESULTS

The thematic synthesis began with the identification of recurring concepts across the selected studies. These initial codes represent the key elements used to conceptualise inclusive classroom environments.

*Table 3: Initial coding matrix: Core concepts and conceptual definitions for the inclusive classroom*

| Initial Code | Conceptual Definition | Sources |
|---|---|---|
| Social reciprocity & peer interaction | The quality and frequency of relationships between students with special educational needs (SEN) and their peers. | (Soto-Icaza et al., 2025; Anđić et al., 2024; Cade, 2023) |
| Universal design for learning (UDL) | A proactive framework for curriculum and instructional design that assumes diversity from the outset. | (Sewell et al., 2022; Almutairi & Alsuwayl, 2023; Efstathiou & Varvarigou, 2025) |
| Technological mediation | The use of immersive tools (VR, AR), 3D printing, and AI as "enabling bridges" for learning and social connection. | (Molloy & Farrell, 2024; Anđić et al., 2024; Ntalindwa et al., 2022) |
| Architecture as "meaning-making" | The concept that school space communicates values of who is an "insider" or "outsider" | (Pasenidou, 2026; Buchner, 2021) |
| Teacher agency & efficacy | The confidence and competence of educators to re-organize space and instruction | (Wang et al., 2025; Olsson & Hansson, 2026) |
| Acoustic & visual "noise" | Physical environmental stressors (overcrowding, lighting, sound) that act as barriers to engagement | (Pasenidou, 2026; Olsson & Hansson, 2026) |
| Transformational leadership | The role of school leaders in "setting the tone" and fostering an inclusive school climate | (Wang et al., 2025; Pasenidou, 2026) |
| Child-centered pedagogy (GPBL) | Guided play-based learning as a strategy for holistic development | (Cade, 2023) |

The initial codes were subsequently grouped into four descriptive themes representing social, pedagogical, spatial, and systemic dimensions of inclusive classroom environments.

*Table 4: Descriptive themes*

| Descriptive Theme | Associated Initial Codes | Representative Sources |
|---|---|---|
| Value-based environment | Belonging, peer reciprocity, social interaction, worldview diversity | (Anđić et al., 2024; Bartz & Bartz, 2018; Bature et al., 2016; Cade, 2023; Chiu & Lim, 2020; Curry et al., 2024; Dere, 2018; Kocaj, 2025; Lindner & Schwab, 2025; Olsson & Hansson, 2026; Polat et al., 2024; Salas García & Rentería, 2024; Soto-Icaza et al., 2025) |
| Pedagogical and organisational space | UDL, differentiated instruction, guided play, immersive technology | (Bakogiannis, 2025; Efstathiou & Varvarigou, 2025; Moustache & Makhoba, 2024; Schnepel et al., 2020; Sewell et al., 2022; Tveitnes & Hvalby, 2024; Wang et al., 2025; Zeedyk et al., 2024) |
| Designed physical environment | Architecture, flexible furniture, acoustics | (Lundqvist, 2021; Pasenidou, 2026b) |
| A design system | Transformational leadership, school climate, teacher efficacy, policy | (Almutairi & Alsuwayl, 2023; Altakhaineh et al., 2026; Anđić et al., 2024; Deb et al., 2018; Diken et al., 2025; Molloy & Farrell, 2024; Ntalindwa et al., 2022; Özergun-Köse & İmer-Çetin, 2025; Sanger, 2020) |

The four conceptual categories were derived through iterative comparison of descriptive themes across the included studies. During coding, concepts related to belonging, participation, and diversity consistently clustered together, forming the category of the

inclusive classroom as a value-based environment. A second cluster centred on teaching strategies, curriculum adaptation, and classroom organisation, leading to the pedagogical and organisational space category. Concepts relating to architecture, accessibility, environmental conditions, and spatial organisation formed the designed physical environment category. Finally, studies emphasising leadership, policy, technology, and institutional support revealed a broader systemic dimension that extended beyond the classroom itself, resulting in the design system category. These categories were retained because they represented conceptually distinct yet interdependent dimensions that recurred consistently across the three domains.

### 3.1 INCLUSIVE CLASSROOM AS A VALUE-BASED ENVIRONMENT

Across the inclusivity domain, the inclusive classroom is primarily conceptualised as a value-based environment that promotes equity, belonging, and participation among learners. In this perspective, inclusion is not limited to physical placement within mainstream classrooms but involves creating learning environments in which all students feel respected, supported, and able to participate meaningfully in educational activities. Several studies emphasise that inclusive classrooms should remove barriers to participation and foster equitable learning opportunities for students with diverse backgrounds and abilities. Literature frequently highlights the importance of developing classroom cultures that recognise diversity as a valuable element of learning rather than as a challenge to be managed. Inclusive environments therefore encourage collaboration, peer interaction, and mutual respect among students (Anđić et al., 2024b; Cade, 2023; Curry et al., 2024; Lindner & Schwab, 2025; Olsson & Hansson, 2026; Salas García & Rentería, 2024; Soto-Icaza et al., 2025). Research also indicates that inclusive classrooms support learners' sense of belonging by integrating culturally responsive teaching practices and flexible participation opportunities. Such practices enable students to contribute through different modes of communication and engagement, reinforcing the principle that educational systems should adapt to learners rather than expecting learners to conform to rigid instructional structures (Curry et al., 2024; Díaz-Boladeras et al., 2025). Within this framing, the inclusive classroom is understood as a socially constructed environment shaped by shared values, relational trust, and supportive interactions. Inclusion is therefore achieved not only through structural arrangements but also through classroom cultures that promote equity, recognition of diversity, and collective participation. This perspective highlights that inclusive classroom design must consider social and relational aspects of learning environments. Spatial arrangements that encourage interaction, visibility, and collaboration may therefore play a role in supporting the values of belonging and participation emphasised in inclusivity literature.

### 3.2 INCLUSIVE CLASSROOM AS A PEDAGOGICAL AND ORGANISATIONAL SPACE

In contrast to the inclusivity perspective, literature within the inclusive education domain emphasises the pedagogical and organisational dimensions of the inclusive classroom. In this body of research, the classroom is viewed as a structured learning environment where teaching strategies, curriculum design, and institutional practices are intentionally adapted to support diverse learners. Several studies highlight the importance of differentiated instruction, curriculum flexibility, and collaborative learning strategies in enabling inclusive educational practices (Sewell et al., 2022; Tveitnes & Hvalby, 2024; Wang et al., 2025). These pedagogical approaches aim to address differences in learning

pace, learning styles, and cognitive needs while maintaining shared participation in classroom activities. For example, teachers may modify teaching methods, adjust instructional pacing, or provide individualized feedback in order to accommodate diverse learning profiles. The literature also emphasises that inclusive classrooms often rely on collaborative practices such as peer-assisted learning, group work, and cooperative problem-solving. These strategies enable students with and without special educational needs to learn together, supporting both academic development and social integration (Zeedyk et al., 2024) However, several studies highlight challenges in implementing inclusive pedagogy, particularly when teachers lack adequate training, resources, or institutional support. Teachers frequently report difficulties adapting curricula or addressing the diverse needs of students in mainstream classrooms, suggesting that effective inclusive education requires coordinated support across multiple levels of the education system (Moustache & Makhoba, 2024; Schnepel et al., 2020). Taken together, this body of literature conceptualises the inclusive classroom as a pedagogically designed environment where instructional strategies, classroom organisation, and teacher practices are adapted to support diverse learners. These findings suggest that classroom environments must be adaptable to support varied instructional strategies such as group work, differentiated instruction, and collaborative learning. Flexible spatial layouts and adaptable furniture may therefore be necessary to enable pedagogical approaches associated with inclusive education.

### 3.3 INCLUSIVE CLASSROOM AS A DESIGNED PHYSICAL ENVIRONMENT

The inclusive design domain introduces a spatial and environmental perspective to the understanding of inclusive classrooms. In this perspective, the classroom is conceptualised as a designed physical environment in which spatial arrangements, architectural features, and material resources influence participation and learning. Several studies emphasise that classroom design can either enable or constrain inclusion. Flexible classroom layouts, accessible circulation paths, and adaptable furniture arrangements are often identified as key design elements that support interaction and collaboration among students (Lundqvist, 2021; Ntalindwa et al., 2022; Pasenidou, 2026b). In addition to spatial layout, the literature highlights the role of environmental resources such as visual supports, sensory tools, and assistive technologies in facilitating participation. Visual schedules, pictograms, and structured classroom displays help students understand routines and expectations, thereby supporting engagement and reducing anxiety in learning environments (Deb et al., 2018; Diken et al., 2025; Ntalindwa et al., 2022). Research also suggests that classroom spaces can communicate institutional values and influence students' experiences of belonging. Architectural design and environmental organisation may therefore shape how students interact, move, and participate within learning environments (Díaz-Boladeras et al., 2025; Lundqvist, 2021; Pasenidou, 2026a). From this perspective, the inclusive classroom is not merely a setting in which learning occurs; rather, it is an actively designed environment that can enhance accessibility, interaction, and engagement for diverse learners. This perspective indicates that spatial design is not merely supportive but actively shapes how inclusive practices are enacted. Classroom layouts, circulation paths, and environmental resources can either enable or constrain the implementation of inclusive pedagogical strategies.

## 3.4 INCLUSIVE CLASSROOM AS A DESIGN SYSTEM

A further insight emerging from the literature is that inclusive classrooms function as part of a broader design system that includes institutional structures, policies, technologies, and professional practices. In this framing, the classroom is not viewed as an isolated environment but as a component within a wider network of educational supports. Several studies indicate that the successful implementation of inclusive classrooms depends heavily on institutional leadership, teacher training, and access to specialised resources (Almutairi & Alsuwayl, 2023; Altakhaineh et al., 2026; Molloy & Farrell, 2024). Many contexts, educators report limited access to assistive technologies, professional guidance, and specialised personnel, which constrains their ability to fully implement inclusive practices. (Deb et al., 2018; Diken et al., 2025; Ntalindwa et al., 2022). Similarly, research highlights gaps between inclusive education policies and classroom practice, suggesting that inclusion often remains accommodation-focused rather than design-oriented. Structural challenges such as limited training, resource constraints, and inconsistent policy implementation may therefore hinder the development of fully inclusive learning environments (Almutairi & Alsuwayl, 2023; Molloy & Farrell, 2024; Sanger, 2020).

This body of literature suggests that inclusive classrooms should be understood as socio-technical systems in which social values, pedagogical strategies, spatial environments, and institutional supports interact. Effective inclusion therefore requires coordinated design across these dimensions rather than isolated interventions at the classroom level. This systems perspective highlights that inclusive classroom depend on coordination between spatial design, institutional policy, technological resources, and teacher capacity. Inclusive learning environments therefore emerge not from isolated interventions but from integrated planning across educational and built environment systems. While the literature conceptualises inclusive classrooms through social, pedagogical, spatial, and systemic perspectives, the thematic synthesis revealed that these dimensions rarely operate independently. Instead, the findings suggest that inclusive classroom environments emerge through dynamic interactions between social relationships, pedagogical practices, spatial conditions, and institutional supports. Through analytical synthesis, four higher-order conceptual framings were developed that extend beyond individual domains and provide a more integrated understanding of the inclusive classroom as a designed learning environment.

*Table 5: Analytical themes and reconceptualization of the inclusive classroom*

| Analytical Theme | Reconceptualization Of the Classroom | Core Data Indicators |
|---|---|---|
| The Architecture of Capability | Space is viewed as a material force that validates a student's "right to be present" rather than a neutral container (Pasenidou, 2026b). | Barrier removal, "pedagogical places," and the rejection of spatialized ability grouping (Pasenidou, 2026b). |
| Technologically-Mediated Relationality | Digital tools act as "relational catalysts" that reverse traditional power dynamics between SEN students and peers (Anđić et al., 2024). | 3D printing, VR/AR, "co-creator" status, and social pride (Anđić et al., 2024; Molloy & Farrell, 2024). |
| Proactive Ecosystemic Design | A shift from "retrofitting" accommodations to strategic, anticipatory design where diversity is the baseline for space and curriculum (Sewell et al., 2022). | Universal Design for Learning (UDL), flexible seating, and cognitive accessibility (Almutairi & Alsuwayl, 2023; Sanger, 2020; Pasenidou, 2026). |
| Relational Systemic Enactment | Inclusion is a top-down and bottom-up flow where leadership acts as an "invisible hand" fostering teacher efficacy (Wang et al., 2025). | Transformational leadership, school climate, and psychological safety for educators (Wang et al., 2025). |

Although the four conceptualisations emerged from different disciplinary traditions, cross-domain comparison revealed important distinctions and complementarities. The inclusivity domain primarily emphasises social belonging, participation, and recognition of diversity, positioning inclusion as a relational and ethical process. In contrast, the inclusive education domain focuses on pedagogical and organisational mechanisms through which participation is enabled, including curriculum adaptation, differentiated instruction, and teacher practices. The inclusive design domain extends these perspectives by highlighting the role of spatial, sensory, and material conditions in shaping participation. While all three domains share a commitment to equitable access and participation, they differ in the primary mechanisms through which inclusion is enacted. Together, these perspectives demonstrate that inclusive classrooms cannot be understood solely through social, pedagogical, or spatial dimensions, but through the interaction of all three. Table 6 explores the "friction" where dimensions conflict and the "synergies" where they work in harmony, directly addressing the fragmented understanding of inclusion

*Table 6: Tensions in the inclusive classroom ecosystem*

| Tension | Evidence From the Literature |
|---|---|
| Pedagogical Intent vs. Spatial Rigidity | Teachers advocate for child-centered, play-based learning (GPBL), but are physically restricted by factors like "overcrowding," "visual noise" from classroom displays, and "background noise" that negatively impacts concentration (Pasenidou, 2026; Olsson & Hansson, 2026). |
| Legal Presence vs. Social Reciprocity | Inclusion policies (IDEA/LRE) guarantee physical placement, but "integration rooms" and a "spatialized version of ability grouping" often construct students as "outsiders" who are physically present but socially isolated from their peers (Pasenidou, 2026; Tveitnes & Hvalby, 2024). |
| Policy vs. Environmental Implementation | Inclusion is "approved and valued" in high-level policy, but yet remains unimplemented because the materiality of the classroom (e.g., stairs, inaccessible washrooms, or inflexible seating) remains hostile to diversity, a state of being "just not right here" (Pasenidou, 2026). |

Cross-domain analysis revealed that the three domains do not always operate harmoniously. While all advocate inclusion, they often prioritise different aspects of the classroom environment, creating tensions in practice. For example, inclusive education promotes differentiated and collaborative pedagogies, yet inclusive design literature demonstrates that rigid classroom layouts and environmental barriers may restrict the implementation of such approaches. Similarly, policies supporting inclusion may guarantee access, while learners continue to experience exclusion through social or spatial barriers. These contradictions highlight the limitations of viewing inclusion through a single disciplinary lens and reinforce the need for a more integrated understanding of inclusive classroom environments.

*Table 7: Synergies in the inclusive classroom ecosystem*

| Synergies | Evidence From the Literature |
|---|---|
| Flexible Space & Differentiated Pedagogy | High accessibility to "group rooms" (breakout spaces) and flexible furniture acts as a prerequisite for differentiated lessons, empowering teachers to move from teacher-centered to "accessible pedagogies" that support student agency (Pasenidou, 2026; Olsson & Hansson, 2026). |
| Digital Scaffolding & Shared Pride | 3D printing and immersive VR create "enabling spaces" where students with disabilities shift from being knowledge "consumers" to "co-creators". This reverses traditional power |

| Synergies | Evidence From the Literature |
|---|---|
| | dynamics, fostering social pride and allowing students to lead peer interactions (Anđić et al., 2024; Molloy & Farrell, 2024). |

The "friction" identified in the literature suggests that when pedagogical goals are pursued without corresponding spatial adaptations, the result is often teacher burnout and student disengagement. For instance, even when inclusive values are held by staff, a "chaotic and unsafe" physical structure can undermine the development of a supportive learning community. Conversely, the identified "synergies" demonstrate how technology and architecture can act as relational catalysts. Ultimately, these interactions prove that access, participation, and belonging are co-constructed across the social, pedagogical, and spatial dimensions. The diagram in the Figure 2 serves as the culmination of the thematic synthesis, visually mapping the interdependencies between the social, pedagogical, spatial, and institutional dimensions of the inclusive classroom.

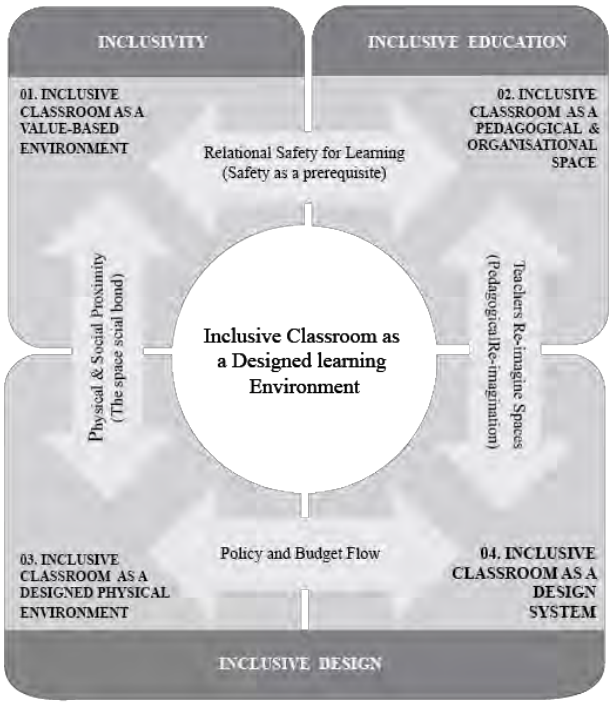



*Figure 2: Illustrates the integrated conceptual framework developed through the literature synthesis*

Figure 2 presents the integrated conceptual framework developed through the thematic synthesis. The framework positions the inclusive classroom as a designed learning environment emerging through the interaction of four interdependent dimensions: social, pedagogical, spatial, and institutional. The social dimension reflects belonging, participation, and relational engagement; the pedagogical dimension encompasses teaching practices, curriculum adaptation, and learning support; the spatial dimension relates to accessibility, environmental design, and material resources; and the institutional dimension includes leadership, policy, technology, and organisational support. The framework illustrates that inclusive classroom environments are not produced by any single dimension in isolation. Rather, inclusion emerges through the dynamic relationships between these dimensions, where strengths or weaknesses in one area influence the effectiveness of the others. The model therefore provides a holistic representation of how inclusive classroom environments are created and sustained.

## 4. CONCLUSIONS

This study examined how the inclusive classroom is conceptualised across the domains of inclusivity, inclusive education, and inclusive design. Through an integrative literature review of 34 studies, four conceptualisations were identified: the inclusive classroom as a value-based environment, a pedagogical and organisational space, a designed physical environment, and a design system. The thematic synthesis further integrated these perspectives into four higher-order analytical framings: Architecture of Capability, Technologically-Mediated Relationality, Proactive Ecosystemic Design, and Relational Systemic Enactment. Collectively, these framings demonstrate that inclusive classrooms are best understood as designed learning environments shaped through the interaction of social, pedagogical, spatial, technological, and institutional dimensions. The study contributes an integrated conceptual perspective that moves beyond fragmented disciplinary understandings of inclusion. The findings have practical implications for multiple stakeholder groups. For educators, the framework highlights the importance of aligning pedagogical strategies with opportunities for participation, collaboration, and learner diversity. For designers and built environment professionals, the findings emphasise that classroom layouts, environmental conditions, accessibility features, and spatial flexibility should be considered integral components of inclusive practice rather than supplementary design considerations. For policymakers and school leaders, the framework underscores the need for coordinated investment in teacher development, assistive technologies, institutional support systems, and inclusive design standards. The proposed framework may also serve as an evaluative tool for examining existing classroom environments or as a guide for the planning and development of new learning spaces. Future research should apply and test the framework within real educational settings to examine how interactions between social, pedagogical, spatial, and institutional dimensions influence learner participation, engagement, and educational outcomes.

## 5. REFERENCES

Ainscow, M. (2020). Promoting inclusion and equity in education: Lessons from international experiences. *Nordic Journal of Studies in Educational Policy*, *6*(1), 7–16. https://doi.org/10.1080/20020317.2020.1729587

Almutairi, N., & Alsuwayl, A. (2023). Assessing the knowledge of elementary school teachers on universal design for learning in Saudi Arabia. *Cogent Education*, *10*(2), 2270295. https://doi.org/10.1080/2331186X.2023.2270295

Altakhaineh, A. R. M., Alkhatib, R. N., & Awad, T. (2026). Integrating artificial intelligence to enhance inclusive education for students with special needs in Jordan and the UAE: Perspectives of teachers and parents. *Acta Psychologica*, *263*, 106252. https://doi.org/10.1016/j.actpsy.2026.106252

Anđić, B., Lavicza, Z., Vučković, D., Maričić, M., Ulbrich, E., Cvjetićanin, S., & Petrović, F. (2024). The effects of 3D printing on social interactions in inclusive classrooms. *International Journal of Disability, Development and Education*, *71*(6), 883–907. https://doi.org/10.1080/1034912X.2023.2223495

Bakogiannis, A. (2025). Inclusivity in focus: Reimagining competency frameworks. *Journal of Learning Development in Higher Education*, (36). https://doi.org/10.47408/jldhe.vi36.1511

Bartz, J., & Bartz, T. (2018). Recognizing and Acknowledging Worldview Diversity in the Inclusive Classroom. *Education Sciences*, *8*(4), 196. https://doi.org/10.3390/educsci8040196

Bature, I. J., Atweh, B., & Treagust, D. (2016). Inclusivity: An Effective Tool for Achieving Quality Mathematics Classroom Instruction in Nigerian Secondary Schools. *Universal Journal of Educational Research*, *4*(1), 173–180. https://doi.org/10.13189/ujer.2016.040122

Booth, T., & Ainscow, M. (2016). *The index for inclusion: A guide to school development led by inclusive values* (Fourth edition). Index for Inclusion Network.

Buchner, T. (2021). The Special School as 'Natural Habitat'? on the persistence of segregated education of students with intellectual disabilities. *On Education Journal for Research and Debate, 4*(11). https://doi.org/10.17899/on_ed.2021.11.8

Cade, J. (2023). Child-centered pedagogy: Guided play-based learning for preschool children with special needs. Cogent Education, 10(2), 2276476. https://doi.org/10.1080/2331186X.2023.2276476

Carney, S. (2022). Reimagining our futures together: A new social contract for education: *Comparative Education*, *58*(4), 568–569. https://doi.org/10.1080/03050068.2022.2102326

Chiu, T. K. F., & Lim, C. P. (2020). Strategic use of technology for inclusive education in Hong Kong: A content-level perspective. *ECNU Review of Education*, *3*(4), 715–734. https://doi.org/10.1177/2096531120930861

Curry, K. A., Olsen, J., Harris, E., Garnett, C., & Danderson, D. (2024). Inclusive settings in Belizean primary schools: A focus on teacher practices. *Journal of Global Education and Research, 8*(1), 1–18. https://doi.org/10.5038/2577-509X.8.1.1263

Deb, S., Suraksha, & Bhattacharya, P. (2018). Augmented Sign Language Modeling (ASLM) with Interaction design on smartphone—an assistive learning and communication tool for inclusive classroom. *Procedia Computer Science*, *125*, 492–500. https://doi.org/10.1016/j.procs.2017.12.064

Dere, Z. (2018). Analyzing social play and social interaction of a child with Autism spectrum disorder in the inclusive kindergarten education. *European Journal of Special Education Research, 3*(4). https://doi.org/10.5281/ZENODO.1470789

Díaz-Boladeras, M., Claver I Díaz, A., & García-Sánchez, M. (2025). Robots for inclusive classrooms: A scoping review. *Universal Access in the Information Society*, *24*(1), 127–151. https://doi.org/10.1007/s10209-023-01065-z

Diken, İ. H., Kürüm Yapıcıoğlu, D., Çelik Demirtaş, S., Kalaycı, G. Ö., Kalaycı, C., Sinoğlu Günden, T., Günden, U. O., Toper, Ö., Diken, Ö., Onur Sezer, G., & Çuhadar, C. (2025). Exploring primary school teachers' perspectives on behavioral problems and speech and language difficulties of their students in inclusive classrooms: Experience-based insights and technology-based resource needs in Turkey. International Technology and Education Journal, 9(1), 14–33. https://doi.org/10.71410/ESApub.ITEJ.2025.2

Efstathiou, R., & Varvarigou, M. (2025). How inclusive are our music classrooms? A theoretical model and case study from a preschool class of a mainstream private nursery school in Cyprus. *Music Education Research*, *27*(2), 148–162. https://doi.org/10.1080/14613808.2025.2454646

Florian, L. (2014). What counts as evidence of inclusive education? *European Journal of Special Needs Education*, *29*(3), 286–294. https://doi.org/10.1080/08856257.2014.933551

Kocaj, A. (2025). Relationships between the inclusion of students with special educational needs and their classmates' school outcomes – a replication study. *Contemporary Educational Psychology*, *83*, 102426. https://doi.org/10.1016/j.cedpsych.2025.102426

Lindner, K.-T., & Schwab, S. (2025). Differentiation and individualisation in inclusive education systematic review and narrative synthesis. *International Journal of Inclusive Education*, *29*(12), 2199–2219. https://doi.org/10.1080/13603116.2020.1813450

Lundqvist, J. (2021). Ways to implement preschool inclusion: A multiple-case study. *International Journal of Educational Research Open*, *2*, 100097. https://doi.org/10.1016/j.ijedro.2021.100097

Molloy, C., & Farrell, R. (2024). Cultivating Positive Classroom Environments: Exploring the Efficacy of Immersive Technologies in Removing Barriers to Learning Among Primary School Students. Computers in the Schools, 41(2), 164–192. https://doi.org/10.1080/07380569.2024.2325441

Moustache, H. M. T. E., & Makhoba, M. (2024). Educators' experiences of teaching learners with hearing loss in inclusive classrooms. *South African Journal of Childhood Education*, *14*(1). https://doi.org/10.4102/sajce.v14i1.1358

Ntalindwa, T., Nduwingoma, M., Uworwabayeho, A., Nyirahabimana, P., Karangwa, E., Rashid Soron, T., Westin, T., Karunaratne, T., & Hansson, H. (2022). Adapting the Use of Digital Content to Improve the Learning of Numeracy Among Children With Autism Spectrum Disorder in Rwanda: Thematic Content Analysis Study. *JMIR Serious Games*, *10*(2), e28276. https://doi.org/10.2196/28276

Olsson, Å., & Hansson, S. (2026). Designing for diversity: Teachers' strategies for creating inclusive learning environments. *Learning Environments Research*, *29*(1), 2. https://doi.org/10.1007/s10984 025-09561-0

Özergun-Köse, I., & İmer-Çetin, N. (2025). Identifying the needs of middle school students with autism for an interactive e-book designed to improve their sustainable development awareness: Insights from teachers' perspectives. *Discover Education*, *4*(1), 412. https://doi.org/10.1007/s44217-025-00804-z

Pasenidou, F. (2026a). The emerging intersection: The role of architecture in promoting inclusive education. *Oxford Review of Education*, *52*(1), 79–95. https://doi.org/10.1080/03054985.2024.2427041

Polat, E., CepdiBi Sibiç, S., CiRiT, N. C., Hopcan, S., & Baştuğ, Y. E. (2024). Educational technology in inclusive classrooms: Assessing teacher awareness and needs. *Journal of Educational Technology and Online Learning*, *7*(1), 116–131. https://doi.org/10.31681/jetol.1355239

Salas García, V. B., & Rentería, J. M. (2024). Students with special educational needs in regular classrooms and their peer effects on learning achievement. *Humanities and Social Sciences Communications*, *11*(1), 521. https://doi.org/10.1057/s41599-024-03002-8

Sanger, C. S. (2020). Inclusive Pedagogy and Universal Design Approaches for Diverse Learning Environments. In C. S. Sanger & N. W. Gleason (Eds.), *Diversity and Inclusion in Global Higher Education* (pp. 31–71). Springer Singapore. https://doi.org/10.1007/978-981-15-1628-3_2

Schnepel, S., Krähenmann, H., Sermier Dessemontet, R., & Moser Opitz, E. (2020). The mathematical progress of students with an intellectual disability in inclusive classrooms: Results of a longitudinal study. *Mathematics Education Research Journal*, *32*(1), 103–119. https://doi.org/10.1007/s13394-019-00295-w

Sewell, A., Kennett, A., & Pugh, V. (2022). Universal Design for Learning as a theory of inclusive practice for use by educational psychologists. *Educational Psychology in Practice*, *38*(4), 364–378. https://doi.org/10.1080/02667363.2022.2111677

Soto-Icaza, P., Oyarzun, M., Yaikin, T., Arcos-Polanco, M., Candia, C., Rodríguez-Sickert, C., & Billeke, P. (2025). Autism shapes social integration and reciprocity in elementary classrooms. *Scientific Reports*, *15*(1), 40473. https://doi.org/10.1038/s41598-025-24190-6

Tveitnes, M. S., & Hvalby, M. (2024). Mentoring Novice Teachers in a Norwegian Context of Inclusive Education. *Teachers and Teaching*, *30*(1), 71–84. https://doi.org/10.1080/13540602.2023.2225442

Wang, T., Deng, M., & Tian, G. (2025). Facilitating teachers' inclusive education intentions: The roles of transformational leadership, school climate, and teacher efficacy. *Humanities and Social Sciences Communications*, *12*(1), 636. https://doi.org/10.1057/s41599-025-04977-8

Whittemore, R., & Knafl, K. (2005). The integrative review: updated methodology. *Journal of Advanced Nursing*, *52*(5), 546–553. https://doi.org/10.1111/j.1365-2648.2005.03621.x

Zeedyk, S. M., Cohen, S. R., Blacher, J., & Eisenhower, A. (2024). Building classroom communities for children with autism spectrum disorder. *International Journal of Inclusive Education*, *28*(7), 1093–1107. https://doi.org/10.1080/13603116.2021.1978002

Menike, G.R.K.A.G. and Perera, K., 2026. Regional identity and regenerative architecture: Reinterpreting Buddhist philosophy in contemporary built environments. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1414-1426. DOI: https://doi.org/10.31705/WCS.2026.103. Available from: https://ciobwcs.com/papers/

# REGIONAL IDENTITY AND REGENERATIVE ARCHITECTURE: REINTERPRETING BUDDHIST PHILOSOPHY IN CONTEMPORARY BUILT ENVIRONMENTS

**G.R.K.A.G. Menike[1] and K. Perera[2]**

## *ABSTRACT*

*The contemporary architectural discourse increasingly emphasizes the need for regenerative approaches that reconnect the built environment with cultural identity, environmental responsibility, and social wellbeing. However, many modern architectural developments continue to prioritize visual image and symbolic representation over philosophical and contextual meaning. This tendency is particularly visible in contemporary Buddhist architecture, where monumental and visually grand structures often contradict the philosophical teachings of Buddhism that emphasize humility, simplicity, and non-attachment to material possessions. This research investigates how Buddhist philosophical principles can inform regenerative architectural thinking within the Sri Lankan context. Drawing from the concept of regionalizing modernism, the study explores how philosophical interpretations of Buddhist teachings can contribute to contemporary architectural design strategies that move beyond purely aesthetic expression. The research adopts a design-based methodology and examines the conceptual development of a proposed Centre for Buddhist Philosophy located in Kandy, Sri Lanka. The project proposes two architectural components a Promotional Centre located near the Temple of the Sacred Tooth Relic and a Knowledge Centre within the Malwatta Temple complex. The design intentionally challenges image driven religious architecture by emphasizing flexible spatial organization, reuse of materials, and the philosophical interpretation of Buddhist values such as impermanence, simplicity, and sustainability. The findings suggest that regional philosophical frameworks can contribute to regenerative architectural strategies that extend beyond conventional sustainability practices. By integrating cultural philosophy, environmental responsiveness, and adaptable construction systems, architecture can promote intellectual engagement, spiritual reflection, and resilient built environments.*

***Keywords:*** *Architectural Modernity; Buddhist Philosophy; Cultural Sustainability; Regenerative Architecture; Regional Identity.*

[1] Graduate Architect, Department of Architecture, University of Moratuwa, Sri Lanka,kamasaranigamlath@gmail.com
[2] Senior Lecturer, Chartered Architect, Department of Architecture, University of Moratuwa, Sri Lanka,kolithaperera@uom.lk

# 1. INTRODUCTION

Architecture plays a significant role in shaping cultural, social, and environmental relationships within the built environment. In recent decades, the concept of regenerative architecture has emerged as a critical framework that moves beyond traditional sustainability approaches by seeking to restore ecological and cultural relationships within architectural practice.

Despite this growing emphasis on regenerative design, many contemporary architectural developments continue to adopt globalized aesthetic models that often neglect regional identity, cultural values, and philosophical traditions. This phenomenon is particularly visible in the architecture of religious institutions, where visual symbolism and monumental expression frequently dominate architectural production.

In the Sri Lankan context, Buddhist religious architecture has historically reflected philosophical values of simplicity, humility, and spiritual reflection. However, contemporary Buddhist buildings increasingly display an emphasis on grandeur, material richness, and symbolic imagery. This tendency creates a contradiction between the architectural expression of Buddhist buildings and the philosophical teachings of Buddhism, which emphasize detachment from material possessions and the cultivation of intellectual and spiritual awareness.

This contradiction raises an important architectural question: how can contemporary architecture reinterpret Buddhist philosophy to produce built environments that support intellectual engagement and spiritual reflection rather than material representation?

The architectural discourse in Sri Lanka has previously explored the relationship between modernism and regional identity through the work of architects such as Geoffrey Bawa and Minnette de Silva. Their work demonstrates how modern architectural principles can be adapted to local climatic and cultural conditions (De Silva, 1998; Bawa & Robson, 2002).

Building on these ideas, this research explores the possibility of regionalizing modern architecture through Buddhist philosophical interpretation. The study investigates how philosophical principles derived from Buddhist teachings can inform architectural design strategies that contribute to regenerative built environments.

To explore this question, the research examines the conceptual development of a proposed Centre for Buddhist Philosophy located in the historic city of Kandy, Sri Lanka. The project serves as an architectural experiment that seeks to reinterpret modern architectural language through philosophical and cultural frameworks.

This research argues that Buddhist philosophy provides a framework through which modernist architectural principles can be regionally reinterpreted. By translating philosophical concepts into architectural strategies, the study explores how regional identity can contribute to regenerative architectural thinking. The proposed Centre for Buddhist Philosophy is therefore examined not simply as a design project, but as a means of investigating the relationship between philosophy, regional identity, and regenerative architecture.

# 2. LITERATURE REVIEW

## 2.1 REGIONAL MODERNISM IN SRI LANKA

Geoffrey Bawa, Minnette de Silva, and Valentine Gunasekara are among the key architects who contributed to the regional adaptation of modern architecture in Sri Lanka. Their work demonstrated how modernist principles could be reconciled with local climate, landscape, materiality, and cultural traditions (de Silva, 1998; Bawa & Robson, 2002; Pieris, 2021). While these approaches successfully regionalized modern architecture through environmental and cultural responsiveness, they largely remained within the formal and spatial language of modernism. This study differs by exploring the regionalization of modernism through Buddhist philosophical principles rather than through environmental adaptation alone.

## 2.2 REGIONALISM AND ARCHITECTURAL IDENTITY

Modernism remains relevant in contemporary architectural discourse because it encourages critical questioning and openness to new ideas. Its emphasis on innovation and the challenge of traditional norms continues to influence fields such as art, literature, design, and architecture (Frampton, 1980). Modernism is fundamentally grounded in rational, scientific, and liberal thinking, emphasizing reason and logical understanding in shaping the built environment.

Interestingly, Buddhist philosophy shares similar intellectual characteristics. Both modernist thought and Buddhist teachings value rationality, critical reflection, and a disciplined approach to understanding the world (McMahan, 2009).

In architecture, rationality plays a crucial role as it ensures that design decisions respond to functional, environmental, and social needs rather than purely aesthetic considerations.

Within modernist architectural theory, aesthetic form is considered secondary to the underlying ideology and functional logic of design. Building on this understanding, this research attempts to reinterpret modernism through Buddhist philosophical principles. Rather than being limited by the formal aesthetics of modern architecture, Buddhist principles are used to regionalize and transform modernist rationality into a philosophically grounded architectural approach.

By moving beyond the traditional aesthetic limitations of modern architecture, architecture can shift its focus from the visual “image” of buildings toward their performance and contextual relevance. In this sense, architecture should respond to purpose, technology, economy, and socio-cultural conditions rather than purely visual expression. To truly regionalize modernism, architectural thinking must engage with cultural, material, construction, labor, and environmental contexts (Frampton, 1983).

Modern architecture emerged during the twentieth century as a response to industrialization, technological development, and social transformation. While modernism introduced new construction technologies and spatial concepts, it often promoted universal architectural principles that neglected local cultural contexts (Frampton, 1980).

In response to this limitation, architectural theorists introduced the concept of critical regionalism, which encourages architects to reinterpret modern architecture through local environmental, cultural, and material conditions (Frampton, 1983). Critical regionalism

advocates for architectural practices that resist the homogenizing effects of globalization by engaging with regional identity and cultural traditions.

In Sri Lanka, modern architecture evolved through a process of adaptation rather than direct imitation of Western modernism. The architectural work of Geoffrey Bawa demonstrates how modern architecture can integrate tropical climate responsiveness, landscape relationships, and local craftsmanship while maintaining modernist spatial concepts (Bawa & Robson, 2002).

Similarly, Minnette de Silva emphasized the importance of integrating local culture, climate, and craftsmanship into architectural design. Her work represents an early attempt to reinterpret modern architecture through regional identity (de Silva, 1998).

These architectural approaches illustrate that modern architecture can evolve through regional reinterpretation rather than strict adherence to universal aesthetic principles.

Unlike previous regional modernist approaches that primarily adapted climate, landscape, and materiality, this study explores the regionalization of modernism through philosophical and ideological interpretation. Rather than focusing solely on environmental adaptation, the research investigates how Buddhist thought can serve as a conceptual framework for shaping contemporary regenerative architecture.

### 2.3 BUDDHIST PHILOSOPHY AND ARCHITECTURAL SPACE

Buddhist philosophy offers a unique perspective on the relationship between materiality, space, and human experience. Central Buddhist teachings emphasize concepts such as impermanence, non-attachment, mindfulness, and simplicity. These principles encourage a deeper understanding of the relationship between individuals, materials, and the environment.

Within Buddhist architectural traditions, simplicity is not merely an aesthetic preference but a philosophical position. The reduction of excessive ornamentation can be understood as a means of minimizing distraction and encouraging contemplation, reflection, and awareness.

Buddhist environments have historically accommodated activities such as meditation, dialogue, learning, and reflection. In this sense, architectural space functions not only as physical shelter but also as a medium that supports intellectual and spiritual engagement.

Contemporary interpretations of Buddhism have highlighted its rational and reflective dimensions, reinforcing its relevance within modern intellectual discourse (McMahan, 2009).

These theoretical perspectives suggest that architecture informed by Buddhist philosophy can contribute to regenerative architectural thinking by promoting mindful relationships between people, materials, and environments.

## 3. METHODOLOGY

This research adopts a Design-Based Research (DBR) methodology that combines theoretical investigation with architectural experimentation. DBR is an established research approach widely used in architecture and design disciplines because it enables theoretical concepts to be tested through design interventions and spatial experimentation. Through iterative processes of analysis, conceptual translation, and design development,

the methodology allows architectural knowledge to be generated through the act of designing itself.

The Centre for Buddhist Philosophy examined in this study is a conceptual architectural proposal developed as an academic design thesis and has not been constructed. The project is therefore used as a speculative design case study to explore how Buddhist philosophical principles can inform regenerative architectural thinking.

The research methodology consists of three main stages:

1. **Theoretical investigation** of regional modernism and Buddhist philosophy within architectural discourse.
2. **Conceptual translation** of philosophical principles into architectural design strategies.
3. **Architectural experimentation** through the development of a design proposal for a Centre for Buddhist Philosophy.

The three stages are interconnected. The theoretical investigation established the conceptual foundation of the study, the conceptual translation stage transformed Buddhist philosophical ideas into architectural principles, and the architectural experimentation stage tested these principles through the proposed design intervention.

The architectural project used as the primary case study for this research is the proposed Centre for Buddhist Philosophy located in Kandy, Sri Lanka. The project explores how spatial organization, material strategies, and architectural language can reflect Buddhist philosophical principles while responding to regional cultural and environmental contexts.

The framework for this research is partially derived from the philosophical meaning embedded in the Buddhist monk's robe. Historically, discarded cloth used to wrap deceased bodies was collected from forests or burial grounds, cleaned, and carefully stitched together by monks to create their robes. These robes were assembled from irregular fragments of fabric and therefore did not follow a predetermined pattern. Instead, the stitching process produced an organic composition resembling the layout of cultivated paddy fields.

This practice reflects several core Buddhist teachings, particularly the ideas of non-attachment, impermanence, and humility in material use. Although the robe becomes the only personal possession of a monk, its origin from discarded materials emphasizes the absence of material value and the importance of understanding its philosophical meaning.

Drawing from this principle, the research interprets the robe as a conceptual model for architectural thinking. The design approach derives architectural strategies from this practice of assembling humble and reused materials into meaningful compositions. Through this interpretation, architectural form is not predetermined by aesthetic intention but emerges through processes of material collection, assembly, and contextual response.

Four guiding principles derived from Buddhist philosophical interpretation informed the design process:

1. Removal of strong visual clarity and symbolic architectural form.
2. Alternative methods for sourcing building materials and construction components.
3. Flexible and fluid material assemblies that encourage intellectual interpretation.
4. Sustainable reuse and lifecycle adaptability of building components.

These principles form the conceptual framework for translating philosophical ideas into architectural design strategies.

The design principles adopted in this study were not arbitrarily selected but were derived from Buddhist philosophical teachings discussed within existing literature on Buddhist aesthetics, materiality, impermanence, and non-attachment (McMahan, 2009). The resulting architectural strategies therefore emerge from a synthesis of theoretical literature and design exploration rather than solely from the author's personal interpretation.

The framework functions as the primary analytical structure of the research. It demonstrates how Buddhist philosophical principles are translated into architectural strategies and subsequently evaluated through the proposed design intervention. In this way, the framework establishes a direct relationship between theory, design development, and architectural outcomes.

# 4. CENTRE FOR BUDDHIST PHILOSOPHY

The proposed Centre for Buddhist Philosophy is located in the historic city of Kandy in central Sri Lanka. Kandy is recognized as a UNESCO World Heritage city and serves as one of the most significant Buddhist cultural centers in the country.

## 4.1 DESIGN STRATEGY: FROM PROMOTIONAL CENTRE TO KNOWLEDGE CENTRE

The design methodology adopts a spatial strategy that moves from provocation to reflection through two interconnected architectural interventions: the Promotional Centre and the Knowledge Centre. These two components are located at two culturally significant Buddhist sites in Kandy: The Temple of the Sacred Tooth Relic and the Malwatta Temple complex. Together, they function as complementary spaces that support intellectual dialogue, philosophical exploration, and spiritual reflection.

The proposed intervention intentionally contrasts with the highly ornamented architectural language of surrounding Buddhist structures. While existing buildings rely on symbolic imagery, decorative craftsmanship, and monumentality, the proposed architecture adopts a restrained language emphasizing material honesty, incompleteness, adaptability, and philosophical reflection.

## 4.2 PROMOTIONAL CENTRE

*Figure 1: Promotional centre at the Temple of the Sacred Tooth Relic*

The first intervention, the Promotional Centre, is located near the Temple of the Sacred Tooth Relic, one of the most visually saturated and symbolically monumental religious environments in Kandy. The architectural language of this site is characterized by strong imagery, ornamentation, gold surfaces, crafted columns, and monumental forms. In deliberate contrast to this context, the proposed building is conceived as a modest and almost hutlike structure constructed from donated, reused, and locally available materials. This contrast is intentional. After passing through golden gateways and highly ornamental architecture, visitors encounter a structure that appears raw, incomplete, and materially unresolved. This visual rupture is designed to provoke immediate questioning: the building does not communicate through symbolic form but instead initiates inquiry. In this sense, architecture becomes a question rather than a finished visual statement.

*Figure 2: Knowledge centre at the Malwatta temple complex*

The structure avoids a fixed architectural image. Materials are assembled according to availability, resulting in a heterogeneous composition in which some areas remain uncovered while others are enclosed using improvised material solutions. This condition intentionally reflects Buddhist teachings related to impermanence, non-attachment, and the transient nature of material existence.

All spaces within the Promotional Centre are intentionally informal, adaptable, and convertible. Spatial arrangements are designed to change depending on use and activity rather than remaining permanently fixed. The ground level functions as an exhibition space that can easily transform into a Dharma discussion area. Upper levels accommodate different scales of intellectual exchange, including indoor and outdoor discussions as well as spaces for both individual and group engagement.

*Figure 3: Convertible Dharma discussion area/Exhibition area*

Meditation spaces within the building are intentionally minimal and sometimes physically challenging rather than comfortable. This design decision reflects the philosophical idea that understanding and spiritual growth require effort and discipline. In certain areas, the building remains intentionally incomplete in Knowledge Centre due to the reliance on donated and reclaimed materials. As a result, environmental conditions such as rain or wind may occasionally affect interior spaces. Users must directly experience these conditions while occupying the building, reinforcing the idea that the search for truth requires endurance, dedication, and awareness.

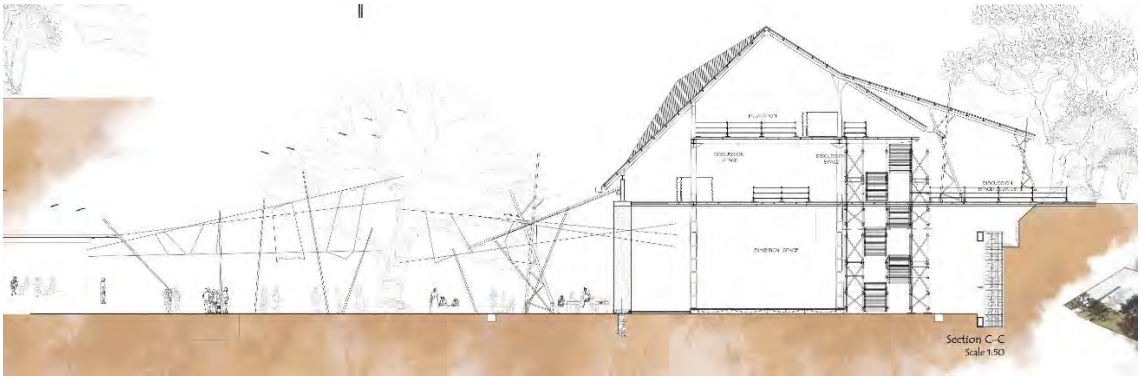



*Figure 4: Cross-section of the promotional centre at the Temple of the Sacred Tooth Relic*

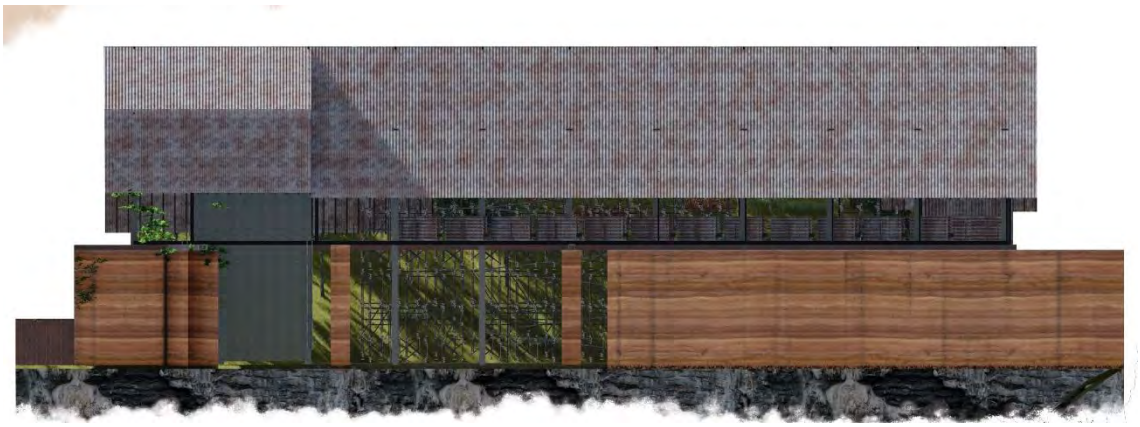


*Figure 5: Front elevation of the promotional centre at the Temple of the Sacred Tooth Relic*

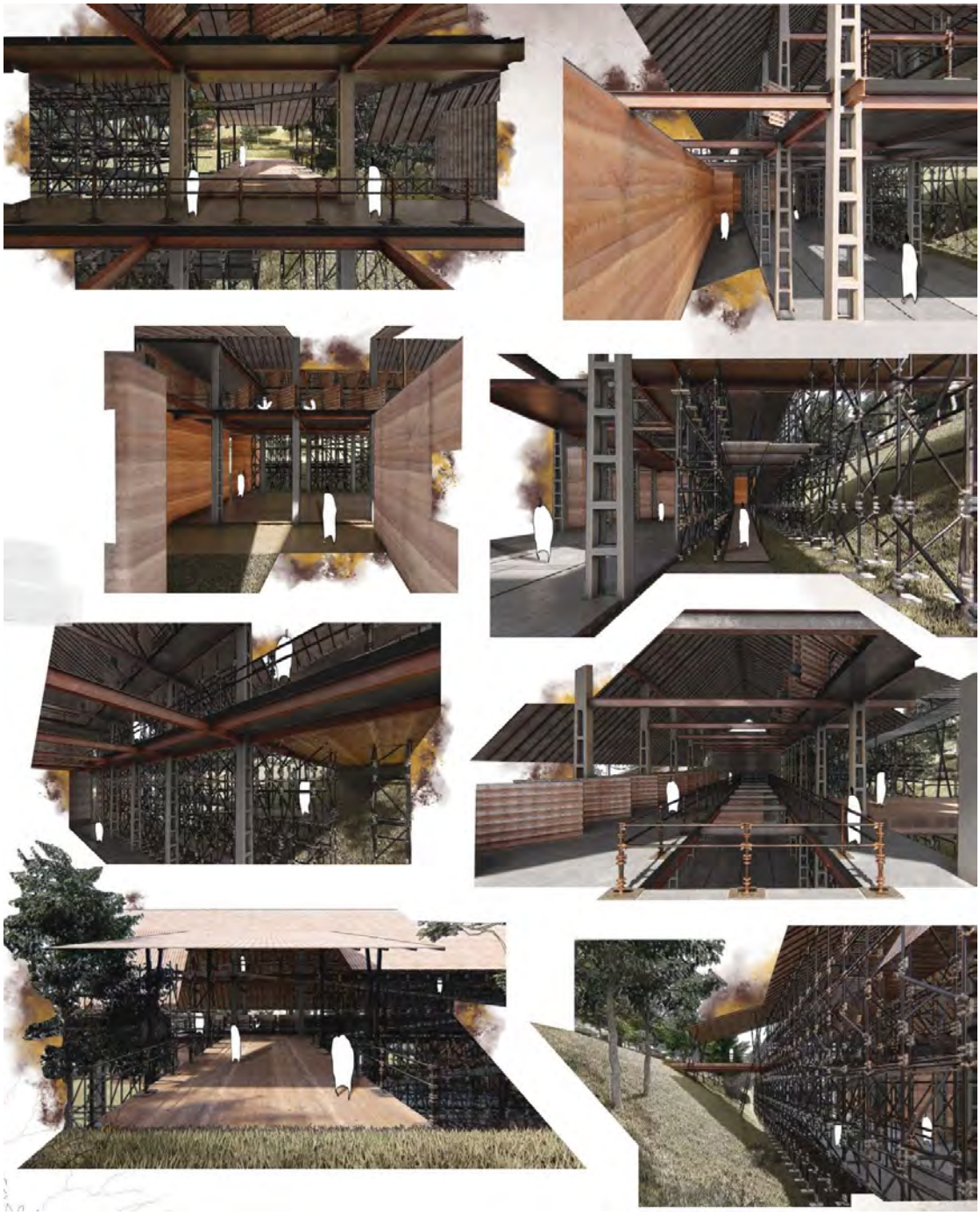


*Figure 6: Spaces of the promotional centre at the Temple of the Sacred Tooth Relic*

The Promotional Centre therefore functions as the entry point of the architectural journey. It provokes curiosity and initiates philosophical dialogue. Individuals who wish to explore these ideas more deeply are then guided toward the second architectural intervention: the Knowledge Centre located within the Malwatta Temple complex.

## 4.3 KNOWLEDGE CENTRE

The Knowledge Centre represents the second stage of engagement and provides a more structured environment for learning. Rather than replacing existing educational functions, the building strengthens them. Weekday tuition classes currently conducted on the site continue to operate within the new structure and transform into Sunday school programs during weekends, maintaining continuity with existing educational practices.

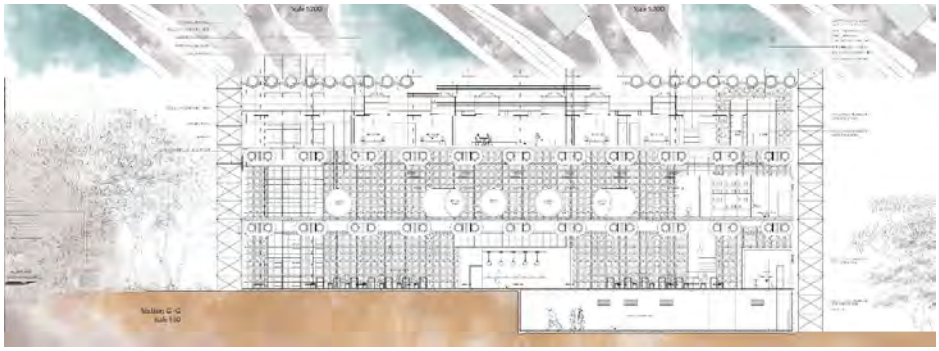


*Figure 7: Long section of the knowledge centre at the Malwatta temple complex*

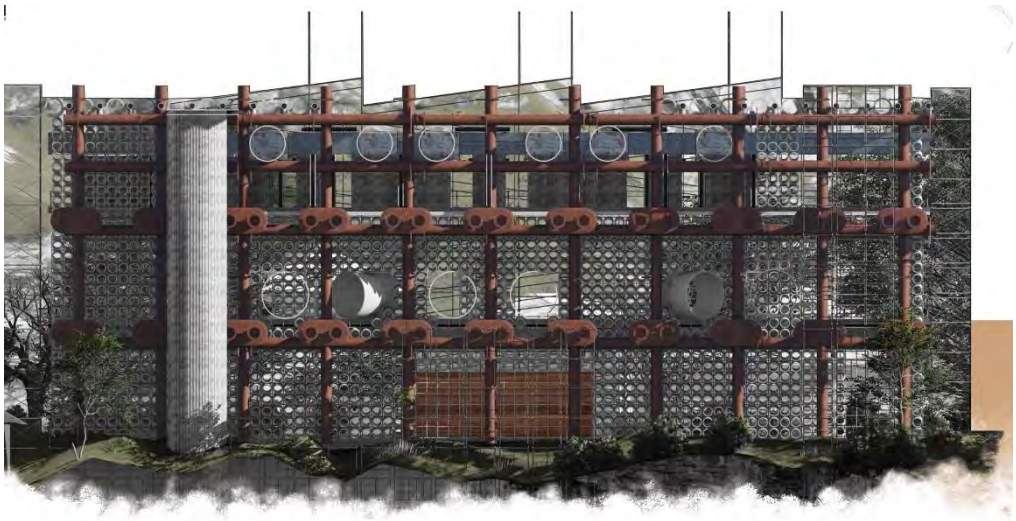


*Figure 8: Front elevation of the knowledge centre at the Malwatta temple complex*

The upper levels of the Knowledge Centre accommodate spaces dedicated to deeper philosophical engagement, including a research library, study areas, discussion rooms, meditation spaces, and residential accommodation for visiting scholars and practitioners. Individual meditation pods located at the uppermost level provide spaces for quiet contemplation and extended meditation practices.

Learning within this environment occurs not only through formal educational content but also through architectural experience itself. Material logic, adaptable spatial organization, environmental exposure, and spatial sequencing shape how users interact with the building.

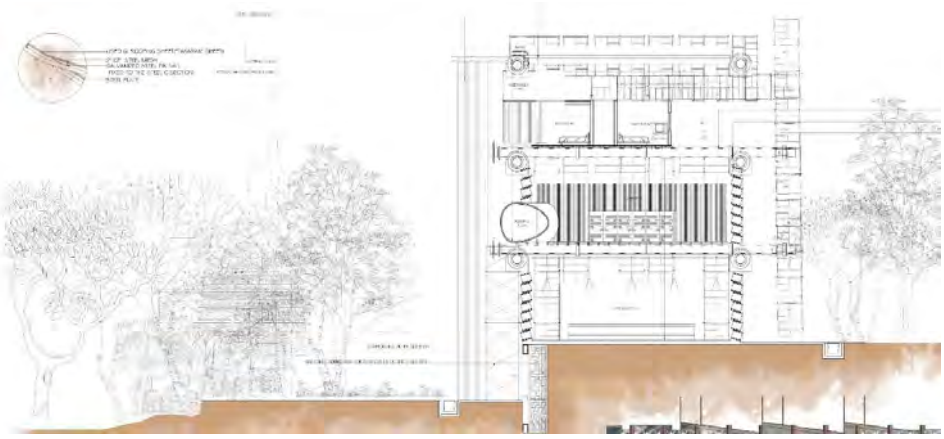


*Figure 9: Cross-section of the knowledge centre at the Malwatta temple complex*

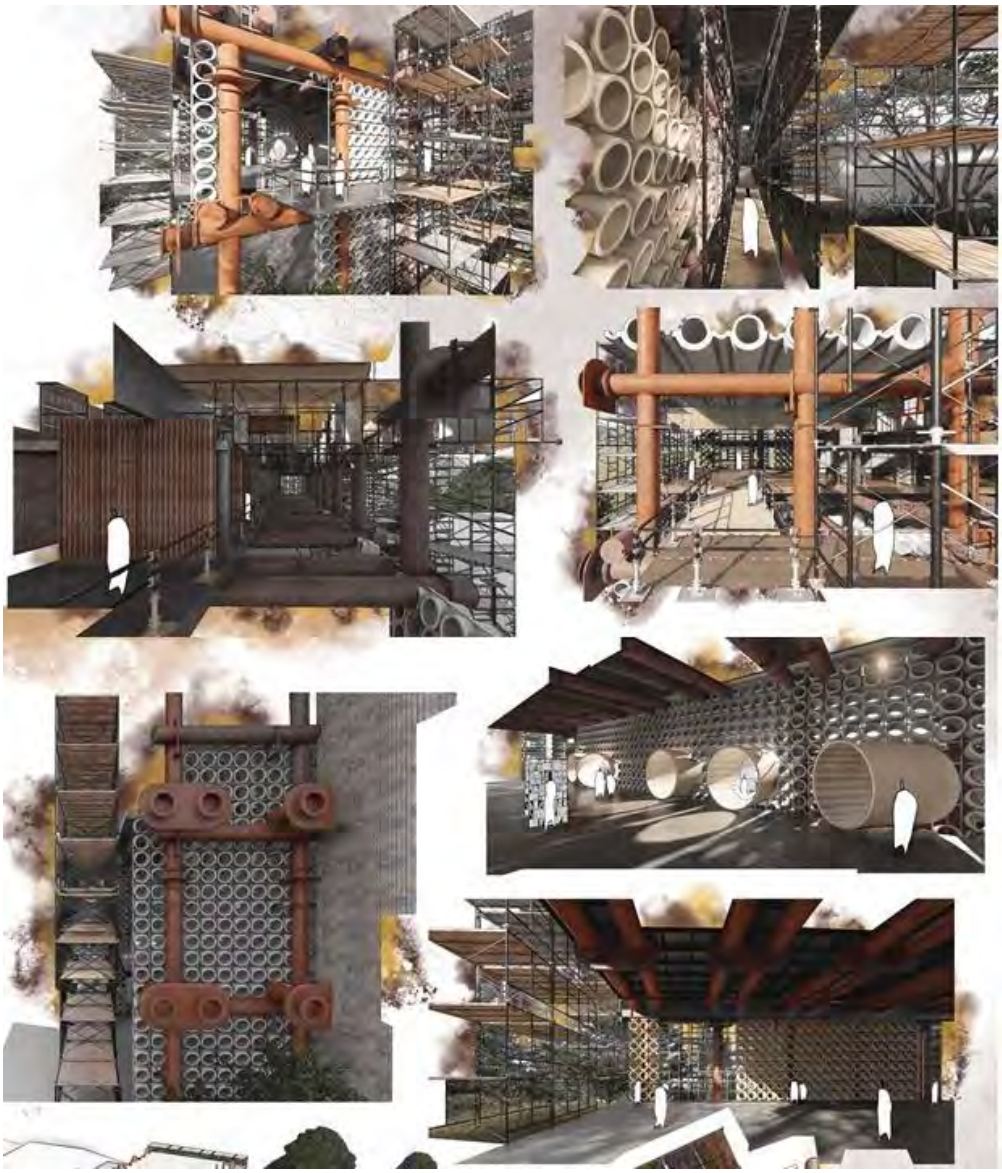


*Figure 10: Spaces of knowledge centre at the Malwatta temple complex*

## 5. DISCUSSION

The research demonstrates that philosophical frameworks rooted in regional cultural traditions can play a significant role in shaping regenerative architectural strategies. By integrating Buddhist philosophical principles into architectural design, the project challenges image driven religious architecture and proposes an alternative approach that prioritizes intellectual engagement, environmental responsibility, and cultural continuity.

The design strategies proposed in this study are informed not only by the author's interpretation but also by established discussions on critical regionalism, Buddhist architectural thought, and regenerative design. The project therefore operates as a theoretical architectural exploration situated within broader architectural discourse rather than a purely personal design proposition.

In the Sri Lankan context, where climate, landscape, and spiritual traditions have integra historically influenced the built environment, regenerative architecture can emerge through the reinterpretation of these deeply embedded cultural principles. The thesis project, *A Center for Buddhist Philosophy - An Ideological Regionalization of Architectural Modernity*, attempts to respond directly to many of the concerns reflected in the theme "Towards a Regenerative Built Environment: From Foresight to Action." Rather than approaching sustainability purely as a technological problem, the project explores how cultural philosophy, regional knowledge, and spatial experience can inform regenerative architectural thinking.

The proposed architectural framework operates through the integration of environmental responsiveness, cultural continuity, and human wellbeing. Climate responsive spatial organization, shaded transitional spaces, passive ventilation strategies, and the integration of landscape are employed to reduce environmental impact while strengthening the relationship between architecture and nature. Material selection also reflects this philosophy. Many building components are derived from reused, reclaimed, or donated materials, demonstrating how Buddhist philosophical values such as restraint, impermanence, and mindfulness can be expressed through architectural materiality while simultaneously promoting sustainable construction practices.

The project also challenges the contemporary tendency toward monumentality in religious architecture by proposing a spatial language that encourages reflection, dialogue, and learning rather than visual dominance. Through the reinterpretation of Buddhist philosophical ideas such as interconnectedness, balance, and non-attachment, the design attempts to create environments that support mental clarity, social interaction, and ecological awareness.

In this sense, the thesis demonstrates how regional philosophy can guide the creation of built environments that regenerate both ecological systems and cultural meaning. Although the project focuses on the specific typology of a centre for Buddhist philosophy, the underlying design principles have broader relevance. Similar approaches could inform the development of educational institutions, cultural facilities, and community spaces within Sri Lanka. By translating philosophical foresight into spatial strategies, the project illustrates how architecture can move beyond theoretical discussions of sustainability and contribute practical design approaches toward the development of regenerative built environments.

## 6. CONCLUSIONS

This research examined the relationship between regional identity, Buddhist philosophy, and regenerative architectural design within the context of contemporary Sri Lankan architecture. Through the case study of the proposed Centre for Buddhist Philosophy in Kandy, the study demonstrates how philosophical concepts can inform architectural strategies that move beyond conventional sustainability approaches. Rather than relying solely on technological solutions, the research highlights a design approach that integrates ecological awareness, cultural continuity, and human wellbeing within architectural practice.

The findings suggest that regional cultural knowledge and philosophical traditions can provide meaningful insights for addressing current environmental and social challenges in the built environment. By reinterpreting Buddhist philosophical principles such as interconnectedness, balance, and mindfulness within modern architectural frameworks, architecture can support environments that encourage intellectual reflection, environmental responsibility, and social resilience. In this sense, architecture functions not only as a physical intervention but also as a medium that shapes human awareness and relationships with the surrounding environment.

Although this research focuses on the typology of a Centre for Buddhist Philosophy, the underlying principles extend beyond a single project and suggest a broader architectural framework applicable to other building types and contexts. Ultimately, the study highlights the potential of philosophy driven architectural approaches to contribute to regenerative built environments that are both culturally meaningful and environmentally responsive, demonstrating how regionally grounded design thinking can help move architectural practice from theoretical foresight toward practical and transformative action.

## 7. REFERENCES

Bawa, G., & Robson, D. (2002). *Geoffrey Bawa: The complete works*. Thames & Hudson. https://iahs.fudan.edu.cn/__local/5/D5/A5/1193382373B36539C85B45EDF3A_088E749C_5F528D.pdf?e=.pdf

de Silva, M. (1998). *The life & work of an Asian woman architect*. Smart Media Productions.

Frampton, K. (1980). *Modern architecture: A critical history*. Oxford University Press.

Frampton, K. (1983). Towards a critical regionalism: Six points for an architecture of resistance. In H. Foster (Ed.), *The anti-aesthetic: Essays on postmodern culture* (pp. 16–30). Bay Press.

McMahan, D. L. (2009). *The making of Buddhist modernism*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195183276.001.0001

Pieris, A. (2021). *Imagining modernity: The architecture of Valentine Gunasekara*. Tambapanni Academic Publishers.

Gamage, P.J. and Chandanie, H., 2026. Reimagining procurement for domestic construction clients. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1427-1439. DOI: https://doi.org/10.31705/WCS.2026.104. Available from: https://ciobwcs.com/papers/

# REIMAGINING PROCUREMENT FOR DOMESTIC CONSTRUCTION CLIENTS

**P.J. Gamage[1] and H. Chandanie[2]**

## *ABSTRACT*

*This study critically examines the impact of procurement systems utilised in domestic housing projects in Sri Lanka. A comprehensive literature review was undertaken to establish the theoretical foundation of standard procurement systems, with particular emphasis on the Traditional and Design and Build (D&B) approaches. Their respective strengths and limitations were analysed in relation to the achievement of time, cost, and quality objectives. A qualitative case study approach was adopted, examining three domestic housing projects across the pre-construction, construction, and post-construction phases. Semi-structured interviews were conducted with key project stakeholders to identify challenges associated with existing procurement practices. The findings reveal significant weaknesses in informal procurement approaches, including inadequate cost planning at the design stage, an over-reliance on architectural drawings for construction execution, and the limited application of competitive tendering. These shortcomings adversely affect cost control, scheduling, and overall project performance. The study concludes that the adoption of a modified procurement framework could enhance the achievement of time, cost, and quality objectives in domestic housing construction projects in Sri Lanka.*

***Keywords:*** *Case studies, Cost–Time–Quality Performance, D&B procurement systems, Separated Procurement System, Sri Lanka, Way forward.*

## 1. INTRODUCTION

Shelter is one of the basic needs of all human being and development of domestic housing construction industry is main parameter that measures the living standards of the public of any country (Ismail et al., 2024). Private owners, looking for a more efficient method of realising residential projects, since most of layman nature clients procure their own housing construction through a D&B procurement system that provides smooth progress during the preconstruction stage and post construction stage due to less risk with the employer. Among the available procurement methods, such as Traditional procurement and Turnkey systems, these are the most used approaches in residential construction. However, under current procurement systems, clients are often unable to achieve their expected requirements. Despite limited research addressing the suitability of procurement systems in residential construction. Therefore, the research focusing on the necessity of modified procurement system for domestic housing construction is become more vital due current practice of informal method of procurement strategies (Ofori, 2012).

[1] Estimator and Precontract Administrations, Department of Estimation and Structural Designing, NextGen Engineering LLC, Houston Texas, United States of America- pamudthaj29@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka- cahndanieh@uom.lk

Procurement system selection plays a significant role in determining the success of construction projects. Ratnasabapathy and Rameezdeen (2007) identified that client requirements are among the most influential factors affecting procurement decisions, emphasising the importance of selecting procurement method that aligns with project objectives. Furthermore, Chanudha et al. (2017) highlighted that project characteristics such as cost certainty, time constraints, and complexity should be carefully considered when choosing a procurement system. Recent studies have also shown that decision-support frameworks can assist clients in selecting appropriate procurement methods and improving project outcomes (Ingle et al., 2025). However, most existing studies focus on large-scale or institutional projects, while limited attention has been given to domestic construction clients in Sri Lanka. Therefore, there is a need to develop a procurement selection framework specifically tailored to the requirements of domestic house-building clients.

Consequently, selecting the most suitable procurement system for residential construction remains a key challenge in the construction industry. A practice of appropriate discipline is a major feature that adapts to any successful procurement system and directly contributes to the sustainable development of any procurement system (Lawrence, 2000). The domestic housing construction industry uses informal procurement methods because of the layman nature of most domestic construction customers. Thus, implementing a suitable procurement system has become essential for the domestic housing construction industry. Further, when look at the global construction context, time, cost and quality of the construction projects become prominent concern and they provide best worth for the project (Tohidi, 2011).

A procurement system primarily concerns the effective delivery of construction projects through the provision of goods, services, and consultancy inputs required to achieve project objectives (Sears et al., 2008). Therefore, several techniques that associated with procurement selection criteria have been implemented by professionals to reach more informed decisions on procurement selection over last two decades (Luu et al., 2003). Further procurement activities range from identifying needs to closing the project, making it ideal for integrating the organization's strategic directions and due to that, academics and industry professionals have widely recognised the strategic importance of the well organised procurement system for the construction project (Rajeev. et al., 2013). Moreover, achieving the required time, cost and quality targets are linked with selected procurement strategy. However, determination of suitable procurement systems is the major challenge for the construction stakeholders, which may be faced at the preconstruction stage. Procurement of the construction project defines as a key process in a construction project that manages and creates the contract (Rajeev. et al., 2013). Consequently, the selection of an appropriate procurement system plays a critical role in shaping project outcomes and overall construction performance.

Therefore, this study aims to critically examine the limitations of currently adopted procurement methods in domestic housing construction and to identify necessary improvements from the client’s perspective. The findings are expected to contribute towards developing more suitable procurement approaches that enhance project efficiency and client satisfaction in the residential construction sector. However, the scope of the study is limited to two-storey domestic housing projects with construction costs ranging between Sri Lankan Rupees 15 million and 20 million.

## 2. LITERATURE REVIEW

The construction industry is widely recognised as a key driver in improving the standard of living of a population and within this sector, residential development is considered a critical determinant of the quality of life and overall well-being of a country's citizens (Lawrence, 2000). The quality of design and construction in residential projects directly influences the efficiency with which productive activities are conducted and essential services are delivered.

The question, "Should housing be prioritised as part of a country's development strategy?" has been widely debated among developers, economists, and policymakers. Housing experts consistently emphasise the importance of residential construction in supporting economic development, citing its direct and indirect linkages with other sectors of the economy. In particular, the domestic housing industry plays a major role within the construction sector, due to its close interactions with related economic activities and its contribution to employment, investment, and social well-being (Ewing & Wang, 2005).

Residential construction has become increasingly significant as private homeowners seek more efficient and reliable methods of delivering their housing projects. However, many domestic clients possess limited technical knowledge of construction processes and procurement strategies (Chan & Ann, 2005). As a result, housing projects are frequently procured through informal arrangements or simplified forms of D&B approach, where responsibilities for design and construction are largely entrusted to a single party. While such arrangements are often perceived to facilitate smoother coordination during the pre-construction and construction stages and to reduce the client's involvement and perceived risk, they may create challenges in terms of cost control, quality assurance, and transparency in project delivery (Chan & Ann, 2005).

Ghadamsi and Braimah (2012) highlighted that among the commonly available procurement methods in the construction industry, Traditional procurement and Turnkey approaches are widely adopted in residential construction. However, in practice, these systems are often implemented in modified or informal forms, which may limit their ability to deliver the expected project outcomes. Consequently, clients frequently experience difficulties in achieving their desired objectives related to time, cost, and quality performance.

Despite the importance of procurement strategies in determining project success, limited research has specifically examined the suitability of procurement systems for domestic housing construction, particularly from the perspective of private clients. This indicates a significant research gap in understanding how procurement practices influence the performance of residential construction projects.

Existing literature on construction procurement has predominantly focused on large scale commercial, infrastructure projects. Although this paper provides valuable insight into procurement systems and project delivery approaches, limited attention has been given to procurement practice adopted by domestic construction clients. Furthermore, there is a lack of context specific research examining procurement system within the Sri Lankan domestic construction industry.

Consequently, a significant gap remains in understanding procurement approaches that are appropriate for domestic construction clients in Sri Lanka. This study, therefore, seeks

to address this gap by exploring procurement practices within the local domestic construction context.

## 3. RESEARCH METHODOLOGY

The research process for this study on improving procurement approaches in domestic housing construction in Sri Lanka is presented in Figure 1.

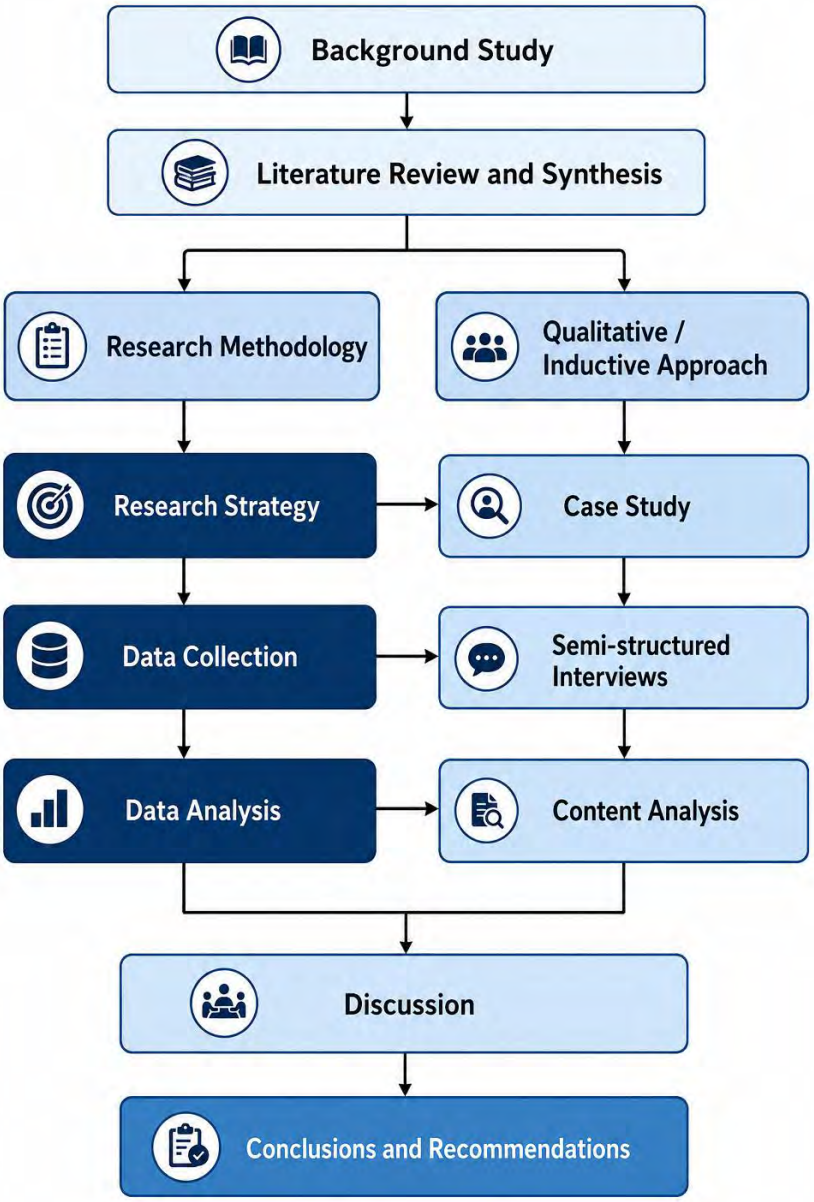



*Figure 1:Research methodology*

Generally, research approach is a process that provides necessary instructions and guidance on achievement of specified research aim and objectives (Smith et al., 2002). According to the types of research approach, there are two fundamental types of research approaches i.e. (i) qualitative approach and (ii) quantitative approach (Kothari., 2004) (Kothari, 2004). The qualitative approach is chosen, when the field of research is based

on values, understandings, beliefs, perceptions, etc. to get new discoveries. In addition, it demonstrates the subjectivity of opinions and behaviors (Cresswell, 2013). Conducting the data collection following a qualitative approach is the most suitable way to review the unclear problems related to the procurement strategies used in residential housing construction with providing strong evidence on real nature of procurement practice in domestic housing construction in Sri Lanka. A qualitative approach is suitable for this study due to its focus on procurement practices in residential housing construction.

A case study strategy was adopted to gather in-depth data on procurement practices used in domestic housing construction in Sri Lanka. Semi-structured interviews were conducted with three domestic housing clients using a pre-prepared guide, and the data were analysed by comparison with relevant literature.

It was required to identify the procurement strategy that are used in residential housing construction. Yet, the most of domestic housing constructions have not been managed by the standardised method of procurement, which are currently practicing in the construction industry. In addition, the available literature is mainly focused on large-scale projects since it is impossible to conduct a proper questionnaire survey and to follow quantitative data analysis. Therefore, requirement of new procurement strategy to the residential housing construction is established through using the in-depth analysis on the real three (03) residential housing construction cases accompanied with more qualitative data. As a result, qualitative approach was essential to be selected.

Accordingly, a qualitative case study strategy was employed to gain detailed insights into procurement practices in domestic housing projects. Selecting an appropriate data collection method was essential for addressing the research objectives, which focused on critically examining the weaknesses and challenges faced by clients under existing procurement systems and identifying potential improvements across the various stages of domestic housing projects.

Semi-structured interviews were conducted with three domestic housing clients (refer Table 1), each representing a unique case of small-scale, owner-driven construction in which the client serves as the principal decision-maker throughout the procurement process. This approach ensured the collection of rich, context-specific data, reflecting the nuanced realities of client experiences in domestic housing procurement.

*Table 1:Case study coding reference*

| Case No | Case reference | Respondent reference |
|---|---|---|
| Case 01 | A | A1 |
| Case 02 | B | B1 |
| Case 03 | C | C1 |

Participants were purposefully selected as key informants due to their direct involvement in procurement decisions, thereby providing experiential knowledge crucial to understanding current practices and their limitations. The case study approach is particularly suitable in this context, as it prioritises depth of understanding and contextual relevance over sample size. Small, carefully chosen samples are widely accepted in qualitative research when participants possess specific, experiential insights directly

relevant to the research problem (Cresswell & Poth, 2018; Yin, 2018). By focusing on a limited number of cases, the study was able to explore procurement challenges in a detailed and holistic manner, enhancing the validity and applicability of the findings within the domestic housing sector.

Data analysis is a critical stage in qualitative research, as it enables the interpretation of collected information and the generation of insights relevant to addressing the research problem. In this study, a manual content analysis approach was adopted to systematically examine the data obtained from semi-structured interviews. The analysis was guided by thematic headings developed from the interview protocol, which reflected the key aspects of procurement practices and client experiences in domestic housing construction.

The process involved multiple stages. First, the interview transcripts were thoroughly reviewed to achieve familiarity with the data. Significant statements and observations were then identified and categorised under the predetermined thematic headings. Subsequently, these categories were further refined and coded to capture emerging patterns, recurring challenges, and contextual nuances. This iterative process facilitated the identification of key themes related to procurement inefficiencies, client decision-making, and areas for improvement in existing procurement systems.

By adopting this structured content analysis approach, the study ensured that interpretations were grounded in the participants' experiential knowledge, enhancing the credibility, depth, and relevance of the findings. The systematic coding and thematic organisation of the data allowed for a comprehensive understanding of current procurement practices, supporting the development of practical recommendations for improving domestic housing construction in Sri Lanka.

## 4. STUDY ANALYSIS AND FINDINGS

In this case study, three contractor quotations were obtained in line with standard procurement practices in the Sri Lankan construction industry to ensure competitiveness and transparency (refer Table 2).

*Table 2: The contractor selection for major work stages in Cases A, B, and C.*

| Case | Work description | Selection of contractor |
|---|---|---|
| **Case A** | Foundation works and super structure columns | Selected a contractor who has previous experience with the client |
| | Slab concreting works | Selected a D&B contractor |
| | Tilling works | Selected a specialised contractor after evaluation of three quotations |
| | Plastering and painting works | Selected a specialised contractor after evaluation of three quotations |
| | Timber works (Door and windows) | Selected a specialised contractor after evaluation of three quotations |

| Case | Work description | Selection of contractor |
|---|---|---|
| | Roof works | Selected a D&B contractor |
| **Case B** | Entire civil construction works | Selected a suitable contractor after observing previous project that has been done by the contractor |
| | Tilling works | Selected a specialised contractor after evaluation of three quotations |
| | painting works | Selected a specialised contractor after evaluation of three quotations |
| | Timber works (Door and windows) | Selected a specialised contractor after evaluation of three quotations |
| **Case C** | Entire civil construction works | Selected a suitable contractor after observing previous project that has been done by the contractor |
| | Tilling works | Selected a specialised contractor after evaluation of three quotations |
| | painting works | Selected a specialised contractor after evaluation of three quotations |
| | Timber works (Door and windows) | Selected a specialised contractor after evaluation of three quotations |

The evaluation process considered multiple criteria, including cost, technical capability, previous project experience, and resource availability. Although the lowest quotation offered initial cost advantages, the selected contractor demonstrated greater expertise and a stronger track record in delivering similar projects. This decision highlights the importance of adopting a value-based procurement approach rather than relying solely on the lowest bid. Such an approach helps to mitigate potential risks related to quality, delays, and performance, which are critical factors in the successful delivery of construction projects (Procurement regulations for burrowers, 2016).

## 4.1 PROCUREMENT CHALLENGES FOR SRI LANKAN DOMESTIC HOUSING CONSTRUCTION

Domestic housing clients face significant procurement challenges from project inception to completion, as illustrated in Figure 2.

Figure 2 highlights key procurement challenges in domestic housing construction projects, from briefing to completion. The main issues include the absence of detailed drawings, reliance on informal tendering, and limited cost planning awareness.

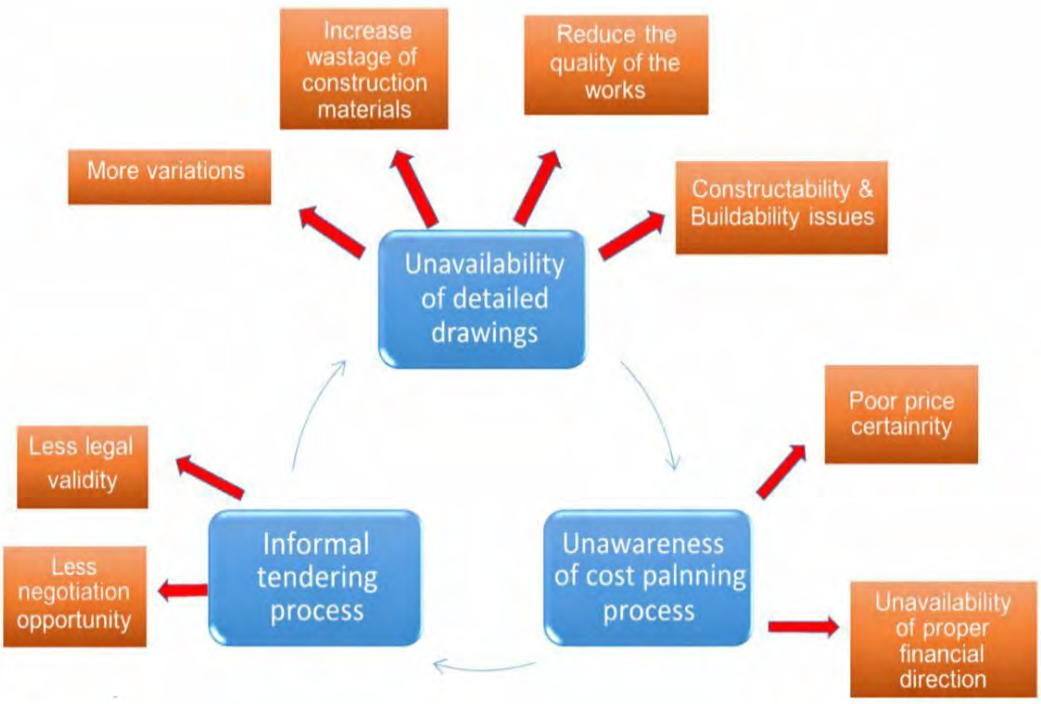



*Figure 1:Procurement challenges in domestic housing construction*

These weaknesses contribute to material wastage, construction quality problems, variations, reduced transparency, and poor financial control, demonstrating the cumulative impact of early-stage procurement deficiencies. The finding emphasises the need for structured procurement approaches, improved technical documentation, and strengthened cost planning to enhance project outcomes in the Sri Lankan domestic housing sector.

The findings from the three case studies revealed that fluctuations in construction material prices considerably increased the overall cost of domestic housing construction projects. Based on the procurement methods adopted in these projects, a significant proportion of the financial risk was transferred to the clients. As a result, cost overruns and financial uncertainty became major challenges faced by domestic housing construction clients.
Furthermore, the analysis identified that most domestic housing projects operate through informal procurement practices rather than standard procurement systems commonly used in the formal construction industry. Clients frequently relied on verbal agreements, direct labour arrangements, and contractor selection based on personal relationships or recommendations. These practices often lacked formal contractual arrangements, proper cost control mechanisms, and effective risk allocation procedures. Consequently, clients became more vulnerable to construction price fluctuations and unexpected project expenses.

Existing literature emphasises that an appropriate procurement system is essential for achieving cost certainty, proper risk allocation, and efficient project delivery. However, the findings indicate that domestic housing clients possess limited awareness regarding formal procurement approaches such as Traditional Procurement and D&B. Therefore,

the theme of Financial Risk Exposure through Informal Procurement Practices emerged as a significant issue within the domestic housing construction sector.

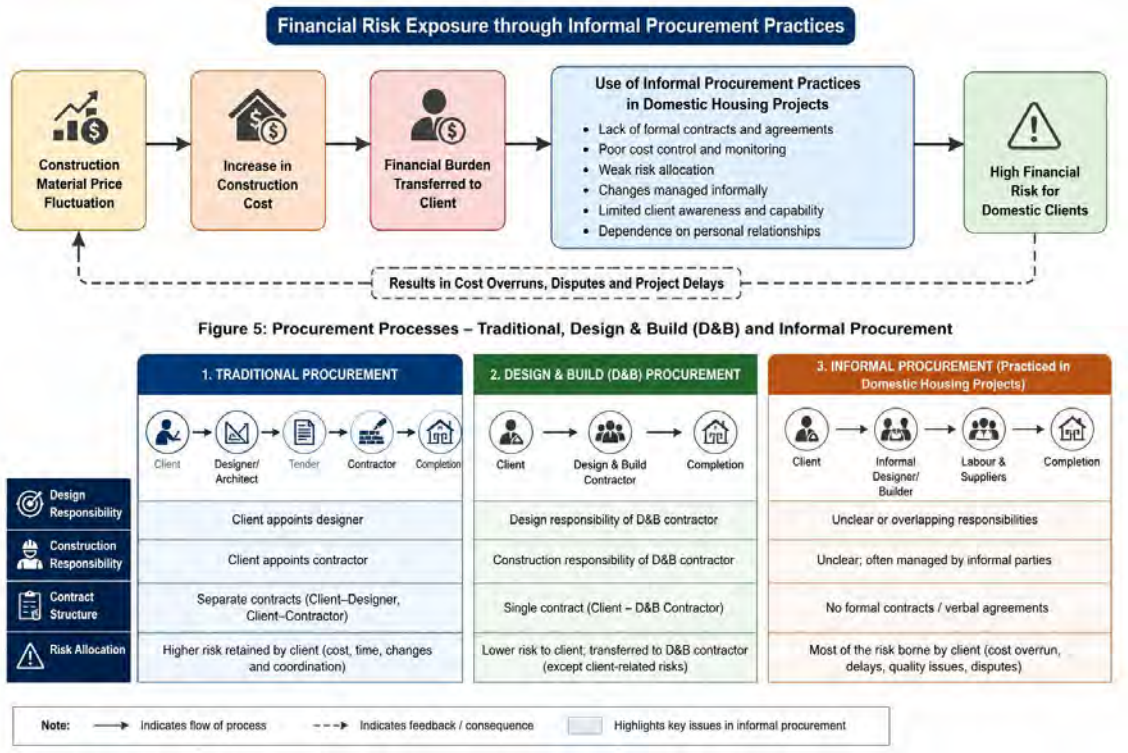



*Figure 3: Overall risks arising from informal procurement practices*

The study identified that domestic housing construction clients are highly exposed to financial risks due to the use of informal procurement practices. The absence of formal contracts, inadequate cost control mechanisms, poor risk allocation procedures, and limited client awareness increase client vulnerability to material price fluctuations and project cost escalation.

## 4.2 COMPARISON BETWEEN PROCUREMENT SYSTEM AND ESSENTIAL PROCUREMENT REQUIREMENTS OF DOMESTIC HOUSING CONSTRUCTION PROJECTS

Figure 4 indicates that most domestic housing clients do not prioritise cost control techniques during the design stage. However, existing literature emphasises the critical role of cost planning in the successful completion of construction projects(Paul & Peter, 1996). Many domestic clients consequently experience uncertainty regarding whether their house can be completed within the allocated budget. The case studies revealed a common error: clients often fail to give sufficient attention to project costs during the design phase. This oversight represents a significant challenge for Sri Lankan domestic housing clients. To address this issue, procurement systems for domestic housing projects should incorporate robust cost control mechanisms at the design stage, rather than relying solely on cost monitoring during construction.

Regarding contractor selection in domestic housing projects, the negotiated method is predominantly used. In Cases A, B, and C, no formal tendering process was followed.

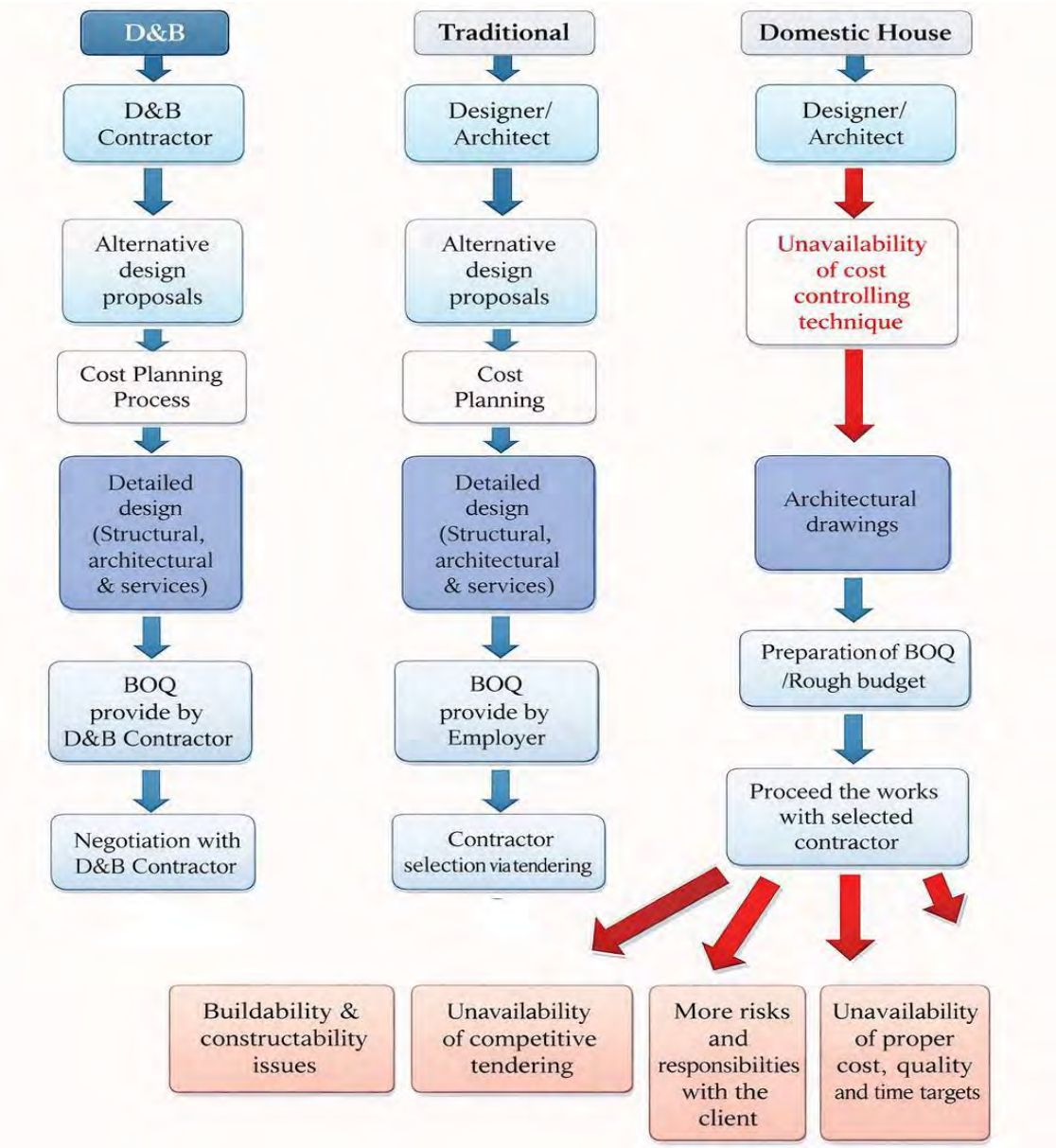



*Figure 4: Comparison between procurement system and essential procurement requirements of domestic housing construction projects*

The main weakness identified in the contractor selection process was the informal approach adopted for Cases A1, B1, and C1. Consequently, clients encounter numerous challenges both recognised and unrecognised relating to cost, quality, and schedule performance. In traditional procurement approaches, contractor involvement during the pre-construction stage is minimal. In the context of domestic housing, where clients often have limited technical knowledge, this low level of early involvement can lead to constructability and buildability issues during post-construction.

Figure 5 presents a more structured and robust procurement approach specifically designed to address the needs of domestic housing clients and improve project outcomes.

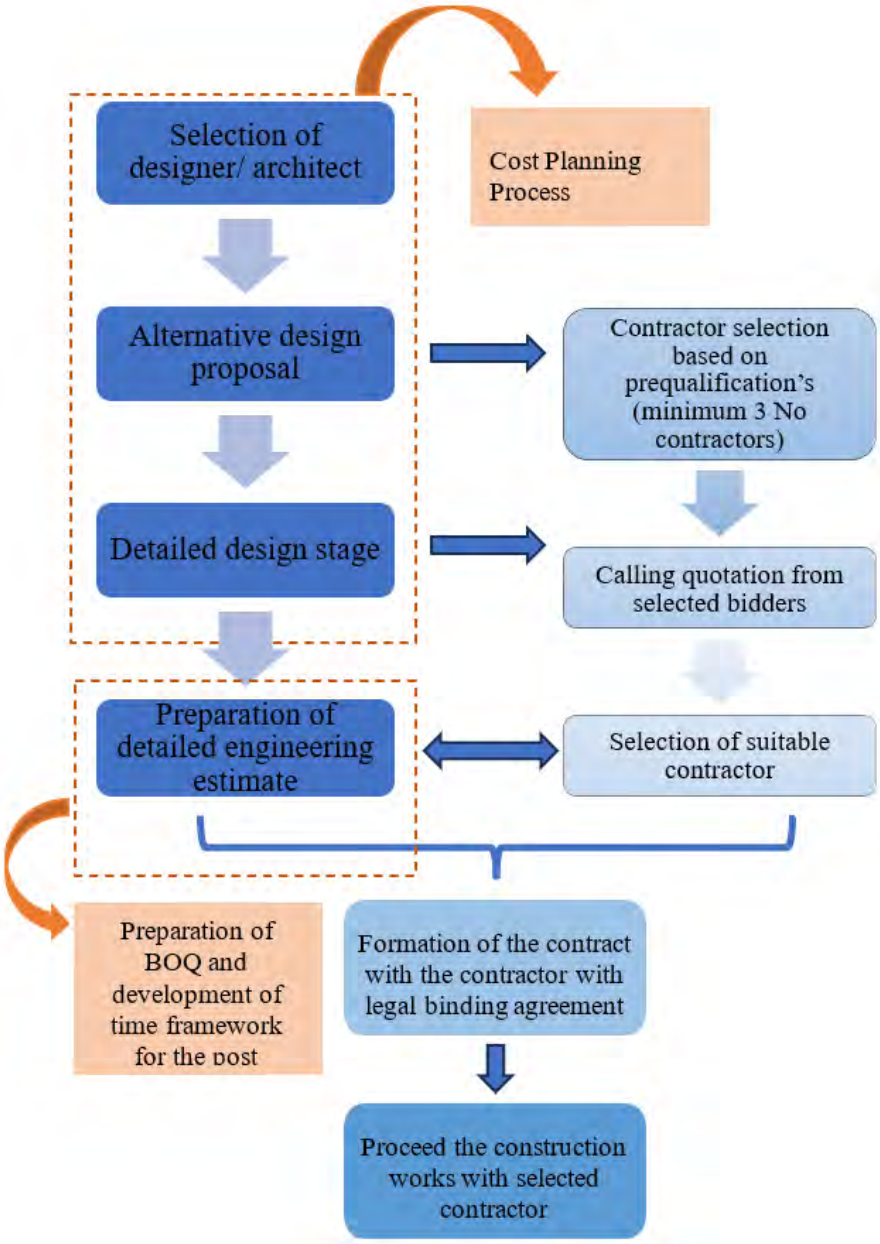



*Figure 5: Proposed modified procurement framework*

Existing research supports the importance of early contractor engagement: Lappalainen et al. (2022) argue that contractor involvement from the design stage enhances quality standards through the application of specialised expertise and collaborative decision-making. Accordingly, selecting an appropriate contractor during the design phase is essential to ensure smoother project execution and improved outcomes in domestic housing construction, particularly given the layman nature of most clients. The primary objective of domestic housing clients is to complete their projects within the expected time, cost, and quality targets. However, due to the unstructured and informal nature of procurement practices in the domestic housing construction industry, clients frequently encounter significant challenges during both the pre-construction and post-construction stages.

Accordingly, appropriate quality standards can be established through the development of a detailed Bill of Quantities (BOQ) and comprehensive design during the pre-construction stage. In addition, preparing a proper construction schedule, allocating suitable time periods for each activity, and pre-identifying project milestones—against which progress can be monitored—are essential modifications that should be incorporated into the existing informal procurement system in the domestic housing construction industry. Early involvement of suitable contractors during the design phase is another key feature of the proposed procurement system. This approach facilitates lower tender prices and minimises design variations, as well as constructability and buildability issues, due to the presence of specialised contractor knowledge from the outset. Furthermore, forming contracts based on legally binding agreements helps to reduce disputes during the post-construction stage.

By integrating these modifications into the existing informal procurement system, a well-structured procurement approach can be established that effectively meets the requirements of domestic housing clients, ensuring improved outcomes in terms of time, cost, and quality.

## 5. CONCLUSIONS

This study demonstrates that most domestic housing clients in Sri Lanka rely on informal procurement methods, which often result in disputes, inefficiencies, and challenges in meeting time, cost, and quality objectives due to clients limited technical knowledge. Analysis of procurement practices from the briefing stage to project completion revealed several critical weaknesses, including insufficient cost planning during the design phase, lack of a well-defined construction schedule, limited legal enforceability of contracts, and reliance on architectural drawings for procuring the entire project. To address these issues, a modified procurement system is proposed, tailored to the domestic housing context. Key features include structured cost planning, early contractor involvement, legally binding contracts, detailed pre-construction documentation, and milestone-based progress monitoring. Implementation of this approach is expected to enhance project efficiency, improve client satisfaction, reduce disputes, and ensure better adherence to time, cost, and quality objectives. The study contributes to both theory and practice by providing evidence of the limitations of informal procurement in domestic housing and demonstrating how modifications to standardised procurement systems can be adapted to the local context. Future research could expand this framework to larger or multi-storey residential projects, explore contractor perspectives, and assess the long-term impact of the proposed procurement modifications on project performance and sustainability in the domestic housing sector.

## 6. ACKNOWLEDGEMENTS

The principal investigator extends sincere gratitude to the research supervisor, and Dilini Rajashilpa for her valuable support in formatting the research paper and assisting in the preparation of several diagrams included in this study.

## 7. REFERENCES

Chan, E. H., & Yu, A. T. (2005). Contract strategy for design management in the design and build system. *International Journal of Project Management*, 23(8), 630–639. https://doi.org/10.1016/j.ijproman.2005.05.004

Chanudha, R., Disaratna, P., Anuruddika, S., & Ariyachandra, M. (2017). Procurement system selection model for the Sri Lankan construction industry. 6th World Construction Symposium 2017,

Cresswell, J. W. (2013). *Resaerch Design: Qualitattive, Quantitative, and Mixed Methods Approaches* Nebraska: SAGE Publications.

Cresswell, J. W., & Poth, C. N. (2018). Qualitative inquiry and research design Choosing among five approaches. *SAGE*.

Ewing, B., T., & Wang, Y. (2005). Single housing starts and macroeconomic activity: an application of generalized impulse response analysis. *Applied Economics Letters*, *12*(3), 187-190. https://doi.org/https://doi.org/10.1080/1350485052000337806

Ghadamsi, A., & Braimah, N. (2012). The influence of procurement methods on project performance: A conceptual framework. The CIB International conference entitled:'management of construction: research to practice,

Ingle, P. V., Adamu, M., Raut, A., & Alyaseen, A. (2025). A multi-criteria decision analytics approach for project delivery system selection in housing projects. . *Decision Analytics Journal*, *17*, 100651. https://doi.org/https://doi.org/10.1016/j.dajour.2025.100651

Ismail, I. H., Al-Hazmi, A. M. A., & Al-Hussein, A. R. (2024). Improving shelter conditions by implementing sustainable housing policies. *Journal of Umm Al-Qura University for Engineering and Architecture*, *15*(2), 120-137. https://doi.org/https://doi.org/10.1007/s43995-024-00047-3

Kothari., C. R., (2004). *Research Methodology methods and techniques (2nd ed)*. Jaipur: New age international.

Lappalainen, E., Uusitalo, P., Pikas, E., Seppänen, O., Peltokorpi, A., Uusitalo, P., Reinbold, A., & Menzhinskii, N. (2022). Improving design quality by contractor involvement: An Empirical Study on effects. *Buildings*, *12*(8), 1188. https://doi.org/10.3390/buildings12081188

Lawrence. (2000). Urban Health: a new agenda? *Reviews on environmental health*, *15*(1-2), 1-12.

Luu, D. T., S Thomas Ng, & Chen, S. E. (2003). A case-based procurement advisory system for construction. *Advances in Engineering Software*, *34*(7), 429-438. https://doi.org/10.1016/S0965-9978(03)00043-7

Ofori, G. (2012). Developing the Construction Industry in Ghana: the case for a central agency. 40-71.

Paul, B. A., & Peter, E. J. (1996). Interpersonal Communication i cost planning during building design phase. *Construction Management and Economics*, *14*(5), 39-404.

*Procurement regulations for burrowers*. (2016).

Rajeev., R. R., Ruparathna@ubc.ca, & Kasun., K. H. (2013). Review of Contemporary Construction Procurement Practices. *Journal of Management in Engineering*, *31*(3). https://doi.org/https://doi.org/10.1061/(ASCE)ME.1943-5479.0000279

Ratnasabapathy, S., & Rameezdeen, R. (2007). A decision support system for the selection of best procurement system in construction. *Built-Environment Sri Lanka*, *7*(2). https://doi.org/10.4038/besl.v7i2.1943

Sears, k. S., Sear, G., A., , & Clough, R., H (2008). *Construction Project Management* John Wiley & Sons.

Smith, E. M., Thorpe, R. R., & Lowe, A. (2002). *Management Research: an Indication*

Tohidi, H. (2011). Review the benefits of using value engineering in information technology project management. *Procedia Computer Science*, *3*, 917-924.

Yin, R. k. (2018). Case study research and applications design and methods.

Hasen, S., 2026. Relationship model of mindfulness practice and construction workers' performance: An exploratory study in Indonesia. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1440 -1454. DOI: https://doi.org/10.31705/WCS.2026.105. Available from: https://ciobwcs.com/papers/

# RELATIONSHIP MODEL OF MINDFULNESS PRACTICE AND CONSTRUCTION WORKERS' PERFORMANCE: AN EXPLORATORY STUDY IN INDONESIA

**Seng Hansen**[1]

## *ABSTRACT*

*Humans are the main resource in construction work. Therefore, attention to human well-being, including aspects of mental health, is key to the success of the construction industry. On the other hand, there is a close connection between mental health and mindfulness practice. However, mindfulness practices have not received proper attention in the construction project environment, especially in Indonesia. This research aims to enhance the understanding of the relationship between mindfulness practice and construction workers' performance. With a quantitative approach, this research presents a questionnaire survey to measure the perceptions of Indonesian construction workers. The data obtained were analysed using the Multiple Linear Regression technique, which established a relationship model between mindfulness practice and construction worker performance. This research highlights the positive influence of mindfulness practice on construction workers. Thus, construction organisations can utilise the results of this research to better understand how mindfulness practices can improve worker performance and, thereby, encourage sustainable implementation of mindfulness practices among their workers.*

***Keywords:*** *Construction; Mindfulness; Model; Performance; Workers.*

## 1. INTRODUCTION

In Indonesia, as in many developing countries, the construction industry employs many workers. Human resources are a key factor in the successful implementation of a construction project. Therefore, construction organisations must pay special attention to improving the quality of human resources and fulfilling the welfare of their workers (Hansen et al., 2023; Sunindijo & Kamardeen, 2017). Fulfilling the welfare of construction workers not only includes physical health and safety but also their mental health.

However, the issue of construction workers' mental health has not received much attention, especially in developing countries like Indonesia (Hansen, 2022). The construction industry still records high rates of poor mental health among its workers (Oni et al. 2023). In fact, there have been many studies that highlight the nature and characteristics of construction work, which requires working for long periods of time, paced work, tight budgets, competitive environment, dynamic and full of risks which

[1] Assoc. Professor, Civil Engineering Department, President University, Indonesia, seng.hansen@president.ac.id

have also influenced the mental health of construction workers (Batubara et al., 2021; Hansen, 2023). Various mental health disorders in construction workers such as depression, anxiety, and decreased cognitive ability (Frimpong et al., 2022) will have an impact on productivity, work quality, and worker safety (Hansen, 2025). All these publications remind the importance of mental health studies in construction, especially considering their socioeconomic implications (Tijani et al., 2023).

On the other hand, there is a close connection between mental health and mindfulness. Various mental health disorders such as stress, anxiety, depression, attention-deficit disorder, post-traumatic stress disorder, and drug addictions are treated with mindfulness practice (Blanck et al., 2018; Chiesa & Serretti, 2014; Reangsing et al., 2021; Sancho et al., 2018; Sharf, 2015). The term "mindfulness" is defined as a state in which attention is focused on current phenomena (Dane, 2011). In recent years, various studies have been conducted to examine the influence of mindfulness practices on worker and organizational performance (Daniel et al., 2022; Daniel et al., 2023; Leung et al., 2024; Melagoda & Rowlinson, 2022; Mellner et al., 2022). In contrast to the general management literature, mindfulness has not garnered as much scientific attention in the construction engineering and management discipline. Because of this troubling lack of study, mindfulness in construction project contexts still needs to be investigated. In Indonesia itself, which is the largest construction market in Southeast Asia, the mental health issue of construction workers has not been understood and studied. Even though there are 9.2 million people working in the construction sector (BPS, 2023), with a project environment that is dynamic, competitive, and interconnected with many parties (Batubara et al., 2021; Hansen, 2022). In carrying out their work, construction workers are often confronted not only with technical and administrative matters, but also with emotional matters such as dealing with clients, managing project conflicts, and mitigating the risk of work delays. These factors make construction workers more vulnerable to mental fatigue and reduce job satisfaction (Hansen et al., 2023).

Based on this background, this research aims to enhance the understanding of the relationship between mindfulness practice and construction workers' performance. This research is important considering the close relationship between mindfulness practices and the mental health of construction workers. Using an empirical approach, this research serves as a preliminary investigation by providing evidence to measure construction workers' perceptions of the influence of mindfulness practices on their performance. Construction organisations can utilise the results of this research to better understand how mindfulness practices can improve worker performance and, thereby, encourage sustainable implementation of mindfulness practices among their workers.

# 2. LITERATURE REVIEW

## 2.1 MINDFULNESS PRACTICES

Mindfulness is often defined as the process of paying attention in the present moment and non-judgmentally (Burmansah et al., 2022; Daniel et al., 2022; Sharf, 2015). A practitioner learns to focus their attention on external and internal stimuli while maintaining a nonjudgmental awareness of the present moment (Kaviani & Hatami, 2016). In psychology, mindfulness is viewed as a practice to develop knowledge and wisdom for oneself (Karunamuni & Weerasekera, 2019). As a cognitive skill, it is usually developed through meditation practice (Creswell, 2017).

Mindfulness has long been studied and practiced. Scholars argue that the understanding of mindfulness is rooted in Buddhism (Hulsheger et al., 2013; Sharf, 2015). This practice was first taught by Siddhartha Gautama, which is one of the essences of Buddha's teachings. In this case, the practice of mindfulness is a part of the Four Noble Truths and the Eightfold Path of Buddhism (Garrison, 2021). Even in the Dhammapada, one of the Buddhist scriptures, the first verse begins with the topic of mind as the pioneer: "Mind precedes all mental states. Mind is their chief; they are all mind-wrought." In practice, mindfulness is developed through mindful meditation. However, various forms of mindfulness practices, to a lesser extent, can also be found in other world religious teachings, such as Christian meditation and the Islamic method of muraqabah.

Research related to mindfulness has been carried out in various fields such as psychology (Brown et al., 2007; Frese, 2007; Garrison, 2021; Mellner et al., 2022), marketing (Bahl et al., 2016), leadership (Burmansah et al., 2022; Eisenbeis & van Knippenberg, 2015; Reb et al., 2014), organizational behaviour (Chandler & Hwang, 2015), information systems (Addas & Pinsonneault, 2018; Beck et al., 2011), religion (Garrison, 2021; Sharf, 2015), education (Ditrich, 2018; Weare, 2019), and project management (Daniel et al., 2022; Mellner et al., 2022). Much of this research is related to the theoretical concept of mindfulness practices (Brown et al., 2007), the benefits of mindfulness practices in the work environment (Daniel et al., 2023; Hulsheger et al., 2013), the application of mindfulness practices in behaviour organizations (Leroy et al., 2013; Li et al., 2021; Vogus & Welbourne, 2003), and the influence of mindfulness practices on project performance (Dane & Brummel, 2014; Daniel et al., 2022).

In the construction sector, research on the practice and benefits of mindfulness has recently become widely studied. For example, Liang and Leung (2015) analysed the relationship between mindfulness practices and stress experienced by construction workers. Feldbauer (2019) adopted mindfulness practice as a soft skill to enhance project management of a complex hospital construction in the Middle East. A mindful project management framework was proposed to improve major hospital building projects. Solomon and Esmaeili (2021) investigated the relationships among mindfulness practices, personality, national culture, and occupational safety in construction projects. Furthermore, Leung et al. (2024) conducted a study regarding the impact of mindfulness-based stress reduction on the performance of construction professionals.

## 2.2 MINDFULNESS CHARACTERISTICS

The main characteristics of mindfulness is awareness. Awareness is the ability to focus one's attention from one moment to the next (Davis & Hayes, 2011). It is the ability to watch how one is thinking, feeling, and perceiving in the moment. It necessitates paying close attention to the mind and body that are intertwined in one's genuine experience, without rejecting that experience (Primasari & Yuniarti, 2021). Furthermore, the non-judgmental aspect of mindfulness implied that one needed to embrace the experience for what it is with compassion, kindness, openness, acceptance, and curiosity (Daniel et al., 2022; Liang & Leung, 2015; Primasari & Yuniarti, 2021).

Kaviani and Hatami (2016) studied the relationship between mindfulness and enhanced personality characteristics, such as openness and pro-social behaviour and found an increase in cognitive function from mindfulness practice, which had an impact on the development of social and political behaviour. Mellner et al. (2022) view this as a form of mental development in a person who becomes more easily satisfied. This cognitive

function also helps a person observe and better explain various phenomena (Breuer & Gebauer, 2011; Daniel et al., 2022; Leung et al., 2024).

Mindfulness is also characterised by non-reactivity (Good et al., 2015; Liang & Leung, 2015). In contrast to non-judgmental, which does not evaluate any experience as good or bad, non-reactivity allows experiences to come and go without responding to change them (Zou et al., 2020). Meanwhile, non-striving is an attitude without ambition to obtain a particular outcome (Radiani, 2021). The researchers also mentioned several other characteristics of mindfulness practice, namely self-regulation, connection, trust, patience, beginner's mind, flexible state of mind, sensitivity to phenomena, and the ability to let go (Burmansah et al., 2022; Daniel et al., 2022; Liang & Leung, 2015; Radiani, 2021; Yesilkus & Ozbozkurt, 2020).

## 2.3 MINDFULNESS BENEFITS

The practice of mindfulness is very beneficial in improving one's mental health. Various studies have agreed to state the health benefits of mindfulness practice in reducing stress, depression, anxiety, and other mental health disorders (Bazarko et al., 2013; Blanck et al., 2018; Chiesa & Serretti, 2014; Leung et al., 2024; Mellner et al., 2022; Reangsing et al., 2021; Sancho et al., 2018; Weare, 2019). Mindfulness practices are believed to improve the quality of human life by increasing awareness and curiosity (Kaviani & Hatami, 2016; Mellner et al., 2022; Scholtenhuis et al., 2014), strengthening experiences (Daniel et al., 2023; Leung et al., 2024), spurring conscious change (Burmansah et al., 2020; Huurne et al., 2022), and fostering self-regulation (Addas & Pinsonneault, 2018; Good et al., 2015; Hulsheger et al., 2013).

Research conducted by Daniel et al. (2022) shows that implementing mindfulness practices can foster awareness, creativity, and innovation, thereby creating space for flexibility of thinking and acting, which can influence the quality of a person's decision-making. Similarly, researchers also agree on the positive benefits of implementing mindfulness practices, which show increased observation and detailing skills, problem-solving, and leadership (Beck et al., 2011; Burmansah et al., 2020; Kaviani & Hatami, 2016; Leung et al., 2024; Radiani, 2021).

In relation to brain function, mindfulness practice is believed to increase cognitive capacity and brain plasticity (Breuer & Gebauer, 2011; Good et al., 2015; Yesilkus & Ozbozkurt, 2020). These researchers also examined how mindfulness practices can foster empathy and compassion, thereby increasing positive relationships and conflict avoidance. Apart from that, mindfulness practice can also slow down ageing and senility (Epel et al., 2009; Good et al., 2015).

The integration of mindfulness practice in a workplace environment has also been widely researched (Brown et al., 2007; Leung et al., 2024; Weare, 2019). The application of mindfulness practices in the workplace has been proven to increase team collaboration and coordination (Good et al., 2015; Scholtenhuis et al., 2014), help allocate resources effectively (Wilson et al., 2011), and improve team communication and understanding (Beck et al., 2011; Khan, 2018). Mindfulness practices applied continuously in the workplace can create a safe, respectful, and enjoyable work environment (Vogus & Sutcliffe, 2007; Yesilkus & Ozbozkurt, 2020). This reduces mental and emotional fatigue due to work and increases job satisfaction (Hulsheger et al., 2013; Weare, 2019). Vogus

et al. (2014) also examined the implications of mindfulness practices for reducing a team's turnover rate.

Finally, many studies have been conducted that reveal the benefits of mindfulness practice in improving individual performance (Addas & Pinsonneault, 2018; Daniel et al., 2022; Leung et al., 2024; Yesilkus & Ozbozkurt, 2020) and its benefits to the overall performance of the project organization (Breuer & Gebauer, 2011; Dane & Brummel, 2014; Eisenbeiss & Knippenberg, 2015; Khan, 2018; Leroy et al., 2013; Mellner et al., 2022; Reb et al., 2014). With so many benefits from mindfulness practice, it should receive proper attention from construction organisations to be implemented sustainably in construction projects.

### 2.4 MINDFULNESS AND WORKERS' PERFORMANCE

Mindfulness practices have become a new concept in efforts to improve worker performance and project success (Khan, 2018). Mindfulness practices can be applied by individuals and groups (Wright et al., 2009). Various studies on the effects of mindfulness practices on individual and group performance have been conducted. For example, Primasari and Yuniarti (2021) studied 28 teenagers aged 17-21 years and found significant improvements in their subjective well-being after participating in a mindfulness program. Likewise, studies on mindfulness practices among workers in the interactive services sector have found that participants experienced less emotional exhaustion and greater job satisfaction (Hulsheger et al., 2013).

There are two distinct forms of mindfulness practice: formal and informal. The formal practice is mindfulness meditation, paying close attention to one's thoughts, feelings, bodily sensations, and sensory experiences throughout each moment while sitting, lying down, standing, or walking. On the other hand, informal mindfulness practice involves practising awareness throughout routine tasks, including eating, walking, bathing, and engaging with others (Meiklejohn et al., 2012).

In Action Regulation Theory (ART) – a theory of self-regulated, goal-directed behaviour, there are three hierarchical modes of cognitive processing (Hacker, 2003). First is the automated processing, which is the lowest level and is used to regulate routine and specific tasks. Second is knowledge-based processing, which regulates schematic action patterns at the intermediate level. Meanwhile, mindful processing is the highest level of cognitive processing, which is used to analyse and synthesise new task information (Addas & Pinsonneault, 2018; Frese, 2007).

Mindfulness is especially useful when someone carries out non-routine or unfamiliar tasks (Addas & Pinsonneault, 2018). Mindfulness is better than automated processing since it enables people to assess and integrate new information effectively and modify action plans as necessary. Theoretically, an individual exhibiting high mindfulness is expected to be receptive not only to novel stimuli and insights but also to diverse perspectives viewed from a broader angle (Beitel et al., 2005). Hence, it creates opportunities to learn effectively and thereby improve one's performance (Addas & Pinsonneault, 2018).

## 3. METHODS

This research applies a quantitative approach to establish a relationship model between mindfulness practices and construction workers' performance in Indonesia. The literature

review identified 15 mindfulness practice variables (marked with code 'X') that can influence workers' performance (marked with code 'Y'), as presented in Table 1. A questionnaire survey was conducted to measure Indonesian construction workers' perceptions of mindfulness practice and its effects on their performance.

*Table 1: Research variables*

| Code | Variable | Sources |
|---|---|---|
| ***Mindfulness Practices (Independent Variables)*** | | |
| X1 | I can focus on the present moment | Leung et al. (2024) |
| X2 | When I notice an absence of mind, I gently return to the experience of the present moment | Leung et al. (2024) |
| X3 | I feel connected to my experience in the present moment | Leung et al. (2024) |
| X4 | I do not pay attention to what I am doing | Leung et al. (2024) |
| X5 | I am easily distracted | Leung et al. (2024) |
| X6 | I spend time identifying and prioritising my activities | Melagoda and Rowlinson (2022) |
| X7 | I discuss alternatives for how to do my work activities better | Melagoda and Rowlinson (2022) |
| X8 | When discussing emerging issues with coworkers, I usually discuss what to look out for | Melagoda and Rowlinson (2022) |
| X9 | I discuss mistakes and ways to learn from them | Melagoda and Rowlinson (2022) |
| X10 | When mistakes happen, I discuss how I could have prevented them | Melagoda and Rowlinson (2022) |
| X11 | I understand my strengths and weaknesses | Leung et al. (2024) |
| X12 | I can identify my coworkers' talents and skills | Melagoda and Rowlinson (2022) |
| X13 | I discuss unique skills with my team so that we know who has relevant specialised skills and knowledge | Melagoda and Rowlinson (2022) |
| X14 | When attempting to resolve a problem, I take advantage of the unique skills of my coworkers | Melagoda and Rowlinson (2022) |
| X15 | When a crisis occurs, I rapidly pool our collective expertise to resolve it | Melagoda and Rowlinson (2022) |
| ***Workers' Performance (Dependent Variable)*** | | |
| Y1 | Mindfulness practices can improve my work performance on projects | Addas and Pinsonneault (2018); Breuer and Gebauer (2011); Daniel et al. (2022); Good et al. (2015); Leung et al. (2024); Mellner et al. (2022); Yesilkus and Ozbozkurt (2020) |

The respondents in this study were selected using a purposive sampling method, based on their active involvement in construction projects. All participants have relevant work experience in the construction sector. However, this sample may not fully represent the broader Indonesian construction workforce, and this limitation should be considered when interpreting the results. A Likert scale is used with 1 representing 'never' to 5 representing 'always' for X (mindfulness practices), and 1 representing 'strongly disagree' to 5 representing 'strongly agree' for Y (performance). The questionnaire was distributed online via Google Forms and yielded 93 responses. However, the results of the

preliminary examination showed that 13 responses were invalid, so only 80 responses were used for analysis. Table 2 presents the respondents' profile.

*Table 2: Respondent profiles*

| Profile | Sum | % | Profile | Sum | % |
|---|---|---|---|---|---|
| ***Age*** | | | ***Gender*** | | |
| 21 – 30 years | 56 | 70,0 | Male | 54 | 67,50 |
| 31 – 40 years | 21 | 26,25 | Female | 26 | 32,50 |
| 41 – 50 years | 3 | 3,75 | Total | 80 | 100 |
| Total | 80 | 100 | ***Job Position*** | | |
| ***Educational Background*** | | | Project manager | 8 | 10,00 |
| High School | 5 | 6,25 | Supervisor/engineer | 27 | 33,75 |
| 3-years Diploma | 33 | 41,25 | QS/estimator | 30 | 37,50 |
| Bachelor | 39 | 48,75 | Engineering staff | 3 | 3,75 |
| Master | 3 | 3,75 | Coelie | 4 | 5,00 |
| Total | 80 | 100 | Others | 8 | 10,00 |
| ***Affiliation*** | | | Total | 80 | 100 |
| Consultant | 25 | 31,25 | ***Working Experience in Construction*** | | |
| Contractor | 22 | 27,50 | Less than 5 years | 54 | 67,50 |
| Employer | 27 | 33,75 | 5 – 10 years | 23 | 28,75 |
| Government | 6 | 7,50 | 10 – 15 years | 2 | 2,50 |
| Total | 80 | 100 | 15 – 20 years | 1 | 1,25 |
| | | | Total | 80 | 100 |

The data obtained was tested for validity and reliability with SPSS software. To assess the validity of the items, a comparison is made between the R count value (based on the Corrected Item-Total Correlation Value) and the R table. By considering the degree of freedom of 78 and probability 0.05, the R table value is 0.2199. A variable is considered valid if R count > R table. Meanwhile, reliability can be seen from the Cronbach's alpha value for each variable above 0.7. The data was then analysed using the Multiple Linear Regression (MLR) technique. It is a statistical technique that uses several independent variables to predict the outcome of a dependent variable. In this study, MLR is used to model the linear relationship between the explanatory variables (mindfulness practices) and the response variable (workers' performance).

## 4. RESULTS

The results of the validity and reliability test analysis for each research variable are presented in Table 3, which displays the Total-Item Statistics matrix. Based on this matrix, it can be concluded that all research variables except X4 and X5 are valid and reliable, as the Corrected Item-Total Correlation is greater than 0.2199 and the Cronbach's Alpha is greater than 0.7. X4 and X5 are declared invalid, so that all variables other than X4 and X5 are used as input for multiple regression analysis.

*Table 3: Validity and reliability tests*

| Code | Corrected Item-Total Correlation | Cronbach's Alpha if Item Deleted | Validity | Reliability |
|---|---|---|---|---|
| X1 | 0.474 | 0.748 | valid | reliable |
| X2 | 0.528 | 0.741 | valid | reliable |
| X3 | 0.411 | 0.753 | valid | reliable |
| X4 | -0.171 | 0.817 | invalid | reliable |
| X5 | -0.288 | 0.826 | invalid | reliable |
| X6 | 0.514 | 0.746 | valid | reliable |
| X7 | 0.579 | 0.738 | valid | reliable |
| X8 | 0.543 | 0.741 | valid | reliable |
| X9 | 0.591 | 0.739 | valid | reliable |
| X10 | 0.439 | 0.750 | valid | reliable |
| X11 | 0.500 | 0.747 | valid | reliable |
| X12 | 0.544 | 0.742 | valid | reliable |
| X13 | 0.547 | 0.742 | valid | reliable |
| X14 | 0.355 | 0.757 | valid | reliable |
| X15 | 0.511 | 0.744 | valid | reliable |
| Y1 | 0.540 | 0.743 | valid | reliable |

Likewise, in the reliability test, the Cronbach's Alpha value is considered reliable if it exceeds 0.7. The results of Cronbach's Alpha analysis for all items are greater than 0.7, so that all variables are reliable. Overall, the Cronbach's Alpha value obtained was 0.816, as seen in Figure 1.

**Reliability Statistics**

| Cronbach's Alpha | Cronbach's Alpha Based on Standardized Items | N of Items |
|---|---|---|
| .768 | .816 | 16 |

*Figure 1: Overall reliability*

The next step is to carry out a multiple linear regression analysis. Figure 2 displays the results of the multiple linear regression analysis by SPSS. Based on these results, the following research model can be obtained (Eq. 1):

$$Y = 1.446 - 0.200X_1 - 0.003X_2 + 0.087X_3 - 0.013X_6 - 0.019X_7 + 0.210X_8 - 0.128X_9 - 0.017X_{10} + 0.204X_{11} + 0.356X_{12} + 0.040X_{13} - 0.083X_{14} + 0.198X_{15} \quad (01)$$

To test the suitability of the independent variable for the dependent variable by testing simultaneously, a simultaneous test (F test) is carried out, which can be found in the ANOVA table. Based on Figure 3, the significance value is 0.000, which is less than 0.05. This means that the independent variable (X) has a significant influence simultaneously on the dependent variable (Y).

**Coefficients[a]**

| Model | | Unstandardized Coefficients B | Unstandardized Coefficients Std. Error | Standardized Coefficients Beta | t | Sig. | 95.0% Confidence Interval for B Lower Bound | 95.0% Confidence Interval for B Upper Bound | Correlations Zero-order | Correlations Partial | Correlations Part | Collinearity Statistics Tolerance | Collinearity Statistics VIF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | (Constant) | 1.446 | .624 | | 2.319 | .024 | .201 | 2.692 | | | | | |
| | X1 | -.200 | .121 | -.199 | -1.659 | .102 | -.442 | .041 | .167 | -.200 | -.158 | .629 | 1.589 |
| | X2 | -.003 | .100 | -.004 | -.028 | .977 | -.202 | .196 | .156 | -.004 | -.003 | .593 | 1.688 |
| | X3 | .087 | .109 | .088 | .796 | .429 | -.131 | .305 | .275 | .098 | .076 | .742 | 1.347 |
| | X6 | -.013 | .121 | -.013 | -.110 | .913 | -.255 | .229 | .137 | -.014 | -.010 | .650 | 1.538 |
| | X7 | -.019 | .113 | -.021 | -.165 | .869 | -.245 | .208 | .293 | -.020 | -.016 | .574 | 1.741 |
| | X8 | .210 | .116 | .232 | 1.806 | .076 | -.022 | .442 | .437 | .217 | .172 | .545 | 1.833 |
| | X9 | -.128 | .128 | -.131 | -1.007 | .318 | -.383 | .126 | .195 | -.123 | -.096 | .534 | 1.873 |
| | X10 | -.017 | .100 | -.020 | -.171 | .865 | -.217 | .183 | .199 | -.021 | -.016 | .660 | 1.516 |
| | X11 | .204 | .123 | .201 | 1.665 | .101 | -.041 | .449 | .326 | .201 | .158 | .621 | 1.611 |
| | X12 | .356 | .117 | .374 | 3.034 | .003 | .122 | .591 | .511 | .350 | .288 | .593 | 1.685 |
| | X13 | .040 | .128 | .041 | .316 | .753 | -.215 | .296 | .336 | .039 | .030 | .527 | 1.897 |
| | X14 | -.083 | .111 | -.089 | -.750 | .456 | -.304 | .138 | .220 | -.092 | -.071 | .639 | 1.564 |
| | X15 | .198 | .111 | .224 | 1.781 | .079 | -.024 | .421 | .443 | .214 | .169 | .572 | 1.748 |

a. Dependent Variable: Y2

*Figure 2: Multiple linear regression*

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 15.730 | 13 | 1.210 | 3.448 | .000[b] |
| | Residual | 23.158 | 66 | .351 | | |
| | Total | 38.887 | 79 | | | |

a. Dependent Variable: Y2

b. Predictors: (Constant), X15, X6, X10, X14, X3, X1, X2, X12, X11, X7, X9, X8, X13

*Figure 3: ANOVA result*

The final step is to measure the model's ability to explain how much influence the independent variables simultaneously have on the dependent variable. This is shown in the model summary table (Figure 4). Based on the analysis, it is known that the R-squared value is 0.476. This figure shows that the independent variable (X) exerts a moderate influence on the dependent variable (Y), at 47.6%. Meanwhile, the other 52.4% comes from various other factors outside the scope of this research.

**Model Summary[b]**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics R Square Change | Change Statistics F Change | Change Statistics df1 | Change Statistics df2 | Change Statistics Sig. F Change |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .636[a] | .404 | .287 | .592 | .404 | 3.448 | 13 | 66 | .000 |

a. Predictors: (Constant), X15, X6, X10, X14, X3, X1, X2, X12, X11, X7, X9, X8, X13

b. Dependent Variable: Y2

*Figure 4: The coefficient of determinant test (R-squared)*

## 5. DISCUSSION

This research established a model linking mindfulness practice to construction workers' performance in Indonesia. This model creates a linear relationship that best approximates all the individual data. It allows construction organisations to predict the effect of mindfulness practices on employee performance based on information available on multiple independent variables. Based on the analysis, the coefficient of determination was obtained, indicating that the independent variable accounts for 47.6% of the variance

in the dependent variable, which falls within the moderate influence category. Thus, 52.4% of the independent variables are outside the scope of this research.

This study includes 15 variables that primarily capture individual mindfulness, awareness, reflection, and team-interaction behaviours among construction workers. These variables provide a detailed view of how workers focus on the present moment, manage attention, learn from mistakes, and collaborate with coworkers. However, the model does not fully control for other important confounding factors, such as psychological conditions (e.g., stress, motivation, or fatigue), work environment (e.g., safety climate, workload, or supervision quality), project characteristics (e.g., project complexity, time pressure, or resource availability), and socio-cultural influences (e.g., communication style, hierarchy, or teamwork culture) (Adah et al., 2025; Hansen, 2026; Yu et al., 2026).

These external factors may also significantly influence worker performance and may interact with the measured mindfulness-related behaviours. For example, a supportive work environment or strong team culture could enhance both mindfulness practices and performance outcomes, while high stress or poor site conditions could reduce them (Yu et al., 2026). Therefore, although the study found that mindfulness-related variables explain 47.6% of worker performance, this result should be interpreted with caution, as the effect may not be attributable solely to mindfulness practices but may also be influenced by unmeasured contextual factors.

The research model show that several variables have stronger positive influence on worker performance, especially X12 (identifying coworkers' talents and skills, $\beta$ = 0.356), X8 (discussing what to look out for with coworkers, $\beta$ = 0.210), X11 (understanding own strengths and weaknesses, $\beta$ = 0.204), and X15 (rapidly pooling team expertise in crisis, $\beta$ = 0.198). These findings suggest that team awareness, communication, and the ability to recognise both individual and collective strengths are key drivers of performance (Gao et al., 2026; Shaikh et al., 2023).

On the other hand, some variables show negative or very small effects, such as X1 (focusing on the present moment, $\beta$ = -0.200), X9 (discussing mistakes, $\beta$ = -0.128), and X14 (using coworkers' skills in problem-solving, $\beta$ = -0.083). This indicates that not all mindfulness-related practices contribute equally to performance. Therefore, it highlights that collaborative and team-based mindfulness practices may have a more practical impact compared to purely individual-focused practices in the construction work context (Daniel et al., 2023; Leung et al., 2024).

This research contributes to the construction management discipline by providing an empirical study related to mindfulness in the construction sector. This research conforms to the influence of mindfulness practice on construction workers' performance as studied by Leung et al. (2024). Kutsch (2020) understands a project as a mindful entity existing for a finite period of time, supported by people, structures, and processes. Project managers and their teams face an increasing number of duties as projects grow in size and complexity. Interest in examining the applicability of current organisational theories to projects has grown since completing a project necessitates a combination of hard and soft skills (Reich et al., 2013). One hypothesis that has been identified as promising for the development of these skills is the mindfulness theory (Geraldi et al., 2021). Hence, mindfulness practice is essential for both individual and group project management (Daniel et al., 2023).

On the other hand, data obtained from construction workers in Indonesia provides strong practical implications of this research for the Indonesian construction context. This research quantitatively reveals the positive relationship between mindfulness practice and construction workers' performance. Thus, this study informs the significance of mindfulness practice for construction workers in Indonesia. Construction organisations should pay attention to this issue and incorporate this practice in their project management. Construction organisations can utilise the results of this research to better understand how mindfulness practices can improve worker performance and, thereby, encourage sustainable implementation of mindfulness practices among workers.

Construction organisations can consider implementing mindfulness training programs. In many studies, mindfulness training has become an important part of the therapeutic plan (Kaviani & Hatami, 2016). Langer and Moldoveanu (2000) believe that mindfulness practice will be useful for addressing various social problems. Similarly, Kaviani and Hatami (2016) encourage that mindfulness training be employed in a variety of social contexts. Huurne et al. (2022) encourage the adoption of construction technology innovation to prioritise a more mindful process instead of a disruptive implementation. All this concludes that mindfulness practice can help a person to be more effective in a complex environment, such as a construction project.

## 6. CONCLUSIONS

This research is among the few studies that quantitatively examine the relationship between mindfulness practice and worker performance in the construction sector. It highlights the significance of mindfulness practices for construction worker performance so that construction organisations can utilise the findings of this research to plan mindfulness training programs to improve both individual and organisational project performance. Apart from that, construction organisations can also use these mindfulness training programs as part of efforts to improve the mental health of construction workers, which has been the focus of attention from various groups, including the government. Fulfilling the mental well-being of construction workers is one form of achieving Sustainable Development Goal 3 (SDG-3), which was launched by the United Nations.

As an initial study, this research contributes to the emerging body of knowledge on mindfulness practice in the workplace by examining its influence on construction workers' performance. However, this study did not identify the type of mindfulness practice implemented. There are many types of mindfulness practices that can be done, such as Vipassana meditation, yoga, deep breathing, and mindful eating. Therefore, this research does not examine how a mindfulness practice operates and influences workers' performance. Clarifying this is recommended in future research so that comparisons can be made between one type of mindfulness practice and another on worker performance. This study also relies on self-reported data, which may introduce bias. Future studies should include objective measures, such as supervisor evaluations or performance KPIs, to improve accuracy. This will help provide a more complete understanding of the relationship.

## 7. REFERENCES

Adah, C. A., Aghimien, D. O., & Oshodi, O. (2025). Work–life balance in the construction industry: A bibliometric and narrative review. *Engineering, Construction and Architectural Management*, *32*(1), 38-58. https://doi.org/10.1108/ECAM-02-2023-0150

Addas, S., & Pinsonneault, A. (2018). E-mail interruptions and individual performance: Is there a silver lining?. *MIS Quarterly, 42*(2), 381-405. https://doi.org/10.25300/MISQ/2018/13157

Bahl, S., Milne, G. R., Ross, S. M., Mich, D. G., Grier, S. A., Chugani, S. K., Chan, S. S., Gould, S., Cho, Y. N., Dorsey, J. D., Schindler, R. M., Murdock, M. R., & Boesen-Mariani, S. (2016). Mindfulness: Its transformative potential for consumer, societal, and environmental well-being. *Journal of Public Policy & Marketing, 35*(2), 198-210. https://doi.org/10.1509/jppm.15.139

Batubara, Z. Z. D. S., Safitri, A. R., & Siregar, S. D. (2021). Faktor kelelahan kerja pada pekerja konstruksi di Proyek Gama Land. *Jurnal Kesehatan Global, 4*(1), 33-40. https://doi.org/10.33085/jkg.v4i1.4751

Bazarko, D., Cate, R. A., Azocar, F., & Kreizer, M. J. (2013). The impact of an innovative mindfulness-based stress reduction program on the health and well-being of nurses employed in a corporate setting. *Journal of Workplace Behavioral Health, 28*(2), 107–133. https://doi.org/10.1080/15555240.2013.779518

Beck, R., Schott, K., & Gregory, R. W. (2011). Mindful management practices in global multivendor ISD outsourcing projects. *Scandinavian Journal of Information Systems, 23*(2), 5-28. https://aisel.aisnet.org/sjis/vol23/iss2/1

Beitel, M., Ferrer, E., & Cecero, J. J. (2005). Psychological mindedness and awareness of self and others. *Journal of Clinical Psychology, 61*(6), 739-750. https://doi.org/10.1002/jclp.20095

Blanck, P., Perleth, S., Heidenreich, T., Kroger, P., Ditzen, B., Bents, H., & Mander, J. (2018). Effects of mindfulness exercises as stand-alone intervention on symptoms of anxiety and depression: Systematic review and meta-analysis. *Behavior Research and Therapy, 102*, 25-35. https://doi.org/10.1016/j.brat.2017.12.002

BPS (Badan Pusat Statistik). (2023). *Construction in Figures, Vol. 12*. Badan Pusat Statistik, Jakarta, Indonesia.

Breuer, H., & Gebauer, A. (2011, March). *Mindfulness for innovation: Future scenarios and high reliability organizing preparing for the unforeseeable*. SKM Conference for Competence-based Strategic Management, Linz, Austria. https://www.uxberlin.com/wp-content/uploads/2012/12/2011_Mindfulness1.pdf

Brown, K. W., Ryan, R. M., & Creswell, J. D. (2007). Mindfulness: theoretical foundations and evidence for its salutary effects. *Psychological Inquiry, 18*(4), 211–237. https://doi.org/10.1080/10478400701598298

Burmansah, B., Rugaiyah, R., & Mukhtar, M. (2020). Mindful leadership: the ability of leader to establish connection to others, community, and deal with changes skillfully - a case study of Buddhist higher education institute leader. *International e-Journal of Educational Studies, 4*(7), 133-149. https://doi.org/10.31458/iejes.618343

Burmansah, B., Sutawan, K., Putra, H. R. P., & Ramadhan, A. (2022). A mindful leader: Mindfulness strengthens the leadership ability of the leaders in Higher Education Institute. *Al-Ishlah: Jurnal Pendidikan, 14*(4), 6587-6602. https://doi.org/10.35445/alishlah.v14i4.2734

Chandler, D., & Hwang, H. (2015). Learning from learning theory: A model of organizational adoption strategies at the microfoundations of institutional theory. *Journal of Management, 41*(5), 1446-1476. https://doi.org/10.1177/0149206315572698

Chiesa, A., & Serretti, A. (2014). Are mindfulness-based interventions effective for substance use disorders? A systematic review of the evidence. *Substance Use & Misuse, 49*(5), 492-512. https://doi.org/10.3109/10826084.2013.770027

Creswell, J. D. (2017). Mindfulness interventions. *Annual Review of Psychology, 68*, 491-516. https://doi.org/10.1146/annurev-psych-042716-051139

Dane, E. (2011). Paying attention to mindfulness and its effects on task performance in the workplace. *Journal of Management, 37*(4), 997-1018. https://doi.org/10.1177/0149206310367948

Dane, E., & Brummel, B. J. (2014). Examining workplace mindfulness and its relations to job performance and turnover intention. *Human Relations, 67*(1), 105-128. https://doi.org/10.1177/0018726713487753

Daniel, C., Daniel, P. A., & Smyth, H. (2022). The role of mindfulness in the management of projects: Potential opportunities in research and practice. *International Journal of Project Management, 40*, 849-864. https://doi.org/10.1016/j.ijproman.2022.07.003

Daniel, C., Hulsheger, U. R., Kudesia, R. S., Sankaran, S., & Wang, L. (2023). Mindfulness in projects. *Project Leadership and Society, 4*, 100086. https://doi.org/10.1016/j.plas.2023.100086

Davis, D. M., & Hayes, J. A. (2011). What are the benefits of mindfulness? A practice review of psychotherapy-related research. *Psychotherapy, 48*(2), 198-208. https://doi.org/10.1037/a0022062

Ditrich, T. (2018). Meditation and ethics in education. In D. K. Ura & J. Phuntsho (Eds.), *Proceedings of the second international conference on Vajrayāna buddhism*, (pp. 169-189). Centre for Bhutan & GNH

Studies. https://www.bhutanstudies.org.bt/publicationFiles/ConferenceProceedings/Vaj%20Proceedings%2027th%20Sept%2018%20for%20printing%20jp.pdf

Eisenbeiss, S. A., & van Knippenberg, D. (2015). On ethical leadership impact: the role of follower mindfulness and moral emotions. *Journal of Organizational Behavior, 36*, 182–195. https://doi.org/10.1002/job.1968

Epel, E., Daubenmier, J., Moskowitz. J. T., Folkman, S., & Blackburn, E. (2009). Can meditation slow rate of cellular aging? Cognitive stress, mindfulness, and telomeres. *Annals of the New York Academy of Sciences*, *1172*, 34–53. https://doi.org/10.1111/j.1749-6632.2009.04414.x

Feldbauer, R. R. (2019). *Mindful project management: A framework to enhance underperformance managing large hospital builds by incorporating principles adapted from High Reliability Organizations* [Doctoral Thesis, Business Administration, University of Liverpool, England]. https://livrepository.liverpool.ac.uk/3043721/1/H00016194_May2019.pdf

Frese, M. (2007). The psychological actions and entrepreneurial success: An action theory approach. In J. R. Baum, M. Frese, & R. A. Baron (Eds.), *The psychology of entrepreneurship* (1st ed., pp. 151–188). Taylor & Francis. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315750989-16/psychological-actions-entrepreneurial-success-action-theory-approach

Frimpong, S., Antwi, A. B., Sunindijo, R. Y., Wang, C. C., Ampratwum, G., Dansoh, A., Boateng, E. S., Hagan, J. A., & Mensah, P. A. (2022). Health status of young construction workers in the Global South: The case of Ghana. *Safety Science, 148*, 105673. https://doi.org/10.1016/j.ssci.2022.105673

Gao, L., Li, H., Zhang, N., & Deng, X. (2026). From individuals to teams: resilience as a driver of international construction success. *Engineering, Construction and Architectural Management, Ahead-of-Print.* https://doi.org/10.1108/ECAM-08-2025-1331

Garrison, R. (2021). A buddhist context for mindfulness. *The Journal of Individual Psychology, 77*(4), 392-401. https://doi.org/10.1353/jip.2021.0033

Geraldi, J., Soderlund, J., & Marrewijk, A. V. (2021). Bright and dark spots in project studies: Continuing efforts to advance theory development and debate. *Project Management Journal, 52*(3), 227–236. https://doi.org/10.1177/87569728211004064

Good, D. J., Lyddy, C. J., Glomb, T. M., Bono, J. E., Brown, K. W., Duffy, M. K., Baer, R. A., Brewer, J. A., & Lazar, S. W. (2015). Contemplating mindfulness at work: An integrative review. *Journal of Management, 42*(1), 114-142. https://doi.org/10.1177/0149206315617003

Hacker, W. (2003). Action Regulation Theory: A practical tool for the design of modern work processes?. *European Journal of Work and Organizational Psychology, 12*(2), 105-130. https://doi.org/10.1080/13594320344000075

Hansen, S. (2022). Identifikasi jenis bahaya dan parameter penilaian bahaya pada pekerjaan konstruksi. *Paduraksa: Jurnal Teknik Sipil Universitas Warmadewa, 11*(1), 94-102. https://pdfs.semanticscholar.org/97ef/fbe217c0ccf2d15d1b1743f1db9980fbbd22.pdf

Hansen, S. (2023). Construction workers' mental health factor domains. *Media Komunikasi Teknik Sipil, 29*(2), 195-204. https://doi.org/10.14710/mkts.v29i2.57822

Hansen, S. (2025). Analisis faktor karakteristik dan manfaat praktik kesadaran penuh (Mindfulness) dalam proyek konstruksi. *Cantilever: Jurnal Penelitian dan Kajian Bidang Teknik Sipil, 14*(2), 133-142. https://doi.org/10.35139/cantilever.v14i2.332

Hansen, S. (2026). Root causes of mental health disorders among construction workers in Indonesia: An integrative literature review and exploratory factor analysis. *INTI Journal, 2026*(1), 97-112. https://doi.org/10.61453/INTIj.20260113

Hansen, S., Rostiyanti, S.F., and Fajra, A. (2023). Tinjauan dan rekomendasi standar kompetensi kerja nasional Indonesia quantity surveyor (SKKNI QS). *Jurnal Ilmiah Desain & Konstruksi, 22*(2), 180-187. https://ejournal.gunadarma.ac.id/archive/index.php/dekons/article/view/9044

Hulsheger, U. R., Alberts, H. J., Feinholdt, A., & Lang, J. W. (2013). Benefits of mindfulness at work: the role of mindfulness in emotion regulation, emotional exhaustion, and job satisfaction. *Journal of Applied Psychology, 98*(2), 310–325. https://doi.org/10.1037/a0031313

Huurne, R. t., Scholtenhuis, L. O., & Doree, A. (2022). Change triggers in early innovation stages: How technology pilots enable routine reflection. *Journal of Construction Engineering and Management, 148*(9), 05022005. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002307

Karunamuni, N., & Weerasekera, R. (2019). Theoretical foundations to guide mindfulness meditation: A path to wisdom. *Current Psychology, 38*, 627-646. https://doi.org/10.1007/s12144-017-9631-7

Kaviani, H., & Hatami, N. (2016). Link between mindfulness and personality-related factors including empathy, theory of mind, openness, pro-social behaviour and suggestibility. *Clinical Depression, 2*(4), 1000119. https://doi.org/10.4172/2572-0791.1000119

Khan, I. (2018). *Does team mindfulness predict project team performance? The role of team cohesion and effective team leadership* [Master thesis, Department of Management Sciences, Capital University of Science and Technology, Islamabad, Pakistan]. https://thesis.cust.edu.pk/UploadedFiles/Ikram%20Khan%20updated%20final-8-oct-2018.pdf

Kutsch, E. (2020). Mindful project management: Resilient performance beyond the risk horizon. *PM World Journal, IX*(X), 1-6. https://pmworldlibrary.net/wp-content/uploads/2020/10/pmwj98-Oct2020-Kutsch-mindful-project-management.pdf

Langer, E. J., & Moldoveanu, M. (2000). Mindfulness research and the future. *Journal of Social Issues, 56*(1), 129-139. https://doi.org/10.1111/0022-4537.00155

Leroy, H., Anseel, F., Dimitrova, N. G., & Sels, L. (2013). Mindfulness, authentic functioning, and work engagement: a growth modeling approach. *Journal of Vocational Behavior, 82*(3), 238–247. https://doi.org/10.1016/j.jvb.2013.01.012

Leung, M. Y., Ahmed, K., & Famakin, I. O. (2024). Impact of mindfulness-based stress reduction intervention on the performance of construction professionals. *Engineering, Construction and Architectural Management, 31*(2), 662-680. https://doi.org/10.1108/ECAM-01-2022-0005

Li, H., Wu, Y., Cao, D., & Wang, Y. (2021). Organizational mindfulness towards digital transformation as a prerequisite of information processing capability to achieve market agility. *Journal of Business Research, 122*, 700–712. https://doi.org/10.1016/j.jbusres.2019.10.036

Liang, Q., & Leung, M. Y. (2015). Analysis of the relationships between mindfulness and stress for construction professionals. In A. B. Raidén & E. Aboagye-Nimo (Eds.), *Proceeding of the 31st annual ARCOM conference* (pp. 469-478). Association of Researchers in Construction Management. https://www.arcom.ac.uk/-docs/proceedings/88344ab39c81f196b3bbfc67c4b1ba56.pdf

Meiklejohn, J., Phillips, C., Freedman, M. L., Griffin, M. L., Biegel, G., Roach, A., Frank, J., Burke, C., Pinger, L., Soloway, G., Isberg, R., Sibinga, E., Grossman, L., & Saltzman, A. (2012). Integrating mindfulness training into K-12 education: Fostering the resilience of teachers and students. *Mindfulness, 3*, 291-307. https://doi.org/10.1007/s12671-012-0094-5

Melagoda, D. G., & Rowlinson, S. (2022). Collective mindfulness: A dimension of construction safety climate. *Proceedings of the 5th European international conference on industrial engineering and operations management* (pp. 1262-1271). IEOM Society International. https://ieomsociety.org/proceedings/2022rome/260.pdf

Mellner, C., Osika, W., & Niemi, M. (2022). Mindfulness practice improves managers' job demands-resources, psychological detachment, work-nonwork boundary control, and work-life balance – A randomized controlled trial. *International Journal of Workplace Health Management, 15*(4), 493-514. https://doi.org/10.1108/IJWHM-07-2021-0146

Oni, O. Z., Olanrewaju, A. L., Khor, S. C., & Akinbile, B. F. (2023). A comparative analysis of construction workers' mental health before and during COVID-19 pandemic in Nigeria. *Frontiers in Engineering and Built Environment, 3*(1), 63-75. https://doi.org/10.1108/FEBE-05-2022-0018

Primasari, A., & Yuniarti, K. W. (2021). Enjoying every moment: Improving adolescent's subjective well-being through adolescent mindfulness program. *Gadjah Mada Journal of Professional Psychology, 7*(2), 115-128. https://doi.org/10.22146/gamajpp.65594

Radiani, W. A. (2021), Mindfullness dan self regulated learning technique dalam mengembangkan pendidikan karakter. *Prosiding Konseling Kearifan Nusantara (KKN), 1*, 49-60. https://proceeding.unpkediri.ac.id/index.php/kkn/article/view/1396

Reangsing, C., Punsuwun, M. N. S. S., & Schneider, J. K. (2021). Effects of mindfulness interventions on depressive symptoms in adolescents: A meta-analysis. *International Journal of Nursing Studies, 115*, 103848. https://doi.org/10.1016/j.ijnurstu.2020.103848

Reb, J., Narayanan, J., & Chaturvedi, S. (2014). Leading mindfully: Two studies on the influence of supervisor trait mindfulness on employee well-being and performance. *Mindfulness, 5*, 36–45. https://doi.org/10.1007/s12671-012-0144-z

Reich, B. H., Liu, L., Sauer, C., Bannerman, P., Cicmil, S., Cooke-Davies, T., Gemino, A., Hobbs, B., Maylor, H., Messikomer, C., Pasian, B., Semeniuk, M., & Thomas, J. (2013). Developing better theory about project organizations. *International Journal of Project Management, 31*(7), 938–942. https://doi.org/10.1016/j.ijproman.2013.07.001

Sancho, M., De Gracia, M., Rodriguez, R. C., Mallorqui-Bague, N., Sanchez-Gonzalez, J., Trujols, J., Sanchez, I., Jimenez-Murcia, S., & Menchon, J. M. (2018). Mindfulness-based interventions for the treatment of substance and behavioral addictions: A systematic review. *Frontiers in Psychiatry, 9*, 95. https://doi.org/10.3389/fpsyt.2018.00095

Scholtenhuis, L. L. O., Hartmann, T., & Doree, A. G. (2014). Comparing mindfulness in manual and 4D supported coordination practices. *Construction research congress 2014* (pp. 160-168). American Society of Civil Engineers. https://doi.org/10.1061/9780784413517.017

Shaikh, A. Y., Osei-kyei, R., Hardie, M., & Stevens, M. (2023). Review of drivers of teamwork for construction health and safety. *International Journal of Building Pathology and Adaptation, 43*(5), 1074-1120. https://doi.org/10.1108/IJBPA-08-2022-0136

Sharf, R. H. (2015). Is mindfulness buddhist? (and why it matters). *Transcultural Psychiatry*, *52*(4), 470-484. https://doi.org/10.1177/1363461514557561

Solomon, T., & Esmaeili, B. (2021). Examining the relationship between mindfulness, personality, and national culture for construction safety. *International Journal of Environmental Research and Public Health*, *18*, 4998. https://doi.org/10.3390/ijerph18094998

Sunindijo, R. Y., & Kamardeen, I. (2017). Antecedents to mental health symptoms in the Australian construction industry. In P. W. Chan & C. J. Neilson (Eds.), *Proceeding of the 33rd annual ARCOM conference* (pp. 340-349). Cambridge, UK. https://www.arcom.ac.uk/-docs/proceedings/ee2e97ec85d772d0526894c67e7ece0f.pdf

Tijani, B., Jin, X., & Osei-Kyei, R. (2023). Theoretical model for mental health management of project management practitioners in architecture, engineering and construction (AEC) project organizations. *Engineering, Construction and Architectural Management*, *30*(2), 914–943. https://doi.org/10.1108/ECAM-03-2021-0247

Vogus, T. J., & Sutcliffe, K. M. (2007). The impact of safety organizing, trusted leadership, and care pathways on reported medication errors in hospital nursing units. *Medical Care*, *45*(10), 997–1002. https://doi.org/10.1097/MLR.0b013e318053674f

Vogus, T. J., & Welbourne, T. M. (2003). Structuring for high reliability: HR practices and mindful processes in reliability-seeking organizations. *Journal of Organizational Behavior*, *24*, 877–903. https://doi.org/10.1002/job.221

Vogus, T. J., Cooil, B., Sitterding, M., & Everett, L.Q. (2014). Safety organizing, emotional exhaustion, and turnover in hospital nursing units. *Medical Care*, *52*, 870–876. https://doi.org/10.1097/MLR.0000000000000169

Weare, K. (2019). Mindfulness and contemplative approaches in education. *Current Opinion in Psychology*, *28*, 321-326. https://doi.org/10.1016/j.copsyc.2019.06.001

Wilson, D., Talsma, A., & Martyn, K. (2011). Mindfulness: a qualitative description of the behaviors charge nurses enact to safely staff patient care units. *Western Journal of Nursing Research*, *33*, 805–524. https://doi.org/10.1177/0193945910396519

Wright, S., Day, A., & Howells, K. (2009). Mindfulness and the treatment of anger problems. *Aggression and Violent Behavior*, *14*(5), 396-401. https://doi.org/10.1016/j.avb.2009.06.008

Yesilkus, F., & Ozbozkurt, O. B. (2020). A contemporary management practice: Mindfulness in the work settings. *European Journal of Educational and Social Sciences*, *5*(2), 145–158. https://izlik.org/JA62CA53PL

Yu, M., Su, Q., Li, J., & Qin, W. (2026). The influence of organisational mindfulness on construction workers' safety behavior: A dual-path model. *Psychology, Health & Medicine*, *Ahead-of-Print*. https://doi.org/10.1080/13548506.2026.2623560

Zou, Y., Li, P., Hofmann, S. G., & Liu, X. (2020). The mediating role of non-reactivity to mindfulness training and cognitive flexibility: A randomized controlled trial. *Frontiers in Psychology*, *11*, 1053. https://doi.org/10.3389/fpsyg.2020.01053

Kumarihami, Y.B.M.C.S., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Remote work for female professionals in Sri Lankan construction industry: Challenges and expectations. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1455-1469. DOI: https://doi.org/10.31705/WCS.2026.106. Available from: https://ciobwcs.com/papers/

# REMOTE WORK FOR FEMALE PROFESSIONALS IN SRI LANKAN CONSTRUCTION INDUSTRY: CHALLENGES AND EXPECTATIONS

**Y.B.M.C.S. Kumarihami[1], K. Thiruchelvam[2] and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*The construction industry is still male-dominated, and female professionals have to face challenges related to work–life balance, organizational culture, and flexibility in work arrangements. The necessity of remote working was accelerated during the COVID-19 pandemic, creating the opportunities to address these challenges. However, the adoption of remote working in Sri Lankan construction is still limited and underexplored. This study examines the challenges faced by female professionals in remote work and evaluates their expectations regarding organizational support to facilitate effective and sustainable remote working arrangements. A quantitative research approach was adopted, and a questionnaire was administered to collect the data from female architects, engineers, and quantity surveyors who are working in Sri Lankan construction industry. In data analysis, one sample t test was utilized to identify the critical challenges and expectations. The results revealed that workload increases and expectations to be "always available online" and "Lack of resources and facilities (Proper technical tools, network, etc.)" are the critical challenges, and "create scheduled virtual "check-ins" for all team members to share updates" and "Promote digital wellness practices (scheduled break times, no-meeting hours)" are the most critical expectations of female professionals in the Sri Lankan construction industry regarding remote working.. These study findings provide a better understanding for the top-level managers in Sri Lankan construction industry to implement effective remote working facilities for the professionals.*

***Keywords:*** *Construction Industry; Female Professionals; Remote Working; Sri Lanka.*

## 1. INTRODUCTION

The construction industry is usually male dominated, with women contributing up less than 10% of the workforce (Senaratne et al., 2025). The construction industry's reputation for macho attitudes, hostile work environments, and long hours can lead to burnout and psychological disorders among women, resulting in lower job satisfaction, difficulty

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, kumarihamiybmcs.21@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

balancing work and personal life, and intention to leave the profession (Pamidimukkala & Kermanshachi 2022).

In the Sri Lankan construction industry, female workers face some challenges related to family, social, cultural, educational, and industrial barriers (Srivishagan & Thalpage, 2021). Significantly, work-life balance has been a major challenge for Asian women because they have more family obligations than their Western counterparts, which also includes a greater emphasis on caring for aging parents (Cheng & Yang, 2021).

During the Covid-19 period, the remote work concept is more trending in the world. However, this pandemic and the subsequent lockdown measures have expedited the trend of enabling employees to work remotely (Battisti et al., 2022). Various terms are used to describe this phenomenon, such as telework, remote work, e-work, virtual work, distance work, home office, mobile working, remote office work, work from anywhere (WFA), home-based work, and work from home (WFH) (Shirmohammadi et al., 2022). Prior to the COVID-19 pandemic, remote working was recognized but not widely practiced (Battisti et al., 2022). However, many women prefer work-from-home opportunities for their independence and flexibility, allowing them to balance their work and family responsibilities (Loezar-Hernández et al., 2023).

During the COVID-19 pandemic, the Sri Lankan construction industry temporarily shifted to remote work but reverted to on-site operations post-pandemic (Adikaram & Naotunna, 2023). This sector still faces significant challenges in adopting novel technologies, which limits the integration of remote working practices. Despite discussions in other industries regarding remote work strategies (Usman, 2024), there is a lack of specific studies addressing these issues within the Sri Lankan construction sector. Furthermore, while existing research highlights the need for investment in technological infrastructure (Gunawardana & Bandaranayake, 2024), it has not adequately examined gender-specific challenges associated with remote work in this industry. However, there is a lack of studies that asses the remote work for female professionals in Sri Lankan construction industry. Therefore, this study aims to investigate the critical challenges of remote working and the expectations for overcoming them among female professionals in the Sri Lankan construction industry, focusing on the following objectives:

1. Identify challenges and expectations of female professionals on remote working environments in the Sri Lankan construction industry.
2. Examine the variations in perception among the different female professional groups regarding the remote working mode in the Sri Lankan construction industry.
3. Identify the critical challenges and expectations for female professionals under remote working in the Sri Lankan construction industry.

# 2. LITERATURE REVIEW

## 2.1 FEMALE ENGAGEMENT IN CONSTRUCTION INDUSTRY

The construction industry, employing around 220 million people, is a significant economic contributor, but employs less than 10% of female workers compared to 90% of male workers, despite females accounting for 50% of the global workforce (Senaratne et al., 2025). Furthermore, women may leave the industry after their education due to a lack

of familiarity with its culture and the challenges of working in a male-dominated environment (Afolabi et al., 2019). Thus, the remote working concept was trendier during the COVID-19 pandemic among female professionals. As the example, In the consulting sector of the Australian construction industry, females have reported higher overall satisfaction with working from home (WFH) and a greater preference for WFH post-pandemic compared to males (Oo et al., 2023).

In Sri Lankan construction industry, A lack of female representation in construction sector due to various barriers to entry. These challenges are related to family, social, cultural, educational, and industrial barriers (Srivishagan & Thalpage, 2021). Additionally, affecting promotions and work-life balance, unequal recruitment practices, and limited knowledge of available opportunities also affect for the women participation and their future in Sri Lankan construction industry (Vijayaragunathan & Rasanthi, 2019).

## 2.2 REMOTE WORKING MODE

Remote working, also known as flexible working, is becoming a trend as a result of many countries' government-imposed lockdowns or movement restrictions caused by the COVID-19 pandemic (Battisti et al., 2022). Furthermore, COVID-19 pandemic has accelerated the adoption of remote work, changing traditional work structures and employee behaviours (Orzel & Wolniak, 2022). In the construction industry, remote working refers to flexible arrangements that allow professionals to work from places other than traditional workplaces (Azizi et al., 2023). The study from Poland indicates that construction professionals' preference for remote work due to its flexibility, time savings, comfort, environmental sustainability through reduced electricity consumption and emissions and safety benefits accelerated digitization trends during the pandemic (Orzel & Wolniak, 2022). In Sri Lankan construction sector, remote working followed as a short-term crisis response rather than a long-term solution (Adikaram & Naotunna, 2023).

There are two types of remote working arrangements, which are classified as hybrid work models and fully remote conditions (Safira et al., 2023). Full remote working allows employees to work from anywhere without needing to go to the workplace, while hybrid working involves going to the office for a few days and working remotely on other days (Pinheiro & Palma-Moreira, 2025). There are different hybrid working arrangements that are employed in the construction sector such as "at will model," "split week model," "shift work model," and "week by week model" (Devinda et al., 2023).

## 2.3 CHALLENGES OF REMOTE WORKING ENVIRONMENT

According to the culture of the construction industry with long working hours, the remote working options are significantly low among construction workers, and the remote workability ratio for construction occupations is less than the other industries, such as agriculture, manufacturing, and retail trades (Dingel & Neiman, 2020).

The challenges faced by remote workers in their working environment, identified from literature reviews, are presented in Table 1.

*Table1: Challenges faced by remote workers in their working environment*

| Challenges | Code | Authors |
|---|---|---|
| Gender bias and stereotypes in promotions/opportunities | C1 | [1] |
| Lack of mentorship and role models | C2 | [2] |
| Difficulty balancing family responsibilities with demanding work schedules | C3 | [3],[4],[5] |
| Limited visibility and recognition when working remotely | C4 | [6] |
| Exclusion from informal discussions/decision-making networks | C5 | [2],[7] |
| Limited opportunities for leadership roles in remote mode | C6 | [8] |
| Lack of organizational support for career development of remote workers | C7 | [2] |
| Technology access gap (hardware, internet, software) | C8 | [7], [9] |
| Psychological stress/isolation in remote work | C9 | [2] |
| Unfair performance evaluations for remote workers | C10 | [10],[11] |
| Workload increases (expectation to be "always available" online) | C11 | [12] |

[1] Holdsworth et al., (2023); [2] Dilipkumar et al., (2024); [3] Pamidimukkala & Kermanshachi (2022); [4] Irawanto et al., (2021); [5] Loezar-Hernández et al., (2023); [6] Wong et al., (2021); [7] (Žvirelienė & Lipinskienė, 2023); [8] Rodrigo et al., (2024); [9] Onyekwere, (2024); [10] Pinheiro & Palma-Moreira, (2025); [11] Gong et al., (2022); [12] Suratkon & Azlan, (2021)

Table 1 presents the remote working challenges faced by employees that were identified from the literature. In the Australian construction industry, the recruitment of females is much lower than that of males (C1) (Holdsworth et al., 2023).Under remote working, lack of interaction with supervisors lowers the mentorship and guidance (C2) (Dilipkumar et al., 2024). Remote working frequently causes workers to have no clear boundaries between work and personal life. It may result in work overload, and difficult to balance work family responsibilities (C3) (Irawanto et al., 2021). Moreover, it is unclear to remote workers how they can demonstrate their dedication, proficiency, and performance in the absence of in-person interactions (C4) (Wong et al., 2021). The physical isolation under remote working reduces organizational visibility, colleague connections, and networking (C5). This lack of social capital may hinder employees' upward mobility because professional advancement is linked to visibility and advocacy from networked relationships within an organization (Dilipkumar et al., 2024). Apart from that, remote workers struggle for access for the advancement opportunities (C6) (Bell, 2012). In some studies, remote workers are considered as having lower employer support than in- office workers for career development (C7) (Dilipkumar et al., 2024). In contrast, remote workers have to face network issues such as limited internet connectivity and access to reliable devices (C8) (Onyekwere, 2024). However, remote working limits the social interactions, and physical isolation reduces organizational visibility, colleague connections, and networking (C9) (Dilipkumar et al., 2024). Another challenge of remote working is assessing employee performance due to the limited scope for traditional supervision and direct observation (C10) (Pinheiro & Palma-Moreira, 2025). Sometime there are higher pressure with more calls and expectations to be always available online (C11) (Suratkon & Azlan, 2021).

### 2.4 CURRENT SITUATION OF FEMALE PROFESSIONALS ENGAGED IN REMOTE WORK IN THE SRI LANKAN CONSTRUCTION INDUSTRY

During the covid pandemic, the Sri Lankan construction industry implemented remote working arrangements as the emergency solution. But many companies planned to follow on-site work after the pandemic situation was settled (Adikaram & Naotunna, 2023). In the Sri Lankan context, female engagement for remote working exhibits a lower level due to their inadequate technical skills, low confidence in digital technologies, and social organizational barriers. In addition, poor professional networking, low interest in ICT skills, and insufficient risk assessment further hinder women's engagement with digital platforms (Kodithuwakku & De Silva, 2025). Furthermore, the use of advanced digital technologies for virtual reality, is also lower in the Sri Lankan construction industry (Perera et al., 2023). Thus, the facilities for remote working arrangements are poor in the Sri Lankan construction industry. Thus, identifying challenges and expectations of employees to work remote working arrangements is significant to further implement in the Sri Lankan construction industry. Moreover, identifying challenges faced by female professionals with the cultural and social environment is most helpful to implement long-term remote working arrangements in the Sri Lankan context without considering gender inequalities.

## 3. RESEARCH METHODOLOGY

The aim of the study is investigating remote working challenges and expectations of female professionals in the Sri Lankan construction industry. The study adapts the quantitative method, which involves the collection and analysis of numerical data (Rana et al., 2021). Figure 1 shows the developed research design of this study.

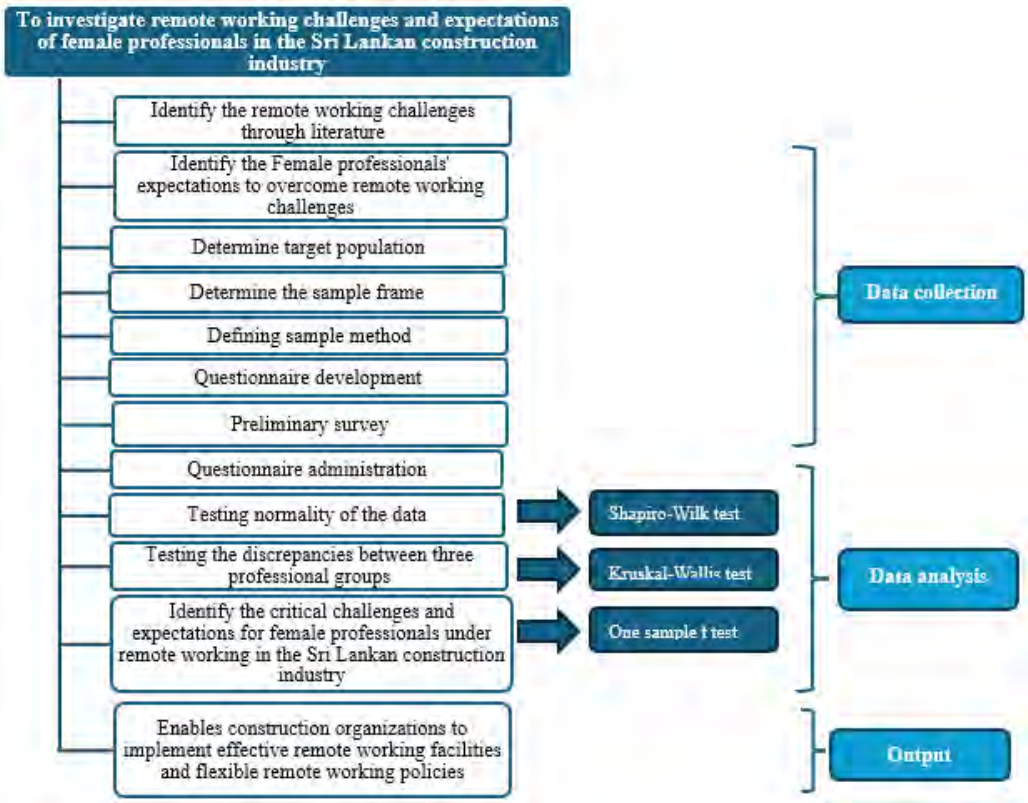



*Figure 1:Research design*

Initially, a literature review was conducted to identify challenges of remote working. Furthermore, it helped to identify current situation of remote working in Sri Lankan construction industry. The target population of this study consist of construction female professionals namely architects, engineers and quantity surveyors working in Sri Lankan construction industry. The sample frame is female professionals in category of engineer, architect and quantity surveying who are working in Sri Lankan construction industry and having experience more than 3 years. Further, purposive sample was used to get views only from female professionals who have knowledge or experience in remote or hybrid working arrangements (Huwae et al., 2024).

A questionnaire was used as a data collection tool because data was to be collected from a larger number of respondents within a shorter time (Ahmed et al., 2018).

According to Hertzog (2008), the recommended sample size for a preliminary survey is in the 10-40 range. Thus, following the identification of remote working challenges through the literature review, to validate their relevance to the Sri Lankan construction industry, a preliminary survey was conducted among the 20 female construction professionals who are aligned with the sample frame. Accordingly, selected female professionals have more than 15 years of overall industry experience and over 5 years of remote working experience in the Sri Lankan construction industry. Respondents were asked to indicate whether each challenge was applicable to the Sri Lankan construction industry, using a "Yes" or "No" response. Challenges that received more than 30% "Yes" responses were retained for the development of the questionnaire. This threshold exceeds the minimum response rate of 27.8% recommended by Lund (2021), for selecting critical factors in questionnaire surveys. Moreover, the expectations of female professionals for overcoming remote working challenges were derived from respondents' opinions provided through an open-ended question in the preliminary survey.

After the preliminary survey, a questionnaire survey was distributed to 75 construction industry female professionals to collect data, as it is sufficient to obtain a moderate response rate of 30–50% (Faleiros et al., 2016). The questionnaires were distributed via Email, LinkedIn, and WhatsApp to enhance accessibility and encourage participation.

After the data collection, a normality test was conducted to check the normality of the data. Shapiro-Wilk test was conducted to check the normality of the data as the sample size (n) < 50 (Avram & Mărușteri, 2022) Hypotheses of the Shapiro-Wilk test are as follows:

- Null hypothesis ($H_0$): Data follows a normal distribution.
- Alternative hypothesis (H1): Data does not follow a normal distribution.

If $p > 0.05$ the null hypothesis is accepted. Otherwise, the null hypothesis is rejected.

To achieve objective 2, Kruskal Wallis test, a nonparametric test was conducted to compare the means of three specific groups: female quantity surveyors, architects and engineers. Hypotheses of the Kruskal-Wallis test are as follows:

- Null Hypothesis (H0): There is no statistically significant difference between the ideas of the groups.
- Alternative Hypothesis (H1): There is a statistically significant difference between the ideas of the groups.

If $p > 0.05$ the null hypothesis is accepted. Otherwise, the null hypothesis is rejected.

According to Ghasemi and Zahediasl (2012), the Central Limit Theorem ensures that the sampling distribution of the mean approaches normality when the sample size exceeds 30. Thus, parametric tests, such as the t-test, are considered robust to violations of normality in large samples. Furthermore, according to, Carifio & Perla (2007), such aggregated scales can be treated as approximate intervals, allowing parametric tests to be applied.

Thus, to achieve objective 3, a one-sample t-test was selected due to its ability to compare the mean score of each challenge and expectation to a predetermined threshold value and ease of use (Waswa & Al-kassab, 2023). Thus, Standardized mean difference is used for variable importance ranking through SPSS software (Kabakova & Panov, 2025).

Ahadzie et al. (2008), highlighted that success criterion was considered critical or important if it had a mean score of 3.5 or higher on the five-point Likert scale. Consequently, this study used 3.5 as the test value in a one-sample t-test.

# 4. RESULTS AND DISCUSSION

## 4.1 RESPONDENT'S DEMOGRAPHIC INFORMATION

In preliminary survey, 20 preliminary questionnaires were distributed, and 15 were returned with valid responses, resulting in a response rate of 75%. Subsequently, the questionnaire survey was distributed to 75 female professionals, of which 40 were returned with valid responses, achieving a response rate of 53.33%. According to Faleiros et al. (2016), the moderate response rate for online surveys is 30–50%. Thus, both surveys have obtained sufficient response rates.

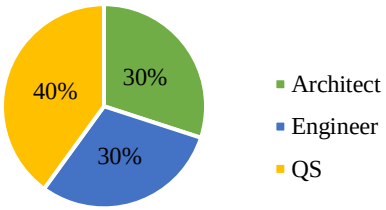



*Figure 2: Respondent's profession*

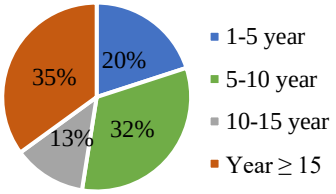



*Figure 3: Respondent's experience:*

As shown in Figure 2, the data collected from three categories of female professionals specifically architects (30%), engineers (30%) and quantity surveyors (40%) who are working in Sri Lankan construction industry. Further, Figure 3 illustrates the years of experience of the respondents participated in questionnaire survey. The average years of experience of the respondents was 12 years. All the respondents had a degree in a relevant field as the minimum educational qualification. As per the demographic analysis of the questionnaire, the average years of experience and minimum qualifications indicate a sufficient level of expertise and knowledge, which ensures the respondents' ability to accurately understand and respond to the questionnaire.

## 4.2 CHALLENGES FACED BY FEMALE PROFESSIONALS UNDER REMOTE WORKING IN SRI LANKAN CONSTRUCTION INDUSTRY

The 11 challenges of remote working were identified from the literature review. Then based on the preliminary survey responses, 4 challenges were excluded as their responses rate was less than 30%. Accordingly, C1, C4, C8 and C10 are the excluded challenges. In the Sri Lankan construction sector, female professionals may not perceive existing

gender norms as a distinct "remote working" challenge, partly due to the prevalence of hybrid or site-based work which reduces issues of visibility and recognition. Many remote workers benefit from basic digital infrastructure provided by their organizations or have adapted independently, making technology access less critical compared to workload and work-life balance issues. Additionally, performance evaluations in Sri Lankan construction organizations often rely on traditional methods, thereby obscuring the visibility of remote work-related challenges. Therefore 7 challenges were included in the questionnaire. The questionnaire was then administered to female professionals in Sri Lankan construction industry, and the data were collected. After data collection, the normality of the data was tested using the Shapiro-Wilk test.

To identify the challenges faced by female professionals under remote working within the Sri Lankan Construction Industry, an assessment was carried out one sample t test to identity the critical challenges based on their experience and knowledge by industry female professionals. The results of the Shapiro-Wilk test, Kruskal Wallis test and One sample t test are presented in Table 2.

*Table 2: Remote working challenges faced by female professionals in Sri Lankan construction industry*

| Code | Challenges | Mean | Std. deviation | Rank | Shapiro-Wilk test Sig. | Kruskal-Wallis test Asymp. Sig. |
|---|---|---|---|---|---|---|
| **C11** | Workload increases and expects to be "always available online" | 3.70 | 0.758 | 1 | < 0.001 | 0.691 |
| **C7** | Lack of resources and facilities (Proper technical tools, network, etc.) | 3.50 | 0.751 | 2 | < 0.001 | 0.980 |
| **C2** | Difficult to take guidance and mentorship from supervisors to achieve my career goals | 3.48 | 0.784 | 3 | < 0.001 | 0.624 |
| **C5** | Less involvement for the informal discussion and decision-making network | 3.40 | 0.955 | 4 | < 0.001 | 0.362 |
| **C9** | Psychological stress/ loneliness | 3.35 | 1.001 | 5 | 0.001 | 0.496 |
| **C3** | Difficulty balancing family responsibilities with stressful work schedules | 3.25 | 0.981 | 6 | < 0.001 | 0.295 |
| **C6** | Limited opportunities for managerial positions | 3.23 | 0.891 | 7 | < 0.001 | 0.709 |

As shown in table 2, all significance (Sig.) values from the Shapiro-Wilk test are less than 0.05 ($p < 0.05$). Thus, the null hypothesis is rejected, indicating that the data does not follow a normal distribution.

Subsequently, to achieve objective 2, Kruskal-Wallis test was applied to determine whether there are differences in perceptions among the professional groups. Consequently, all the challenges had $p > 0.05$. This indicates that there is no statistically significant difference in perceptions among the groups regarding C2, C3, C5, C6, C7, C9,

C11. This may be because these challenges are common and experienced equally among these professions, which means they impact all the industry professionals as a whole rather than being specific to any one profession.

According to table 2, to achieve objective 3, the mean score of each challenge was compared to a predetermined threshold value (3.5). Moreover, challenges were ranked based on their mean values, with higher mean values assigned higher ranks. In cases where challenges had the same mean value, the standard deviation was used as a secondary criterion, with lower standard deviation indicating a higher rank. Thus, the blue-highlighted rows in Table 2 indicate that both C11 and C7 were critical challenges, as they had a mean score of 3.5 or higher, ranking 1st and 2nd, respectively. Hamour et al. (2023), highlighted that remote workers have to stay online more time to demonstrate they are not avoiding their work responsibilities. In the Sri Lankan construction industry, female professionals face a significant challenge regarding their availability online under remote working. The improper working schedule followed by their organizations may be the reason for that. The second critical challenge in the Sri Lankan context is lack of resources and facilities, such as proper technical tools, networks, etc. Onyekwere (2024), noted that some employees who are engaging in remote working are facing challenges such as limited internet connectivity and access to reliable devices. The lack of resources and facilities for remote working in the Sri Lankan construction industry may be mainly caused by high technology and software costs, inadequate ICT and internet infrastructure, economic and foreign exchange constraints, data security concerns, and weak government and industry-level support.

### 4.3 FEMALE PROFESSIONALS' EXPECTATIONS TO OVERCOME THE REMOTE WORKING CHALLENGES IN THE SRI LANKAN CONSTRUCTION INDUSTRY

To successfully implement remote work, organizations must reorganize work processes and provide support to employees. For effective remote work and enhanced employee job satisfaction, proper motivations, qualifications, technological advancements, and organizational support are necessary (Žvirelienė & Lipinskienė, 2023).

According to the preliminary survey, the identified expectations regarding remote working from female professionals in the Sri Lankan construction industry are presented in Table 3.

*Table 3: Expectations regarding remote working from female professionals*

| Expectations | Code |
|---|---|
| Implement flexible working hours instead of strict 8–5 schedules | E1 |
| Create scheduled virtual "check-ins" for all team members to share updates | E2 |
| Use digital collaboration tools (Miro, shared dashboards) to ensure visibility of contributions. (These tools facilitate engaging virtual meetings, visual thinking, project management, etc.) | E3 |
| Promote digital wellness practices (scheduled break times, no-meeting hours) | E4 |
| Create clear remote work policies (defining expected online hours, response times, and after-hours boundaries) | E5 |

Some companies use performance monitoring systems, flexible work schedules (E1), and virtual collaboration tools to improve attraction for remote working (E2) (Al-dahabi et al., 2024) Furthermore, video conferencing, messaging applications, project management software, and virtual whiteboards have become essential tools to support virtual meetings, team collaboration, and project management (E3) (Žvirelienė & Lipinskienė, 2023). As an example, the United Arab Emirates uses the advanced digital technologies to work remotely in the construction industry (Elrefaey et al., 2022). Moreover, organizations should communicate clearly issues such as breaks and availability on online platforms for maintaining work-life balance (E4). It is important to set rules and boundaries about how (communication platforms) and when it is okay to contact employees so there won't be a conflict between their personal life and work life (Žvirelienė & Lipinskienė, 2023). Sometimes employees difficult to separate personal and work life during remote work. Hence, organizations may reduce these problems and encourage a healthier work environment by implementing clear policies and providing emotional support (E5) (Pinheiro & Palma-Moreira, 2025).

Following the preliminary survey, respondents were requested to rate the expectation in questionnaire survey. The results of the one sample t test for the identification of the critical expectations are presented in Table 4.

*Table 4: Female professional's expectations on organization to overcome their remote working challenges*

| Code | Expectations | Mean | Std. deviation | Rank |
|---|---|---|---|---|
| **E2** | Create scheduled virtual "check-ins" for all team members to share updates | 3.95 | 0.552 | 1 |
| **E4** | Promote digital wellness practices (scheduled break times, no-meeting hours) | 3.95 | 0.597 | 2 |
| **E5** | Create clear remote work policies (defining expected online hours, response times, and after-hours boundaries) | 3.90 | 0.591 | 3 |
| **E1** | Implement flexible working hours instead of strict 8–5 schedules | 3.90 | 0.810 | 4 |
| **E3** | Use digital collaboration tools (Miro, shared dashboards) to ensure visibility of contributions. (These tools facilitate engaging virtual meetings, visual thinking, project management, etc.) | 3.78 | 0.660 | 5 |

Similar to the remote working challenges, to achieve object 3, the mean score of each expectation was compared to a predetermined threshold value (3.5). Thus, the blue highlighted rows in Table 2 indicate that all the expectations (E2, E4, E5, E1 and E3) are critical due to having a mean score of 3.5 or higher. Furthermore, expectations were also ranked based on their mean values, with higher mean values assigned higher ranks and standard deviation used as a secondary criterion in cases of equal mean values. Thus, E2 and E4 are the most critical expectations of female professionals working in the Sri Lankan construction industry, ranking 1st and 2nd, respectively.

Gong et al. (2022), noted that the organizations should provide social support resources, including virtual networking opportunities. Thus, female professionals in Sri Lankan

construction industry also highly expect to create scheduled virtual “check-ins” (E2) for all team members to share updates. It may be more helpful for remote working to daily office interaction, ensuring communication, clarity, accountability, and a smooth workflow. The second highest ranked expectation is promoting digital wellness practices, such as scheduled break times, no-meeting hours, etc. (E4). Studies that have focused on women's remote work experiences indicate that schedule flexibility enables mothers to keep up full-time employment upon childbirth and under remote working, there should be flexibility to accommodate employee work-life balance in various situations, with hours per week distributed to accommodate both work and family essential needs (Shirmohammadi et al., 2022). Thus, in the Sri Lankan context also, female professionals may expect to promote digital wellness practices under remote working to reduce burnout, improve mental well-being, enhance productivity, and support sustainable work–life balance. Moreover, Pinheiro and Palma-Moreira (2025) noted that the effective remote work policies support the remote workers in balancing their work and personal responsibilities with reducing stress and increasing job satisfaction. In the Sri Lankan context, a female-dominated culture can be seen in household works. Hence, “Create clear remote work policies (E5)” may allow women to rest and care about their family while balancing work responsibilities. According to Žvirelienė and Lipinskienė (2023), job satisfaction, enthusiasm, and employee engagement are increased by flexible working hours. Thus, instead of following the traditional working schedule of 8-5 working hours in Sri Lanka, most female professionals expect a flexible working schedule (E1) through a remote working arrangement. It may also be important for female professionals to maintain a healthy balance between home and work life. In addition to that, using digital collaboration tools (E3) is another critical expectation under remote working of female professionals in the Sri Lankan construction industry. Furthermore, video conferencing, messaging applications, project management software, and virtual whiteboards have become essential tools to support virtual meetings, team collaboration, and project management (Žvirelienė & Lipinskienė, 2023). These tools have been able to stay connected, collaborate efficiently under remote working.

This study highlights the critical challenges female professionals face under remote working, specifically” workload increases and expect to be always available online" and "lack of resources." It may have occurred due to the absence of structured work boundaries in remote working arrangements and lower support from organizations. Thus, organizations should establish well-defined remote work policies that specify working hours, response times, and after-hours communication limits. It directly aligns with the highly ranked expectations of E4, E5, and E1. Moreover, organizations may invest in sufficient digital infrastructure, which includes reliable internet access, licensed software, and the necessary hardware with advanced technologies. It is clearly indicated by the highly suggested expectations of E2 and E3. Then, organizations can enhance communication, coordination, and efficiency in remote working environments. Furthermore, when fulfilling the above mentioned expectation, communication gaps and limited visibility in remote work can be reduced, preventing burnout and psychological stresses of female professionals. The flexible working hours or hybrid working modes also may be helpful to female professionals for balancing their family work responsibilities under remote working. Consequently, organizations may provide long-term, effective remote working facilities for female professionals in the Sri Lankan construction industry to improve their job satisfaction.

## 5. CONCLUSIONS

In the Sri Lankan context, the remote working engagement of female professionals is lower due to several obstacles they face during remote working mode. Thus, this study investigated the challenges encountered by female professionals under remote working arrangements in the Sri Lankan construction industry and identified their expectations to enable effective and sustainable remote work practices. Here, the professionals selected the quantity surveyors, architects, and engineers who are working in the Sri Lankan construction industry. The findings reveal that there are critical challenges under remote working and expectations from female professionals to overcome those challenges. As per one sample t test results, increased workload and the expectation to remain constantly online (C4) and Lack of resources and facilities (C7) are identified as the critical challenges regarding the remote working in Sri Lankan construction industry, securing the 1st and 2nd positions, respectively. Moreover, according to one sample t test results, all the identified expectations of Create scheduled virtual "check-ins" for all team members to share updates (E2), Promote digital wellness practices (E4), Create clear remote work policies (E5), Implement flexible working hours (E1) and Use digital collaboration tools (E3) are the critical expectations of female professionals regarding remote working in Sri Lankan construction industry. The findings show that female professionals in Sri Lanka's construction industry continue to face fundamental challenges in terms of resources and infrastructure for remote working. This contrasts with research conducted in developed countries such as Australia, where higher levels of satisfaction and preference for remote work have been reported as a result of improved digital infrastructure and organizational support (Oo et al., 2023). This disparity demonstrates the different levels of remote work readiness in developed and developing construction contexts. Further, future research can be conducted by comparing different perceptions of both male and female professionals. The study presents that remote working can become a viable and empowering work model for female professionals in Sri Lankan construction if organizations adopt proper remote working schedules and technological facilities.

## 6. REFERENCES

Adikaram, A. S., & Naotunna, N. P. G. S. I. (2023). Remote working during COVID-19 in Sri Lanka: lessons learned and what the future holds. *Employee Relations: The International Journal*, *45*(4), 1035–1056. https://doi.org/10.1108/ER-06-2022-0259

Afolabi, A., Oyeyipo, O., Ojelabi, R., & Patience, T. O. (2019). Balancing the female identity in the construction industry. *Journal of Construction in Developing Countries*, *24*(2), 83–104. https://doi.org/10.21315/jcdc2019.24.2.4

Ahadzie, D. K., Proverbs, D. G., & Olomolaiye, P. O. (2008). Critical success criteria for mass house building projects in developing countries. *International Journal of Project Management*, *26*(6), 675–687. https://doi.org/10.1016/J.IJPROMAN.2007.09.006

Ahmed, R., Robinson, R., Elsony, A., Thomson, R., Bertel Squire, S., Malmborg, R., Burney, P., & Mortimer, K. (2018). A comparison of smartphone and paper data-collection tools in the Burden of Obstructive Lung Disease (BOLD) study in Gezira state, *Sudan. PLoS ONE*, *13*(3). https://doi.org/10.1371/journal.pone.0193917

Al-dahabi, Z.M.A., Al-dahabi, A., Algazo, F. A., Hajjaj, R. Y., & Abukhait, R. O. (2024). Remote work and human resource management: Challenges and solutions. *World Journal of Advanced Research and Reviews*, *24*(1), 1204–1208. https://doi.org/10.30574/WJARR.2024.24.1.3126

Avram, C., & Mărușteri, M. (2022). Normality assessment, few paradigms and use cases. *Revista Romana de Medicina de Laborator*, *30*(3), 251–260. https://doi.org/10.2478/rrlm-2022-0030

Azizi, Z. M., Cochrane, J., Thurairajah, N., & Azizi, N. S. M. (2023). Remote working in construction: assessing the affordance of digitisation. *Built Environment Project and Asset Management*, *13*(1), 5–19. https://doi.org/https://doi.org/10.1108/BEPAM-12-2021-0148

Battisti, E., Alfiero, S., & Leonidou, E. (2022). Remote working and digital transformation during the COVID-19 pandemic: Economic–financial impacts and psychological drivers for employees. *Journal of Business Research*, *150*, 38–50. https://doi.org/10.1016/j.jbusres.2022.06.010

Bell, B. (2012). Remote work: Examining current trends and organizational practices. *International HR Adviser*, *49*, 4-6. https://ecommons.cornell.edu/server/api/core/bitstreams/2394d66b-881b-442a-bf92-811c9667277e/content

Carifio, J., & Perla, R. J. (2007). Ten common misunderstandings, misconceptions, persistent myths and urban legends about likert scales and likert response formats and their antidotes. *Journal of Social Sciences*, *3*(3), 106–116. https://doi.org/https://doi.org/10.3844/jssp.2007.106.116

Devinda, W. A. S. S. S., Sandanayake, T. C., & Mufitha, M. B. (2023). Evaluation of employee engagement towards work performance in a hybrid working model in the Sri Lankan construction industry. In *6th International Conference on Business Research (ICBR 2023)*, (pp. 1–13). Business Research Unit, Faculty of Business, University of Moratuwa. https://doi.org/10.31705/ICBR.2023.19

Dilipkumar, B.V., Basavaraj, K., & Indrajit, D. (2024). Navigating career paths in a remote world: the influence of work from home on employee advancement and organizational support. SSRN. https://ssrn.com/abstract=5028999

Dingel, J. I., & Neiman, B. (2020). How many jobs can be done at home? *Journal of Public Economics*, *189*, 26948. http://www.nber.org/papers/w26948

Elrefaey, O., Ahmed, S., Ahmad, I., & El-sayegh, S. (2022). Impacts of COVID-19 on the use of digital technology in construction projects in the UAE. *Buildings*, *12*(4), 489. https://doi.org/10.3390/buildings12040489

Faleiros, F., Käppler, C., Pontes, F. A. R., Silva, S. S. da C., de Goes, F. dos S. N., & Cucick, C. D. (2016). Use of virtual questionnaire and dissemination as a data collection strategy in scientific studies. *Texto e Contexto Enfermagem*, *25*(4). https://doi.org/10.1590/0104-07072016003880014

Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: A guide for non-statisticians. *International Journal of Endocrinology and Metabolism*, *10*(2), 486–489. https://doi.org/10.5812/ijem.3505

Gong, B., Tobias, P., & Young-Bristol, J. (2022). Leveraging resources to improve supervisors' vision in the remote workplace. *Management Research Review*, *46*(6), 777–789. https://doi.org/10.1108/MRR-12-2021-0916

Gunawardana, M. D. D., & Bandaranayake, D. (2024). Technological infrastructure for remote construction works in Western province of Sri Lanka. *Journal of Research in Technology and Engineering*, *5*(4), https://www.jrte.org/wp-content/uploads/2024/10/Technological-Infrastructure-for-Remote-Construction-Works-in-Western-Province-of-Sri-Lanka.pdf

Hamour, R. A., Alfouri, A., & Alshurideh, M. (2023). Remote working in the COVID-19 era. In A.E. Hassanien, A. Haqiq, A.T. Azar, K.C. Santosh, M.A. Jabbar, A. Sowik & P. Subashini (Eds.), *International Conferences on Artificial Intelligence and Computer Vision*. (pp. 459–473). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-27762-7_43

Hertzog, M. A. (2008). Considerations in determining sample size for pilot studies. *Research in Nursing & Health*, *31*(2), 180–191. https://doi.org/10.1002/NUR.20247

Holdsworth, S., Turner, M., & Sandri, O. (2023). Gender bias in the Australian construction industry: Women's experience in trades and semi-skilled roles. *Social Sciences*, *12*(11), 627. https://doi.org/10.3390/socsci12110627

Huwae, V. E., Tabelessy, W., Tamher, E. R., Tehuayo, E., & Lewaherilla, N. C. (2024). The effect of brand image and electronic word of mouth on Xiaomi smartphone purchasing decisions. *Khazanah Sosial*, *5*(4), 700–716. https://doi.org/10.15575/KS.V5I4.32381

Irawanto, D. W., Novianti, K. R., & Roz, K. (2021). Work from home: Measuring satisfaction between work–life balance and work stress during the Covid-19 pandemic in Indonesia. *Economies*, *9*(3), 96. https://doi.org/10.3390/economies9030096

Kabakova, E. A., & Panov, V. G. (2025). Some methods for estimating the importance of variables in statistics. I. Effect size. *Research Trajectory: Humans, Nature, Technology*, *2*(14). https://doi.org/10.56564/27825264_2025_2_37

Kodithuwakku, D. S., & De Silva, I. W. (2025). Challenges in implementing digital employment platforms for women's participation in Sri Lanka: A structural equation modeling approach. *International Journal of Advanced and Applied Sciences*, *12*(3), 216–224. https://doi.org/10.21833/ijaas.2025.03.021

Loezar-Hernández, M., Briones-Vozmediano, E., Ronda-Pérez, E., & Otero-García, L. (2023). Juggling during lockdown: Balancing telework and family life in pandemic times and its perceived consequences for the health and wellbeing of working women. *International Journal of Environmental Research and Public Health*, *20*(6), 4781. https://doi.org/10.3390/ijerph20064781

Lund, B. (2021). The questionnaire method in systems research: An overview of sample sizes, response rates and statistical approaches utilized in studies. *VINE Journal of Information and Knowledge Management Systems*, *53*(1), 1–10. https://doi.org/10.1108/VJIKMS-08-2020-0156

Onyekwere, L. A. (2024). Digital divide in remote work among employees and organizational effectiveness in South-South Nigeria. *South Asian Research Journal of Humanities and Social Sciences*, *6*(04), 142–155. https://doi.org/10.36346/sarjhss.2024.v06i04.002

Oo, B. L., Lim, B. T. H., & Kim, S. (2023). Working from home during Covid-19 and beyond: Exploring the perceptions of consultants in construction. *Buildings*, *13*(1), 166. https://doi.org/10.3390/buildings13010166

Orzel, B., & Wolniak, R. (2022). Digitization in the design and construction industry-remote work in the context of sustainability: A study from Poland. *Sustainability*, *14*(3), 1332. https://doi.org/10.3390/su14031332

Pamidimukkala, A. & Kermanshachi, S. (2022). Occupational health and safety challenges in construction industry: A gender-based analysis. In *Construction research congress 2022* (pp. 491-500). https://ascelibrary.org/doi/abs/10.1061/9780784483985.050

Perera, W. S. D., Ranadewa, K. A. T. O., Parameswaran, A., & Weerasooriya, D. (2023). Status quo of digitalisation in the Sri Lankan construction industry. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, T. Ramachandra, K.A.T.O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023, (pp. 944–959). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2023.76

Pinheiro, A., & Palma-Moreira, A. (2025). Job satisfaction, perceived performance and work regime: What is the relationship between these variables? *Administrative Sciences*, *15*(5), 175. https://doi.org/10.3390/admsci15050175

Rana, J., Gutierrez, P. L., & Oldroyd, J. C. (2021). Quantitative methods. In Farazmand, A. (Eds.) *Global Encyclopedia of Public Administration, Public Policy, and Governance* (pp. 1–6). Springer International Publishing. https://doi.org/10.1007/978-3-319-31816-5_460-1

Rodrigo, N., Wijewickrama, M. K. C. S., Rajenthiran, N., Jayathilaka, W., & Chang, R. (2024). Challenges and solutions for women in construction industry related disciplines: a literature review. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, K.A.T.O. Ranadewa & H. Chandanie (Eds.), *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, (pp. 330-340). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2024.26

Safira, N.A., Hanami, Y., & Batubara, M. (2023). Multidimensional well-being of remote workers: A qualitative comparison between full-remote and hybrid workers. Analitika, *15*(2), 89–100. https://doi.org/10.31289/analitika.v15i2.10211

Senaratne, S., Jayakodi, S., Pascoe, R. D., & Atkins, A. (2025). Challenges and strategies for the retention of female construction professionals: An empirical study in Australia. *Buildings*, *15*(13), 2187. https://doi.org/10.3390/buildings15132187

Shirmohammadi, M., Au, W. C., & Beigi, M. (2022). Remote work and work-life balance: Lessons learned from the COVID-19 pandemic and suggestions for HRD practitioners. *Human Resource Development International*, *25*(2), 163–181. https://doi.org/10.1080/13678868.2022.2047380

Srivishagan, V., & Thalpage, R. (2021). Issues and challenges of women in Sri Lankan construction industry. *In International Research Symposium - 2021,* (pp. 495-500). University of Vocational Technology. https://www.researchgate.net/publication/374965346_Issues_and_Challenges_of_Women_in_Sri_Lankan_Construction_Industry

Suratkon, A., & Azlan, A. S. (2021). Working From Home (WFH): Challenges and practicality for construction professional personnel. *International Journal of Sustainable Construction Engineering and Technology*, *12*(4), 11–19. https://doi.org/10.30880/ijscet.2021.12.04.002

Usman, I. (2024). HR management practices in the digital age: Challenges of remote working, digital communication, and employee wellbeing. *Proceeding of Research and Civil Society Desemination*, *2*(1), 85–97. https://doi.org/10.37476/presed.v2i1.63

Vijayaragunathan, S., & Rasanthi, T. (2019). An insight to women in construction for fostering female careers in Sri Lankan construction industry. *Journal of International Women's Studies, 20*(3), 14. https://vc.bridgew.edu/jiws/vol20/iss3/14

Waswa, D. W., & Al-kassab, M. M. (2023). Mathematics learning challenges and difficulties: A students' perspective. In D. Zeidan, J.C. Cortés, A. Burqan, A. Qazza, J. Merker, G. Gharib, (Eds.), *Mathematics and Computation. IACMC 2022* (pp. 311-323). Springer Proceedings in Mathematics and Statistics. https://doi.org/10.1007/978-981-99-0447-1_27

Wong, A. H. K., Cheung, J. O., & Chen, Z. (2021). Promoting effectiveness of "working from home": Findings from Hong Kong working population under COVID-19. *Asian Education and Development Studies*, *10*(2), 210–228. https://doi.org/10.1108/AEDS-06-2020-0139

Cheng, K., & Yang, R. (2021). The career challenges and success factors for professional Asian women career development in New Zealand construction industry. In *2021 ASEE Midwest Section Conference*, 17 November 2021. ASEE. https://doi.org/10.18260/1-2-1152-38318

Žvirelienė, R., & Lipinskienė, D. (2023). Organizational support for remote workers in extreme situations: Theoretical insights. *Applied Research in Studies and Practice, 19*(1), 129–135. https://ojs.panko.lt/index.php/ARSP/article/view/218

Krishanth, K. and Vidhushan, V., 2026. Resilient and culturally responsive plantation housing: Socio-spatial adaptation in Dunsinane estate, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1470-1483. DOI: https://doi.org/10.31705/WCS.2026.107. Available from: https://ciobwcs.com/papers/

# RESILIENT AND CULTURALLY RESPONSIVE PLANTATION HOUSING: SOCIO-SPATIAL ADAPTATION IN DUNSINANE ESTATE, SRI LANKA

**K. Krishanth[1] and V. Vidhushan[2]**

## *ABSTRACT*

*The tea plantation housing originated in the colonial era, shaped by standardisation, efficiency and minimised cost, resulting in home spaces that are insufficient to support sociocultural practices, climatic comfort and long-term resilience. Although state and donor-led initiatives (e.g., India-funded programmes) have substituted communal line rooms with separate units, formal provision remains inadequate to lived spatial, cultural and infrastructural realities of marginalized plantation communities. This results in informal retrofitting and spatial change by residents, raising concern about the sustainability and responsive housing development. This paper analyses the socio-spatial factors of housing adaptation in Dunsinane Estate, Nuwara-Eliya, with reference to the interplay between cultural and physical limitations. The methodology comprised semi-structured interviews and household surveys (n = 40), field observations, and spatial documentation of domestic modifications. The results show that adaptation is affected by the embedded needs for privacy, social boundaries, hospitality rituals, and religious practices, including layout changes, veranda enclosures, and prayer-oriented spaces. At the same time, physical limitations, including limited floor area, inadequate sanitation, poor thermal performance in upcountry climates, and construction defects also drive housing adaptation. These transformations show the resourcefulness and resilience of plantation communities, exposing the shortcomings of standardized housing plans that treat homes as static rather than adaptable. This study suggests that sustainable housing should allow flexibility, climate-responsive design, participatory planning, and incremental frameworks to reduce unsafe construction and support long-term liveability. The findings contribute to socio-spatial theory while offering practical guidance for culturally responsive and adaptable housing design in plantation communities.*

***Keywords:*** *Incremental Upgrading; Plantation Settlements; Resilient Housing; Socio-Cultural Adaptation; Sustainable Housing Policy.*

## 1. INTRODUCTION

Built in the late 19th and early 20th centuries, these line houses were intended to provide housing for small, migrant working families. They provided little in the way of comfort, privacy, hygiene or future expansion (Hollup, 1993). Although the socio-economic conditions of plantation families have changed over time, with increasing aspirations,

[1] K. Krishanth, Department of Architecture, University of Moratuwa, Sri Lanka, krishanthk.20@uom.lk
[2] V. Vidhushan, Department of Architecture, University of Moratuwa, Sri Lanka, vvidushan@uom.lk

increasing family size and new lifestyle requirements, the basic housing structures have largely remained unchanged (Hapuarachchi & Kariyawasam, 2021). Recent government and donor-led projects have replaced communal units with individual houses (World Bank Group, 2017). Overcrowding, lack of hygiene and vulnerability to upcountry climate extremes are evident, as reflected in widespread informal redevelopment such as verandah dwellings and internal partitioning (Krieger & Higgins, 2002). This challenge extends beyond welfare provision, creating a built environment resilience concern and a whole-of-life sustainability issue, where unplanned housing changes can create safety risks, repeated material consumption, poor thermal performance and long-term infrastructure stress (Azami & Razavian, 2013). Estate housing should therefore be understood as a socio-technical system where long-term sustainability depends on adaptability, cultural adequacy and climate efficiency rather than the provision of minimal shelter (Chiu, 2004).

Standardised individual housing, while improving upon line room conditions, often imposes uniform layouts that respond inadequately to the socio-cultural needs of estate households, including privacy for gendered domestic boundaries, hospitality practices and religious spatial requirements (Abed et al., 2023; De Macedo et al., 2022; Van Noorloos et al., 2020). As a result, residents are forced into cycles of escalating adaptation, often engaging with limited technical guidance, highlighting both the social agency and the systemic shortcomings of standard housing delivery models (Boonyabancha, 2009).

Existing scholarship on Sri Lankan estate housing has predominantly focused on policy analysis, poverty alleviation and historical labour traditions, with limited empirical attention to how residents have actively constructed domestic environments through adaptation, particularly within new housing schemes (Abed et al., 2023; Hapuarachchi & Kariyawasam, 2021). Accordingly, this study aims to examine the socio-spatial drivers of housing adaptation in plantation communities, with particular focus on the interaction between socio-cultural practices and physical constraints within estate housing. To achieve this aim, the study objectives are to: (1) identify dominant patterns of user-led spatial modification, (2) analyse socio-cultural and physical factors influencing adaptation, and (3) propose context-responsive housing strategies.

# 2. LITERATURE REVIEW

## 2.1 HOUSING ADEQUACY, SUSTAINABILITY, AND CULTURAL RESPONSIVENESS

Housing is not merely physical shelter, but is widely recognized as a fundamental determinant of health, dignity, social inclusion and cultural continuity (Krieger & Higgins, 2002). International frameworks establish good housing as a fundamental human right, extending beyond the structural provision of housing to include access to services, affordability, security, and cultural practices (Hapuarachchi & Kariyawasam, 2021). In marginalized settlement contexts, the provision of standardized housing often fails to align with everyday domestic practices and socio-cultural expectations (Chiu, 2004).

Within the sustainability discourse, housing adequacy is increasingly understood through a whole-of-life perspective. Sustainable housing should ensure long-term livelihoods,

resilience and adaptability rather than short-term quantitative provision (Geels, 2002). Cultural adequacy is therefore inseparable from sustainability, as houses that ignore household norms, gendered privacy requirements, hospitality customs and ritual practices are often subject to informal changes, generating additional material waste, unsafe renovations and low life cycle performance (Abed et al., 2023).

## 2.2 PLANTATION HOUSING IN SRI LANKA: COLONIAL LEGACY AND CONTEMPORARY CHALLENGES

Sri Lanka's plantation settlements are historically rooted in colonial labour regimes, where housing was designed primarily to support the economic efficiency of tea production rather than domestic well-being (Hollup, 1993). Characterized by a series of small units arranged in linear rows with shared sanitation, line housing embodies a spatial logic of containment, minimal investment, and restricted privacy (Periyasamy, 2018). These houses are not designed to accommodate multi-generational family structures, culturally rooted practices, or future expansion, resulting in persistent overcrowding, infrastructural deficiencies, and limited adaptability over time (Hapuarachchi & Kariyawasam, 2021). Even after decades of improvements, estate housing still shows significant differences in quality and conditions. Recent government and donor supported programmes have introduced individual housing units to replace colonial line houses and improve living conditions (Asian Development Bank, 2016). These programmes focus on physical upgrading but often prioritise delivery targets over daily adequacy. This reflects a quantitative approach that overlooks lived spatial needs. Significant issues include poor infrastructure integration, weak basic service coordination, low building standards, unclear ownership, and inadequate responsiveness to social and cultural needs (World Bank Group, 2017). These limitations demonstrate that housing inadequacy in plantation settlements extends beyond physical conditions and must also be understood through the relationship between social practices and spatial organisation.

## 2.3 SOCIO-SPATIAL THEORY AND THE PRODUCTION OF DOMESTIC SPACE

Socio-cultural factors refer to social values, religious practices, beliefs, rituals, privacy, and everyday behavioural patterns that influence domestic life within housing environments (Chiu, 2004; Fallah Tafti et al., 2026; Jabareen, 2005). Whereas socio-spatial theory explains how these practices actively shape and produce space. In socio-spatial studies, housing adaptation is understood as a dynamic process rather than viewing houses as fixed physical objects (Bruyns, 2018; Pelsmakers & Warwick, 2022). Theoretical perspectives emphasize that space is actively produced through everyday practices, social relations, and cultural meanings (Lefebvre & Nicholson-Smith, 2013; Soja, 1980). The concept of spatial production argues that home environments are continually shaped through lived experience rather than being passively occupied (Lefebvre & Nicholson-Smith, 2013). Similarly, socio-spatial dialectics emphasises the reciprocal relationship between built form and social practices, where families reshape spaces in response to evolving needs and identities(Soja, 1980).

In low-income and community-based settlements, domestic spaces often serve as a site of cultural reproduction, hospitality, gender roles, and religious practices (Abed et al., 2023; Chiu, 2004). In plantation communities, housing is not merely shelter, but a structure where identity, dignity, and belonging are negotiated daily. Modifications such as connecting verandas to the living room, reorganizing interiors, or creating prayer areas

represent culturally embedded spatial practices rather than isolated informal actions(Abed et al., 2023; Van Noorloos et al., 2020).

## 2.4 HOUSING ADAPTATION, FLEXIBILITY, AND INCREMENTAL UPGRADING

Housing adaptation has been widely documented as an inevitable process in low-income settlements, where rigid layouts rarely accommodate changing household structures, livelihood practices, or cultural expectations (Yates & Milligan, 2007). User-centred housing theories emphasize that residents adapt dwellings over time to achieve functional adequacy and social meaning, particularly in low-income and marginalised settlements where formal housing provision often fails to respond to evolving household needs (Boonyabancha, 2009). These adaptations are often responses to limited space, inadequate services or the need to accommodate guests, ensure privacy, and support religious rituals (Van Noorloos et al., 2020) .

International experiences with modular and participatory housing highlight the value of flexible structures that allow for safe and planned change. Projects such as the Baan Mankong Development Initiative in Thailand demonstrate that community-led adaptation can produce more sustainable and inclusive housing outcomes when institutionally supported (Denaldi & Cardoso, 2021). Similarly, progressive housing approaches in Latin America proves that design for periodic development can improve affordability, resilience, and long-term livelihoods (Ferguson & Navarrete, 2003). However, in Sri Lanka's plantation sector, housing provision remains largely standardised allowing limited capacity for formal adaptation (Chiu, 2004). As a result, residents conduct informal renovations without technical guidance, concerns about safety, durability, and environmental performance. Therefore, Sustainable plantation housing needs to integrate flexibility and incremental development mechanisms to reduce unsafe construction cycles and improve whole-life outcomes (Asian Development Bank, 2016).

## 2.5 CLIMATE RESPONSIVENESS AND WHOLE-LIFE PERFORMANCE IN UPCOUNTRY HOUSING

Over the time, performance of tea estate homes are affected by the climatic and infrastructural circumstances of the upcountry area (Abeyrathna et al., 2024; Asian Development Bank, 2016). Housing that fails to respond to local microclimatic conditions such as temperature and air flow , often requires residents to improve roofs, penetrations, or change spatial layouts, affecting energy efficiency and indoor comfort (Abeyrathna et al., 2024).

Unplanned changes often result in increased carbon footprints over time, increasing material consumption, and continuous maintenance requirements (Cabeza et al., 2014). Therefore, climate-responsive design strategies such as improved envelopes, ventilation planning, and infrastructure integration are essential for regenerative housing development in plantation environments. Sustainable development must consider environmental performance alongside community way of living (Cabeza et al., 2014; Chiu, 2004)

## 2.6 CONCEPTUAL FRAMEWORK FOR THE STUDY

The conceptual framework is based on socio-spatial theory, in particular to the socio-spatial dialectic of Lefebvre and Soja, which views the dialectic between social

behaviours and the physical environments as a function of ongoing development of domestic space. The framework also includes ideas of housing adaptation and incremental development, noting the transition of housing as a dynamic reaction to the socio-cultural and environmental changes.

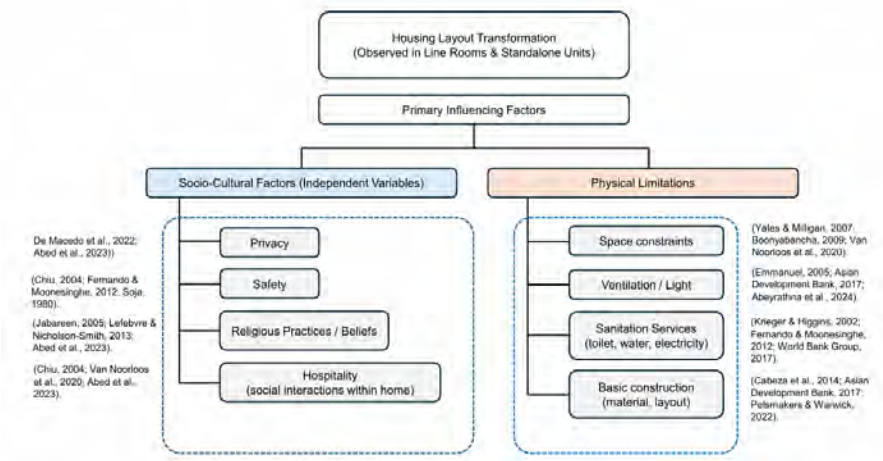



*Figure 1: Framework of analysis*

Based on the above literature, Figure 1 conceptualizes tea plantation-house adaptation as a result of two interrelated domains: socio-cultural factors and physical limitations (Lefebvre & Nicholson-Smith, 2013; Soja, 1980; Van Noorloos et al., 2020). Socio-cultural factors include privacy needs, perceptions of safety, religious practices and hospitality norms, (Abed et al., 2023; Chiu, 2004; De Macedo et al., 2022). Physical constraints include space constraints, light and ventilation, sanitation and basic services, thermal comfort, construction quality (Abeyrathna et al., 2024; Asian Development Bank, 2016; Cabeza et al., 2014; Emmanuel, 2005). This framework establishes the interaction between cultural practices and spatial constraints as the core driver of housing adaptation.

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN

This study adopted a mixed-methods case study approach to capture measurable trends and lived experiences. Semi-structured interview data were analysed using thematic analysis and household survey data were analysed using descriptive statistics.

Purposive sampling technique was used to select 40 households in government supported standalone housing units in Dunsinane Estate. Households were selected on occupancy status, willingness to engage, and representation of diverse spatial adjustments.

Data collection was conducted in parallel, allowing survey, semi structured interview and observations. Quantitative data from questionnaires were analysed using descriptive statistical methods. Qualitative semi-structured interview data were analysed using thematic analysis to identify recurring socio-spatial patterns. Field observations and photographic documentation were used to support and validate reported spatial practices.

## 3.2 CASE STUDY CONTEXT: DUNSINANE ESTATE

The study was conducted at Dunsinane Estate in the Nuwara Eliya District in the central Province of Sri Lanka. The estate represents a typical upcountry plantation settlement

transitioning from line houses to new government supported individual housing schemes. It was selected because of its recently constructed standardized housing units, the widespread emergence of informal spatial adaptations, and the culturally distinct Indian Tamil plantation community, where domestic space is closely linked to norms of privacy, hospitality practices, and religious rituals.

## 3.3 DATA COLLECTION METHODS

Table 1 shows the key data gathering methods and their respective analytical roles within the study.

*Table 1: Data collection methods and analytical purpose*

| Factor | Data to Collect | Tool/Method | Reason for Method Use |
|---|---|---|---|
| Privacy | Perceptions of privacy, room use, shared spaces | Questionnaire survey, Semi-structured Interview | Understand subjective experience and spatial usage |
| Safety | Safety concerns (indoor/outdoor), design issues | Questionnaire survey, Semi-structured interview | Capture gendered risks and environmental conditions |
| Religious Practices | Prayer spaces, Vaastu orientation, ritual use | Questionnaire survey, Semi-structured Interview, | Cultural meaning is best captured through open dialogue |
| Hospitality | Use of veranda/yards, comfort with visitors | Questionnaire survey, Semi-structured interview, Photographic documentation | Reflects spatial needs for interaction & community ties |
| Spatial Constraints | Spatial layout modification ,room usage | Observation, sketches | To visually validate reported crowding/use |
| Light & Ventilation | Natural light, cross-ventilation, air quality | Observation, photographic documentation, Semi-structured Interview | Comfort and health perception must be observed + reported |
| Sanitation and infrastructure | Water, electricity, toilet access | Questionnaire survey, Field Notes, Semi-structured Interview | Mixed methods allow for reliability cross-checks |
| Basic Construction | Wall/roof/floor condition, maintenance issues, | Observation, Semi-structured Interview | Needs direct field observation and resident insight |

## 3.4 ETHICAL CONSIDERATIONS

Ethical sensitivity was essential given the marginalized context of the tea plantation communities. Participation was entirely voluntary, and participants were informed of the

research purpose prior to data collection. All photographic documentation, observations, and interviews were conducted with consent.

The questionnaire was originally prepared in Tamil language to suit the participants, as they are comfortable reading and responding in Tamil. However, some individuals were unable to read or write. Therefore, verbal interviews were conducted in Tamil, each question was verbally asked and marked their responses accordingly. To ensure clarity and transparency, observations and photographs were recorded with appropriate consent, ensuring respectful engagement with the home environments.

### 3.5 LIMITATIONS OF THE STUDY

As a case study focusing on a single estate settlement, the findings may not be statistically generalizable to all plantation communities in Sri Lanka. However, the study provides transformative insights into broader patterns of socio-spatial adaptation within standardized low-income housing schemes. In addition, informal adaptations are dynamic and constantly evolving, meaning that documented adaptations reflect conditions at the specific time of fieldwork. The study is limited to analysing residential spatial modifications and will not cover macro level urban or economic transformations. Limited access to official housing documents and pandemic-related restrictions may pose minor limitations during fieldwork.

## 4. RESULTS AND ANALYSIS

Survey findings reveal quantitative trends relating to housing adaptation patterns, while interview data offer qualitative insights into residents' lived experiences, cultural practices, and views of domestic space.

### 4.1 SOCIO-CULTURAL DRIVERS OF HOUSING ADAPTATION

This section presents the findings of the sociocultural elements affecting home adaptation in Dunsinane estate. In order to explain how privacy, safety, religious practices, and hospitality influence household spatial alterations, it combines quantitative survey results with qualitative insights from interviews and field observations. Each sub-section first presents survey-based trends, followed by qualitative interpretations that explain residents' lived experiences and adaptive strategies.

#### 4.1.1 Privacy and Gendered Domestic Boundaries

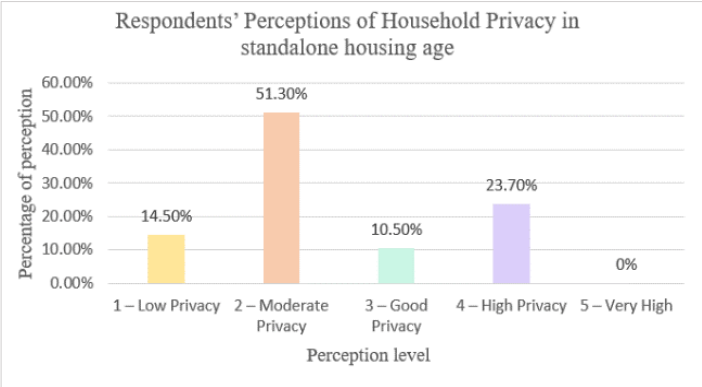



*Figure 2: Respondents' perceptions of household privacy in standalone housing (n=40)*

Survey results (Figure 2) show that 51% of households have moderate satisfaction with privacy, while approximately 15% reported low satisfaction, particularly among large families with 5-7 members and households with adolescent daughters or elderly members.

Interviews provide further context for these quantitative results. They demonstrate how family structures negotiate privacy both socially and spatially. As a result residents have introduced a number of informal spatial strategies. Common adaptations include the construction of timber/metal sheet partition walls. Sometimes they use curtain dividers, rearranging furniture, and installing internal doors to create separations within small interiors. Verandas and external corridors are often enclosed or partially screened to reduce visibility from neighbour houses and passing streets.

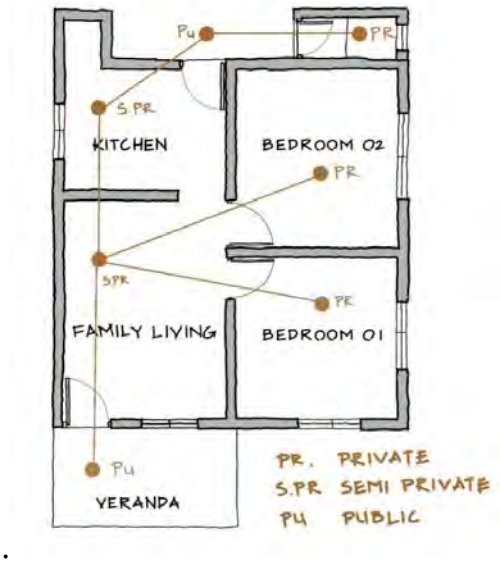



*Figure 3: Typical Dunsinane standalone house unit*

As shown in Figure 3 limited internal flexibility available in the initial home layout, emphasising the necessity for design adaptations that can retain culturally relevant privacy limitations without damaging informal rearrangements.

### 4.1.2 Safety Perceptions and Semi-Permeable Boundaries

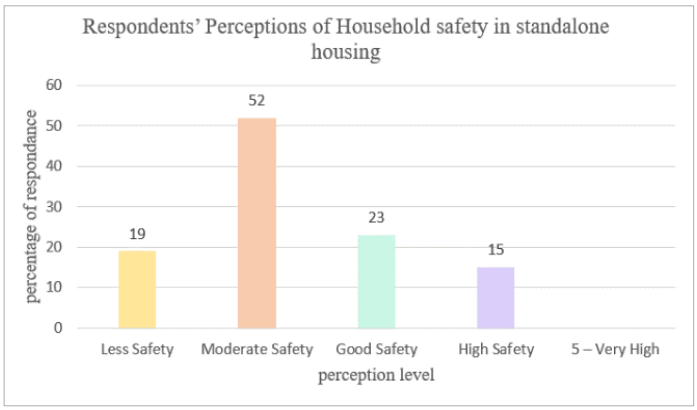



*Figure 4: Respondents' perceptions of household safety in standalone housing (n=40)*

Survey responses (Figure 4) indicates that no households reported full satisfaction with security conditions. Approximately 53% households expressed moderate satisfaction, while 17% reported low safety.

Traditionally, estate settlements have relied on communal living arrangements and informal community monitoring, which reduces the need for formal security barriers (Chiu, 2004). However, with the changing social conditions, individuals gradually begin to enclose areas by constructing fencing and claim them as partially private. Although these boundaries remain easily temporary, they indicate a growing necessity for personal privacy while preserving community connections.

### 4.1.3 Religious Practices and Ritual Space Production

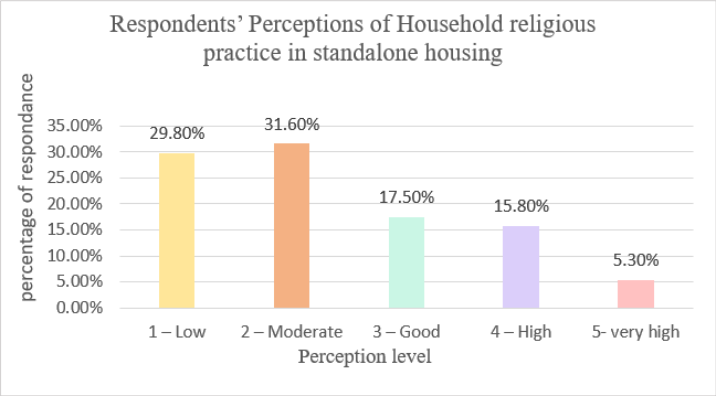



*Figure 5: Respondents' perceptions of household religious practices and beliefs in standalone housing (n=40)*

As shown in Figure 5, low satisfaction with religious spatial adequacy recorded in Dunsinane estate, with 31.6% indicating moderate satisfaction and 29.8% indicating low satisfaction.

Residents generally modify their home layout to incorporate prayer area (Poojai Arai), ritual objects, and spatial orientations based on Vaastu Shastra principles. Interviews found that most families prefer prayer areas located in the northeast corners (Easanya Moolai), and kitchen layouts are sometimes altered to correspond to traditional directional, facing southeast. Outdoor ritual behaviours, such as growing Tulsi (Holy Basil) plants at home entrances and preparing outdoor spaces before festival events like drawing kolam, further extend home space beyond the building envelope.

### 4.1.4 Hospitality Norms and Multi-Use Living Space

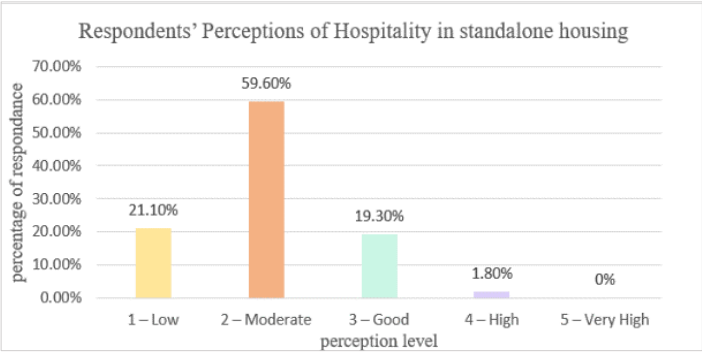



*Figure 6: Respondents' perceptions of hospitality in standalone housing (n=40)*

The survey results as shown in Figure 6 shows that 59.6% of households reported moderate satisfaction with entertaining guests, while 19.3% of households express low satisfaction. To preserve hospitality practices, residents commonly transform porches into semi-formal seating areas, reassign bedrooms for guest use, or create outdoor seating extensions. This reflects the continued cultural importance of hospitality in plantation communities despite limited and inadequate housing space.

## 4.2 PHYSICAL LIMITATIONS DRIVING INCREMENTAL RETROFITTING

This section discusses findings on physical and environmental constraints affecting housing modifications, differentiating them from socio-cultural factors. Key influences include infrastructure constraints, construction quality, environmental comfort, and spatial inadequacy. The results illustrate that physical limitations primarily drive incremental retrofitting habits, supported by survey data, field observations, and interview responses.

### 4.2.1 Space Constraints and Functional Inadequacy

Field observations and interviews reveal that housing units are generally comfortably adequate only for up to three occupants. Field observation indicates that kitchen is spatially inadequate for larger families, meal preparation and dining occur within the lobby or bedroom, and circulation zones become multi-purpose zones like study area, prayer zones. Similarly, bathrooms are poorly serviced, generally lacking internal toilet facilities, separate shower facilities, and proper storage. Such functional shortcomings encourage residents to undertake incremental extensions, albeit with limited means and insufficient technical assistance.

### 4.2.2 Thermal Comfort, Light, and Ventilation Challenges

Although most households report sufficient daylight for essential activities, climatic discomfort is a chronic problem in the upcountry household. The lack of insulation under the metal roof leads to cold indoor conditions during cold seasons. Interview responses and field observations revealed that many residents have used their own funds to install ceiling to improve thermal comfort. This also reduces rain noise. Toilets generally lack sufficient daylight and ventilation, and at night, outdoor street lighting is inadequate, contributing to discomfort and insecurity.

### 4.2.3 Sanitation and Infrastructure Deficiencies

Field observations show that there is no integrated sewage system, and wastewater often flows openly through informal canals. Toilets are small and poorly serviced, while kitchens suffer from inadequate drainage and maintenance limitations. Figure 7 shows how residents are forced into self-constructed sanitation changes, that can compromise health and environmental performance.

### 4.2.4 Construction Quality and Durability Issues

Construction related issues further encourage housing modifications. While units are generally constructed using cement block walls and reinforced concrete frames. Although interview participants frequently reported concerns regarding poor plastering quality, weak fittings, incomplete floor finishes poor material of penetrations and early cracking and settlement after completion in 2018. These durability issues create additional home

maintenance cycles and underscore the importance of improved construction standards within sustainable housing supply for these low-income people.

*Figure 7: Inappropriate sewage*

# 5. DISCUSSION

## 5.1 ADAPTATION AS SOCIO-CULTURAL RESILIENCE

The findings from Dunsinane Estate reveal that resident-led change is a continuous process of incremental renewal shaped by everyday socio-cultural needs rather than physical inadequacy. Adaptations related to privacy, hospitality, religious practice and security reveal how households deliberately alter domestic space to maintain dignity, identity and functional living within limited housing situations. These findings align with socio-spatial theories that interpret housing as a socially produced environments shaped via everyday actions, cultural values, and lived experience rather than as a permanent architectural product. Consistent with the socio-spatial theories of Henri Lefebvre, residents actively reshape domestic space through privacy negotiations, ritual practices, and social interaction, demonstrating that housing transformation is embedded within everyday social life.

At the same time, these developments often reflect a form of communal resilience achieved through informal means. While people demonstrate greater agency, the burden of improvement is directed at the home, often without expert supervision, increasing vulnerability to safety risks and material inefficiencies. Cultural appropriateness therefore emerges as a key prerequisite for sustainable housing. When privacy standards, hospitality customs and ritual practices are not supported in design, change is inevitable.

## 5.2 LIMITS OF STANDARDISED HOUSING AND WHOLE-LIFE IMPACTS

The ongoing pattern of reconfigurations within newly constructed independent units highlight the limits of uniform housing models. Despite improvements over colonial line houses, standardized plans sometimes fail to address culturally expected separations between public and private areas, leading people to rearrange interiors, add verandas, and extend dwellings beyond the original layout.

Unplanned modifications in housing design lead to long-term performance problems throughout the life cycle. Temporary alterations and poor thermal performance point to gaps in the original design in terms of flexibility and thermal comfort. Consequently, tea estate housing challenges continue after occupation, necessitating whole life housing strategies that allow for safe incremental changes over time.

### 5.3 TOWARDS REGENERATIVE AND PARTICIPATORY UPGRADING

The results emphasize the need for regenerative housing frameworks that allow for intentional adaptation rather than treating change as informal. Policies should lead to flexible design, incremental expansion capacity, and climate-responsive built envelopes that are suitable for healthy environments. Collaborative planning and post-occupancy evaluation are essential for aligning formal provision with modern realities, reducing hazardous rebuilding phases, and promoting sustainable livelihoods.

## 6. CONCLUSIONS AND POLICY RECOMMENDATIONS

### 6.1 CONCLUSIONS

The study demonstrates that adaptation is significantly shaped by interaction between socio-cultural expectations and physical housing limitations. Resident-led spatial adjustments related to privacy, safety, hospitality, religion, and thermal comfort demonstrate that plantation housing functions as a socially generated living space rather than a fixed physical construction. Recent standalone housing schemes have improved living conditions compared to colonial line rooms, the persistence of informal adaptation illustrates the limitations of standardised housing forms that poorly react to current household requirements and cultural realities.

The findings suggest that sustainable plantation housing evaluation requires more than just quantitative measures of housing delivery or physical upgrades. Long-term resilience relies on flexibility, climate responsiveness, cultural adequacy, and the ability for safe incremental adaptation. Housing transformation in plantation communities highlights the agency of residents and the need for participatory and context-sensitive housing strategies.

The study on a Sri Lankan plantation settlement gives insights into housing adaptation for marginalized communities in the Global South, highlighting how standard low-income housing often overlooks socio-spatial needs. It argues for future plantation housing policies to adopt participatory planning, adaptive architecture, and climate-responsive solutions to create dignified, resilient, and culturally relevant living conditions.

### 6.2 POLICY AND DESIGN RECOMMENDATIONS

This study emphasises the need for a full review of housing plans for plantation communities, calling for alternatives that are culturally sensitive and responsive to occupant needs. Key recommendations include the introduction of community spaces such as prayer areas, kitchens for socializing, guest rooms, and considerations for family privacy in dwelling designs. Current difficulties such as overcrowding and insufficient activity spaces must be addressed in future plans, which should also feature critical facilities like kitchens, dining areas, and dedicated study spaces for youngsters.

Moreover, improvements in sanitation, drainage, wastewater management, and water availability are necessary. The home designs must take into account climatic factors, ensuring proper insulation, ventilation, and natural light. Outdoor public areas should be created deliberately, combining streetlights and buildings that preserve privacy while stimulating community connection. Importantly, plantation communities should be actively involved in planning and construction processes to ensure the housing meets their ambitions and requirements. Such involvement can increase community stability and well-being, ultimately generating healthier living environments that prioritize the cultural and social requirements of plantation communities. Policy and design recommendations are summarized in Figure 8.

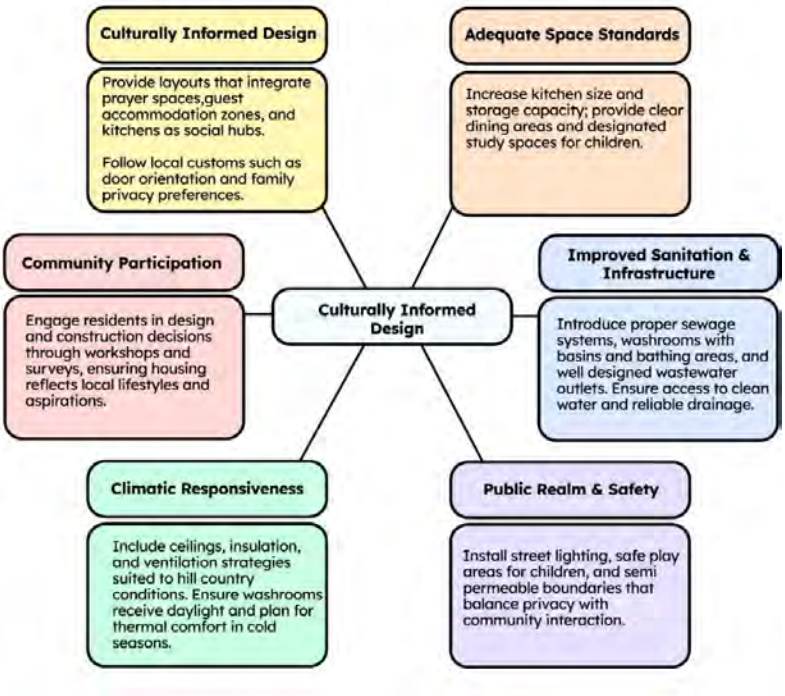



*Figure 8: Policy and design recommendations*

## 7. REFERENCES

Abed, A., Obeidat, B., & Gharaibeh, I. (2023). The impact of socio-cultural factors on the transformation of house layout: A case of public housing - Zebdeh-Farkouh, in Jordan. *Journal of Asian Architecture and Building Engineering*, *22*(3), 1195–1208. https://doi.org/10.1080/13467581.2022.2074021

Abeyrathna, W. P., Ariyarathna, I. S., Halwatura, R. U., Arooz, F. R., Perera, A. S., & Kaklauskas, A. (2024). ANN prediction model to improve employees' thermal satisfaction in tropical green office buildings. *Asian Journal of Civil Engineering*, *25*(1), 343–358. https://doi.org/10.1007/s42107-023-00779-y

Asian Development Bank. (2016). *Sri Lanka: Plantation Development Project* (PPE:SRI 2016-06). Asian Development Bank. https://www.adb.org/sites/default/files/evaluation-document/167392/files/in74-16_6.pdf

Azami, A. S., & Razavian, M. (2013). Analysis Moving Towards Sustainable Development of a City with Emphasis on the Quality of Urban Life: The Case of Noor. *Environment and Urbanization ASIA*, *4*(1), 31–56. https://doi.org/10.1177/0975425313477725

Boonyabancha, S. (2009). Land for housing the poor — by the poor: Experiences from the Baan Mankong nationwide slum upgrading programme in Thailand. *Environment and Urbanization*, *21*(2), 309–329. https://doi.org/10.1177/0956247809342180

Bruyns, G. (2018). The Social and the Spatial, Urban Models as Morphologies for a 'Lived' Approach to Planning. *Cubic Journal*, (1), 52–73. https://doi.org/10.31182/cubic.2018.1.003

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, *29*, 394–416. https://doi.org/10.1016/j.rser.2013.08.037

Chiu, R. L. H. (2004). Socio-cultural sustainability of housing: A conceptual exploration. *Housing, Theory and Society*, *21*(2), 65–76. https://doi.org/10.1080/14036090410014999

De Macedo, P. F., Ornstein, S. W., & Elali, G. A. (2022). Privacy and housing: Research perspectives based on a systematic literature review. *Journal of Housing and the Built Environment*, *37*(2), 653–683. https://doi.org/10.1007/s10901-022-09939-z

Denaldi, R., & Cardoso, A. L. (2021). Slum Upgrading beyond incubation: Exploring the dilemmas of nation-wide large scale policy interventions in Brazil´s growth acceleration programme (PAC). *International Journal of Urban Sustainable Development*, *13*(3), 530–545. https://doi.org/10.1080/19463138.2021.1958336

Emmanuel, R. (2005). Thermal comfort implications of urbanization in a warm-humid city: The Colombo Metropolitan Region (CMR), Sri Lanka. *Building and Environment*, *40*(12), 1591–1601. https://doi.org/10.1016/j.buildenv.2004.12.004

Fallah Tafti, F., Rollo, J., & McGann, S. (2026). Conceptualising a model for understanding socio-cultural and spatial factors in housing: Insights from a systematic scoping review. *Frontiers of Architectural Research*, *15*(1), 119–143. https://doi.org/10.1016/j.foar.2025.05.005

Ferguson, B., & Navarrete, J. (2003). New approaches to progressive housing in Latin America: A key to habitat programs and policy. *Habitat International*, *27*(2), 309–323. https://doi.org/10.1016/S0197-3975(03)00013-4

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Hapuarachchi, S. P., & Kariyawasam, S. S. (2021). An Evaluation of National Housing Policy Related to Plantation Housing in Sri Lanka. *Cities People Places : An International Journal on Urban Environments*, *5*(1), 94. https://doi.org/10.4038/cpp.v5i1.55

Hollup, O. (1993). Caste Identity and Cultural Continuity Among Tamil Plantation Workers in Sri Lanka 1. *Journal of Asian and African Studies*, *28*(1–2), 67–87. https://doi.org/10.1177/002190969302800105

Jabareen, Y. (2005). Culture and Housing Preferences in a Developing City. *Environment and Behavior*, *37*(1), 134–146. https://doi.org/10.1177/0013916504267640

Krieger, J., & Higgins, D. L. (2002). Housing and Health: Time Again for Public Health Action. *American Journal of Public Health*, *92*(5), 758–768. https://doi.org/10.2105/AJPH.92.5.758

Lefebvre, H., & Nicholson-Smith, D. (2013). *The production of space* (33. print). Blackwell Publishing.

Pelsmakers, S., & Warwick, E. (2022). Housing adaptability: New research, emerging practices and challenges. *Buildings and Cities*, *3*(1), 605–618. https://doi.org/10.5334/bc.266

Periyasamy, N. (2018). Update on the health status of plantation community in Sri Lanka. *Journal of the College of Community Physicians of Sri Lanka*, *23*(4), 135. https://doi.org/10.4038/jccpsl.v23i4.8135

Soja, E. W. (1980). The socio-spatial dialectic. *Annals of the Association of American Geographers*, *70*(2), 207–225. https://doi.org/10.1111/j.1467-8306.1980.tb01308.x

Van Noorloos, F., Cirolia, L. R., Friendly, A., Jukur, S., Schramm, S., Steel, G., & Valenzuela, L. (2020). Incremental housing as a node for intersecting flows of city-making: Rethinking the housing shortage in the global South. *Environment and Urbanization*, *32*(1), 37–54. https://doi.org/10.1177/0956247819887679

World Bank Group. (2017). *Multisectoral Nutrition Assessment in Sri Lanka's Estate Sector*. Washington, DC: World Bank. https://doi.org/10.1596/26328

Yates, J., & Milligan, V. (2007). Housing affordability: A 21st century problem. *Australian Housing and Urban Research Institute*. https://www.ahuri.edu.au/research/final-reports/105

Wijesundara, W.M.I.H., Wimalaratne P.L.I. and Kulatunaga, U., 2026. Revisiting methodological taxonomy: Locating design science research within research design hierarchies. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1484-1497. DOI: https://doi.org/10.31705/WCS.2026.108. Available from: https://ciobwcs.com/papers/

# REVISITING METHODOLOGICAL TAXONOMY: LOCATING DESIGN SCIENCE RESEARCH WITHIN RESEARCH DESIGN HIERARCHIES

**W.M.I.H. Wijesundara[1], P.L.I. Wimalaratne[2] and U. Kulatunga[3]**

## *ABSTRACT*

*Design Science Research (DSR) is recognised as a leading paradigm in information systems, engineering disciplines, and construction management fields. Despite its wide use and application, confusion still exists regarding its methodological placement as a research strategy, approach, or methodology. Notably, some of the most widely accepted methodological frameworks, such as the "research onion" developed by Saunders, Lewis, and Thornhill, has not positioned DSR in their taxonomic framework. This paper fills this conceptual gap through a systematic literature review and thematic analysis of existing literature. A 40 number of peer-reviewed articles were examined to establish how DSR is labelled and conceptually justified in existing literature. The results of this synthesis suggest that DSR is positioned as a research strategy, as justified by its prescriptive epistemology, logic of DSR inquiry, and structuring of the entire research process. Based on this synthesis of existing knowledge, a modified version of the widely accepted "research onion" is presented with DSR positioned as part of the research strategy layer of this framework. This paper contributes to methodological clarity, informs doctoral design decisions, and refines existing knowledge in the theoretical debate on research methods.*

***Keywords:*** *Design Science Research; Epistemology; Methodological Taxonomy; Research Onion; Research Strategy; Systematic Literature Review.*

## 1. INTRODUCTION

DSR has emerged as the leading paradigm in the development of prescriptive knowledge in the realm of sciences that deal with artifact development, innovation, and problem-solving (Akoka et al., 2023). The intellectual antecedents of DSR can be traced to the concept of artificial sciences proposed by Simon (1969). Simon proposed that there are two types of science: (i) natural sciences, which explain the world, and (ii) design sciences, which develop useful, purposeful artifacts. Hevner et al. (2004), formalised DSR as a research paradigm in the context of information systems research and proposed a set of guidelines that deal with the integration of rigor and relevance in design science research through an iterative process of design and evaluation. Further elaboration of the

[1] Research Assistant, Department of Building Economics, University of Moratuwa, Sri Lanka, wijesundarawmih.25@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, indraniw@uom.lk
[3] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk

design science research methodology, as proposed in the design science process model by Peffers (2006) and Vaishnavi (2007), has consolidated DSR as a research paradigm.

Yet, despite its maturity and application in information systems, engineering, management disciplines, and even in some built environment disciplines, a fundamental ambiguity exists regarding its methodological position (Holopainen et al., 2020). DSR is alternatively identified as a "research methodology" (Hevner et al., 2004), "research paradigm" (Gregor & Hevner, 2013), "design-oriented approach" (Johannesson & Perjons, 2021), and on some occasions as a "research strategy." This is not simply a matter of terminology; it is a fundamental ambiguity regarding its position on the hierarchy of the research design architecture. This ambiguity is clearly highlighted when DSR is compared with existing methodological taxonomies. The "research onion" developed by Saunders et al. (2019) is arguably one of the most widely accepted taxonomies of structuring research design in management and construction research disciplines. The framework comprises different layers of research design, including research philosophy, research approach, research strategy, method choice, time horizon, and techniques. DSR is not mentioned in this framework. While strategies such as experiment, case study, survey, and action research are clearly defined, the absence of DSR raises a conceptual question: Does DSR operate at the level of research strategy, or does it belong at a different methodological layer?

This gap is theoretically significant for three reasons. Firstly, DSR establishes a unique logic of research that focuses on artifact development and evaluation (Hevner et al., 2004). Such a logic may be said to be closer to a research strategy that guides the overall direction of research rather than research method or research technique. Secondly, DSR establishes a clear epistemology (Estany, 2020). DSR research is often said to be associated with pragmatism and prescriptive theory building (Gregor & Hart, 2010). In methodology theory, research strategies are said to be informed by epistemology. If DSR establishes the foundation for valid knowledge creation, then its classification as a research method may not be conceptually sound. Thirdly, the lack of DSR in the dominant model of research methodology may create confusion in training doctoral research and research design in fields like construction management and digital innovation in the built environment (Rensburg & Goede, 2019). Such confusion may cause DSR to be considered as a research technique rather than its role in structuring research design. Although prior studies have refined DSR processes (Peffers, 2006), clarified its theoretical contributions Gregor & Hevner, 2013), and debated its rigor, no study to date has systematically examined how DSR is positioned across the literature relative to established methodological taxonomies. In particular, there has been no systematic literature review combined with epistemological analysis aimed at determining whether DSR satisfies the defining criteria of a research strategy. Accordingly, this study addresses the following primary research question: 'How should Design Science Research be positioned within established methodological taxonomies?'

To operationalise this inquiry, four sub-questions are examined:

How is DSR labelled across peer-reviewed literature (strategy, approach, methodology, or method)?

What conceptual arguments are used to justify these labels?

Does DSR satisfy the defining characteristics of a research strategy as articulated in methodological theory?

Where should DSR be located within an extended research onion framework?

By systematically mapping the positioning of DSR in the literature and evaluating its epistemological characteristics, this study seeks to provide conceptual clarification and to propose a theoretically justified extension to existing methodological taxonomies. In doing so, it contributes to methodological rigor and supports clearer research design decisions in construction and built environment scholarship.

# 2. THEORETICAL FOUNDATIONS

## 2.1 RESEARCH STRATEGY, RESEARCH APPROACH, AND RESEARCH METHOD

Research design literature commonly distinguishes between research philosophy, research approach, research strategy, and research methods (Abutabenjeh & Jaradat, 2018). These layers collectively determine how knowledge is generated and validated within a study. The philosophy of research comprises underlying beliefs about the nature of reality (ontology), the nature and limits of knowledge (epistemology), and the importance of values in research (axiology) (Assoreira, 2025). Research approaches describe the rules of reasoning (e.g., deductive, inductive, or abductive), research strategies provide the plan for conducting the study, and research methods represent the techniques used to collect and analyse data (Phillips, 2023). The hierarchical nature of research design has been widely illustrated through the research onion model developed by Mark Saunders and colleagues. The model conceptualises research design as a set of nested methodological layers that guide the development of systematic and coherent research processes. At its outer layers, the model addresses philosophical assumptions and research approaches, while the inner layers focus on research strategies, methodological choices, time horizons, and data collection techniques (Snyder, 2019). In this structure, research strategies represent the overarching methodological frameworks used to address research problems. Common strategies include experiments, case studies, surveys, grounded theory, and design-oriented research (Stoecker & Avila, 2021). Research methods, by contrast, represent the operational techniques used for data generation and analysis, including interviews, surveys, observations, modelling, or computational analysis. Despite the widespread adoption of the research onion framework, ambiguity remains regarding the positioning of design-oriented research within the hierarchy. DSR is frequently described interchangeably as a research paradigm, methodology, strategy, or method, leading to conceptual inconsistencies in research design reporting. Addressing this ambiguity requires examining the theoretical development of DSR and its methodological characteristics.

## 2.2 EVOLUTION OF DESIGN SCIENCE RESEARCH

The intellectual foundations of design-oriented research originate in the work of Simon (2019) who distinguished between natural sciences that explain phenomena and sciences of the artificial that focus on the creation of artefacts intended to solve practical problems. Simon's perspective introduced the notion that scientific inquiry could legitimately involve the systematic design and evaluation of artefacts. Building on this foundation, DSR was formalised as a methodological approach for developing and evaluating artefacts that address real-world problems (Johannesson & Perjons, 2021). The framework proposed by Hevner et al. (2004), articulated design science as a rigorous

research paradigm emphasising the creation of artefacts such as models, methods, constructs, and systems. Subsequent methodological developments further operationalised DSR. The design science process model introduced by Peffers (2006) structured DSR activities into sequential stages, including problem identification, objective definition, artefact design, demonstration, evaluation, and communication. In parallel, theoretical contributions from Shirley Gregor emphasised the role of design theory in linking artefact creation with knowledge production. Despite these contributions, the terminology used to describe DSR remains inconsistent. Studies alternately refer to DSR as a paradigm, methodology, strategy, or research method, which complicates its integration within established research design frameworks such as the research onion. This inconsistency motivates the need for a systematic examination of how DSR is positioned within the methodological hierarchy.

# 3. RESEARCH DESIGN AND METHODOLOGY

## 3.1 OVERALL RESEARCH DESIGN

This study adopts a qualitative research design to clarify the methodological positioning of Design Science Research. The research process integrates systematic literature review (SLR), thematic analysis, and philosophical reflection to develop a framework positioning DSR within the hierarchy of research methodology. The overall workflow consists of four sequential stages: systematic literature review, thematic coding of methodological definitions, philosophical reflection of the extracted concepts, and development of an extended research onion framework incorporating Design Science Research. Systematic review procedures follow established guidelines for evidence synthesis proposed by (Kitchenham, 2004; Tranfield, 2002).

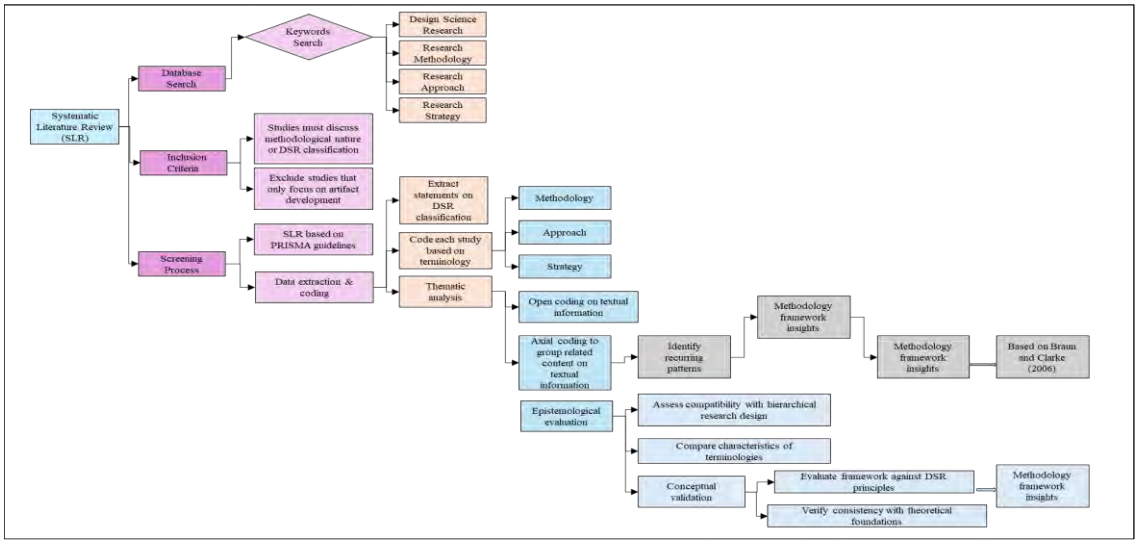



*Figure 1: Research process*

The approach to conducting this research was a SLR since it was not the aim of this research to empirically test anything, yet rather to perform conceptual synthesis (Tarhan et al., 2016). The SLR approach facilitates clear and structured extraction of concepts, classifications, and controversies in existing literature (Vilches et al., 2017). As the study is focused on understanding the place that DSR occupies in methodological taxonomies, the systematic review approach appeared to be appropriate.

## 3.2 CONCEPTUAL VALIDATION

To ensure conceptual coherence, the resulting framework was evaluated against established design science principles articulated by Shirley Gregor and Alan R. Hevner. This step verified that the proposed positioning of DSR remains consistent with the theoretical foundations of design science while aligning with established research design frameworks.

## 3.3 DESCRIPTIVE MAPPING

This study conducted a SLR to identify and classify scholarly discussions on DSR as a research methodology, strategy, or approach. The review used a structured search string: <Title ABS key> "Design Science Research" AND (methodology OR strategy OR approach OR paradigm), along with variations such as "Design Science Research methodology," "Design Science Research approach," and "Design Science Research strategy." Searches were performed in Scopus and Web of Science, yielding 282 and 44 records, respectively. Only peer-reviewed journal articles and conference papers published in English were included. Following duplicate removal and screening of titles, abstracts, and full texts against inclusion criteria, the final dataset was prepared for analysis. The screening process is illustrated in a PRISMA diagram. This SLR provides a rigorous, transparent, and reproducible foundation for the subsequent thematic analysis and epistemological evaluation. The Scopus and Web of Science databases were chosen since they have been established as two of the most comprehensive and trustworthy multidisciplinary citation databases (Mongeon & Paul-Hus, 2016). They provide extensive access to peer-reviewed literature relevant to DSR and methodology.

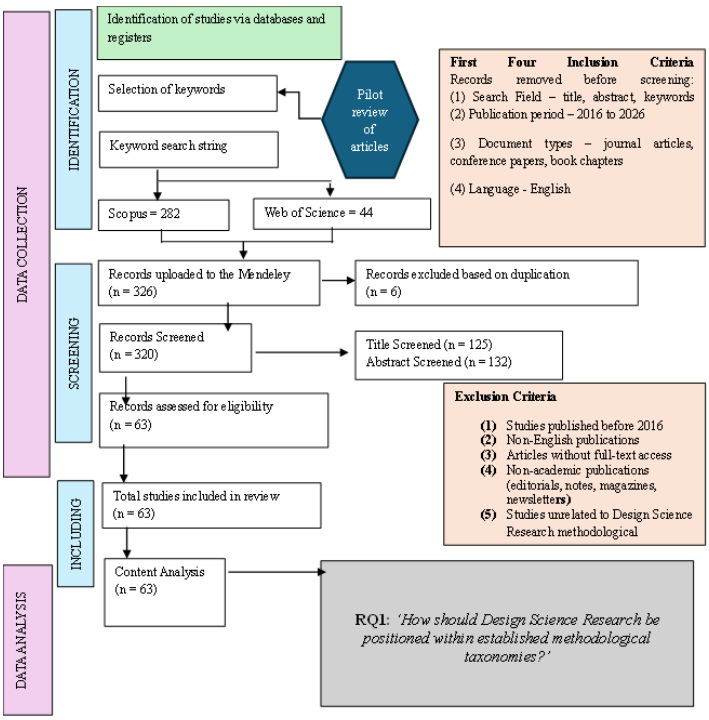



*Figure 2: PRISMA Standard mapping for the SLR to identify the studies that are related to the search string, and the studies that lead to thematic findings and epistemological evaluation*

### 3.3.1 Data Representation

The next step was to synthesise the results from the selected studies using a qualitative content analysis method (Briner & Denyer, 2012). This method is particularly relevant for analysis because it provides a systematic means for interpreting texts based on patterns, themes, or relationships that exist between them. The analysis was undertaken manually without the help of any computer program for qualitative data analysis. This was particularly relevant for ensuring a deeper level of analysis that could filter out any weaker conceptual or methodological work in favour of high-quality insights (Toyin et al., 2025). The studies selected for analysis were coded based on different dimensions, such as the research taxonomy for studies as a foundation, research methodology, research strategy, and research approach to understanding.

## 4. FINDINGS

The section presented the findings and analysis of SLR, thematic analysis, and the epistemological findings.

### 4.1 OVERVIEW OF THE INCLUDED STUDIES

The last set included studies consisting of peer-reviewed journal articles, review articles, conference publications, and book chapters published between 2002 and 2026, reflecting the increased interest in biomimicry-based building materials and innovation in sustainability in the built environment (Pedersen Zari & Hecht, 2020).

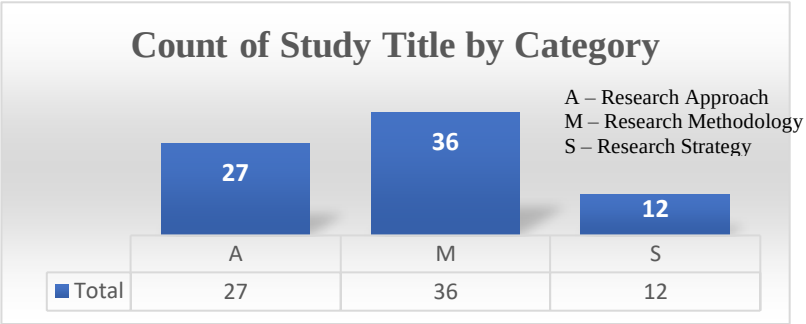



*Figure 3: Studies by the term*

*Note: There is no exclusivity between the categories. Many studies used in the review made reference to DSR employing various categorizations such as methodology, approach, strategy, and paradigm. Thus, the total number is more than that of the reviewed studies.*

The studies have been considered based on the term, as shown in Figure 3.

### 4.2 DOMINANT POSITIONING OF DSR AS A RESEARCH METHODOLOGY IN THE RESEARCH ONION

The systematic literature review reveals that the majority of studies conceptualise DSR as a research methodology. Out of the analysed studies, 36 publications position DSR as a methodological framework**,** highlighting its structured process for designing and evaluating artefacts. Foundational and subsequent studies emphasise that DSR provides systematic procedures for conducting design-oriented research, including artefact development, demonstration, and evaluation stages. For example, a study by Peffers et al. (2007), explicitly refers to DSR as a methodological framework guiding the research

process. Similarly, several studies emphasise the methodological rigor embedded in DSR through structured design cycles and evaluation mechanisms, considering the research onion. Researchers such as Goecks et al., (2021) and Tommelein (2020), highlight the systematic research procedures that characterise DSR. These studies collectively demonstrate that DSR provides a structured methodological pathway for developing and evaluating artefacts, which aligns with the defining characteristics of a research methodology at the point of Saunders' research onion. The predominance of methodological interpretations in the reviewed literature suggests that researchers widely recognise DSR as more than a general research orientation. Instead, it functions as a comprehensive methodological framework capable of guiding the entire research lifecycle**,** from problem identification to artefact evaluation and knowledge contribution.

### 4.3 DSR AS A DESIGN-ORIENTED PROBLEM-SOLVING METHODOLOGY

One of the primary reasons for the strong positioning of DSR as a research methodology is its explicit focus on problem-solving through artefact creation. Many studies highlight that DSR enables researchers to address complex organizational and technological problems by designing innovative solutions such as models, systems, frameworks, and methods. For instance, studies by such as Diaz Schery et al., (2025) illustrate how DSR is applied to develop practical artefacts that address real-world challenges. Similarly, research such as Tommelein (2020) demonstrates how DSR facilitates the development of technological solutions in industry contexts. These studies collectively emphasise that DSR provides a systematic methodological framework for generating practical solutions, reinforcing its positioning as a research methodology rather than merely a research approach or strategy.

### 4.4 STRUCTURED RESEARCH PROCESSES AND EVALUATION MECHANISMS

Another factor supporting the classification of DSR as a research methodology is its structured research process and evaluation mechanisms. Numerous studies emphasise that DSR incorporates clearly defined stages that guide the development and validation of artefacts. Researchers such as Aparicio et al. (2023), Gomera and Mramba (2023), and Muntean and Militaru (2022) highlight the importance of evaluation within the DSR process. These studies describe how artefacts developed through DSR must be rigorously assessed to ensure their effectiveness and relevance. Furthermore, studies such as *On Experiments in Design Science Research and Theory Development: A Literature Review* and *Design Science Research Evaluation* emphasise that the evaluation phase plays a critical role in validating the artefacts produced through the research process. The presence of these systematic evaluation mechanisms further reinforces the methodological nature of DSR. Overall, the findings of the systematic literature review indicate that Design Science Research demonstrates the strongest conceptual alignment with the characteristics of a research methodology for the research onion. While several studies frame DSR as a research approach and a smaller subset conceptualises it as a research strategy, the predominance of methodological interpretations suggests that DSR provides the most value when positioned as a structured research methodology. This conclusion is supported not only by the frequency of studies identifying DSR as a methodology, yet by the methodological characteristics consistently highlighted in the literature, including structured research stages, artefact development processes, and rigorous evaluation mechanisms.

### 4.5 THEMATIC ANALYSIS

The findings of this study were derived through a two-stage analytical process consisting of a SLR followed by thematic analysis. The SLR systematically identified and collected relevant scholarly publications on the methodological positioning of DSR. Through database searches, screening procedures, and eligibility assessment, studies that explicitly discussed the classification or conceptual role of DSR within research design were selected for further analysis. While the SLR provided a structured process for identifying the relevant body of literature, it did not by itself reveal how DSR is conceptually interpreted. To address this, the textual statements extracted from the selected studies were analysed thematically, following the procedures proposed by Braun and Clarke (2006, 2012). In this stage, statements describing the role, function, or classification of DSR were coded and grouped into conceptual categories. Open coding was first applied to identify key terms and descriptions used by authors. These codes were subsequently consolidated through axial coding to identify recurring patterns across the literature. Through this process, three dominant interpretations of DSR emerged from the analysed studies: DSR as a research methodology, DSR as a research strategy, and DSR as a research approach.

These themes represent the different ways in which researchers conceptualise the methodological nature of design-oriented inquiry. The first theme interprets DSR as a research methodology. In this interpretation, DSR is described as a structured methodological framework that guides the systematic design, development, and evaluation of artefacts. Studies adopting this perspective typically emphasise methodological principles and procedural guidance for conducting design-oriented research. Such interpretations frequently reference the design science guidelines proposed by Hevner et al. (2004), which outline principles for rigorous artefact creation and evaluation. The second theme conceptualises DSR as a research strategy. Within this interpretation, DSR functions as a structured plan that organises research activities around the iterative design and evaluation of artefacts intended to address practical problems. Authors adopting this perspective emphasise the role of DSR in structuring the research process rather than prescribing specific research techniques. This interpretation often reflects the process-oriented model proposed by Peffers et al. (2018), where DSR is presented as a sequence of research activities including problem identification, artefact design, demonstration, and evaluation. The third theme interprets DSR as a research approach. In this view, DSR is treated as a broader orientation toward knowledge generation that prioritizes constructive problem solving through artefact creation. This interpretation reflects the philosophical foundations of design-oriented inquiry originally articulated by Simon (2019), who distinguished between explanatory sciences and sciences concerned with the design of artificial artefacts. The identification of these three themes demonstrates that the literature does not consistently classify DSR within a single layer of research design. Instead, scholars emphasise different aspects of design-oriented research, leading to multiple interpretations of its methodological status.

## 5. PHILOSOPHICAL REFLECTION

To further examine the methodological positioning of DSR, an epistemological evaluation was conducted based on the classifications identified through the systematic literature review. While the SLR provided a descriptive mapping of how DSR is labelled across studies, the epistemological evaluation aims to interpret these classifications

within the broader hierarchy of research design. The SLR results indicate considerable variation in how DSR is positioned within the research design structure. As illustrated in Figure 4, the majority of studies (36) describe DSR as a research methodology, while a substantial number of studies (27) interpret it as a research approach. Only a limited number of studies positions DSR as a research strategy (12), while very few studies conceptualise DSR at higher epistemological levels, such as research philosophy (2) or research paradigm (2). These findings demonstrate that the literature predominantly emphasises the methodological and procedural characteristics of DSR, particularly its structured frameworks for artefact design and evaluation. At the same time, the presence of approach-level interpretations suggests that some scholars view DSR more broadly as a mode of inquiry oriented toward design-based knowledge generation. The epistemological evaluation, therefore, highlights the conceptual diversity in the methodological positioning of DSR within the literature, indicating that scholars interpret the role of DSR at multiple levels of the research design hierarchy.

There have been different interpretations of the epistemological foundations of DSR, particularly concerning the relationship between pragmatism and design science epistemology. Goldkuhl (2020), argues that pragmatism provides an important foundation for DSR, whereby knowledge is judged according to its practical consequences and usefulness in addressing real-world problems. In contrast, design science epistemology places greater emphasis on the purposeful creation and evaluation of artefacts to generate prescriptive knowledge. Thus, while pragmatism primarily focuses on the utility of knowledge, design science epistemology highlights the processes of design, intervention, and artefact evaluation as mechanisms for knowledge generation.Furthermore, Iivari (2015) distinguishes between theory-oriented and problem-solving-oriented forms of DSR, demonstrating that the nature of knowledge produced and the criteria used for its validation may vary depending on the objectives of the inquiry.

*Figure 4: SLR findings directed towards Epistemological evaluation*

*Note: There is no exclusivity between the categories. Many studies used in the review referred to DSR employing various categorizations such as methodology, approach, strategy, and paradigm. Thus, the total number is more than that of the reviewed studies.*

This plurality of epistemological assumptions suggests that DSR does not prescribe a single form of knowledge generation but rather provides a flexible framework through which knowledge can be created and evaluated. Consequently, these epistemological characteristics support the positioning of DSR as a methodological choice, as its underlying assumptions inform how artefacts are designed, evaluated, and used to produce scientifically rigorous and practically relevant knowledge.

# 6. POSITIONING DESIGN SCIENCE RESEARCH WITHIN THE EXTENDED RESEARCH ONION

The systematic literature review and epistemological evaluation conducted in this study demonstrate that DSR functions as a research methodology rather than merely a research strategy or approach. To conceptually position this finding within established methodological frameworks, this study introduces an extended version of the research onion model, incorporating Design Science Research at the research methodology layer. The research onion, developed by Mark Saunders, Philip Lewis, and Adrian Thornhill, is widely used to explain the hierarchical structure of research design (Saunders et al., 2019). The framework conceptualises methodological decision-making as a set of layered choices through which researchers move from philosophical assumptions toward specific research techniques. These layers typically include research philosophy, research approach, research strategy, method choice, time horizon, and techniques and procedures.

Despite its extensive adoption in management, information systems, and construction research, the original research onion does not explicitly include Design Science Research. This omission reflects the historical development of methodological frameworks, which primarily emphasise explanatory research traditions such as experiments, surveys, and case studies. In contrast, design-oriented research approaches have developed more prominently within engineering and information systems disciplines. The intellectual origins of design-oriented inquiry can be traced to the work of Simon (2019), who introduced the concept of the sciences of the artificial, emphasising research aimed at creating artefacts that address real-world problems (Simon, 2023). Building on this perspective, Hevner et al. (2004), formalised DSR as a paradigm focused on the development and evaluation of artefacts that generate practical and theoretical knowledge (Hevner et al., 2004). Later, Peffers et al. (2018), proposed a structured Design Science Research Methodology (DSRM) consisting of stages, including problem identification, artefact design, demonstration, evaluation, and communication (Peffers, 2006).

Based on these foundations and the findings of the systematic literature review, this study proposes an extended methodological research onion that explicitly incorporates DSR as a research methodology. The structure of the extended model is illustrated in Figure 5. Positioning DSR at the methodology layer reflects its ability to structure the entire research process while integrating multiple research strategies and empirical methods. Unlike conventional explanatory methodologies, DSR generates prescriptive knowledge through the design and evaluation of artefacts such as models, frameworks, systems, and decision-support tools. As noted by Gregor and Hevner (2013), the outputs of DSR include technological artefacts and design principles that contribute to both theoretical advancement and practical innovation (Gregor & Hevner, 2013). Consequently, the extended research onion proposed in this study provides a clearer methodological structure for positioning design-oriented research, particularly in applied disciplines such as construction management, information systems, and engineering.

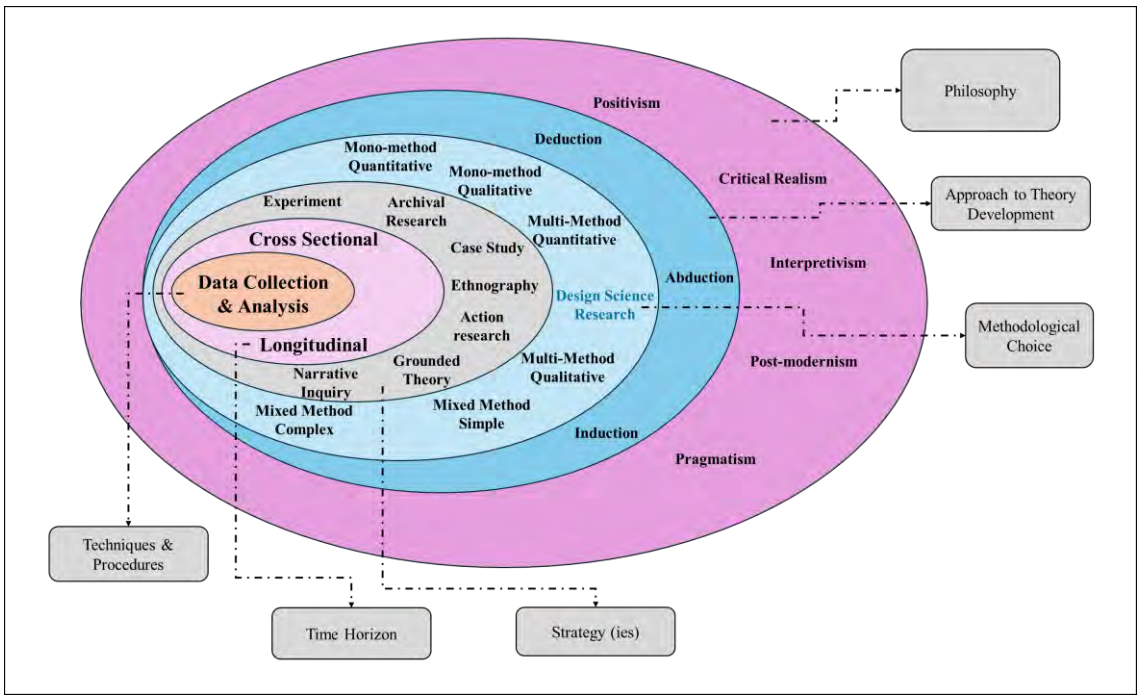



*Figure 5: Extended research onion*

*Source – Author's own work - Devised the research onion by (Saunders et al., 2019)*

DSR is appropriately conceptualised as a research methodology because it provides a structured framework that guides the overall research process, including the design, development, and evaluation of artefacts. By facilitating the integration of appropriate methods and techniques within a coherent process, DSR enables the generation of both rigorous and practically relevant knowledge (Abutabenjeh & Jaradat, 2018; Saunders et al., 2019).

## 7. LIMITATIONS AND FUTURE RESEARCH

Despite its contributions, this study has several limitations that should be acknowledged. First, the study relies on interpretive analysis of conceptual descriptions within the literature. Although systematic review procedures were used to minimise bias, the classification of studies inevitably involves a degree of interpretive judgement. Second, the scope of the literature review is limited to publications identified through the selected academic databases. While these databases provide extensive coverage of relevant journals, additional studies discussing Design Science Research may exist outside the search scope. Third, the extended research onion framework proposed in this study represents a conceptual model rather than an empirically validated framework. Future research could examine the applicability of the model by analysing how Design Science Research is employed in empirical studies across different disciplines. Further research may also explore how Design Science Research interacts with different research philosophies and methodological approaches within interdisciplinary contexts.

## 8. CONCLUSIONS

This study sought to clarify the methodological positioning of DSR within the hierarchy of research methodologies. Through a systematic literature review, thematic analysis, and epistemological evaluation, the study examined how DSR has been conceptualised across

the academic literature. The results show that DSR is mainly considered a research methodology in prior literature. According to the research onion, DSR can be classified as a research methodology. This conceptual framework provides a clearer methodological structure for design-oriented research and helps address longstanding ambiguity surrounding the classification of DSR. By clarifying the methodological status of Design Science Research, this study enhances research design transparency and supports the integration of design-oriented inquiry into established methodological frameworks from the perspective of Saunders' research onion.

# 9. REFERENCES


Abutabenjeh, S., & Jaradat, R. (2018). Clarification of research design, research methods, and research methodology: A guide for public administration researchers and practitioners. *Teaching Public Administration*, *36*(3), 237–258. https://doi.org/10.1177/0144739418775787

Akoka, J., Comyn-Wattiau, I., Prat, N., & Storey, V. C. (2023). Knowledge contributions in design science research: Paths of knowledge types. *Decision Support Systems*, *166*, 113898. https://doi.org/10.1016/j.dss.2022.113898

Aparicio, J. T., Aparicio, M., & Costa, C. J. (2023). Design Science in Information Systems and Computing In A. Rocha, H. Adeli, G. Dzemyda, F. Moreira, & A. M. Ramalho Correia (Eds.), *Trends and Innovations in Information Systems and Technologies* (pp. 409–419). Springer. https://doi.org/10.1007/978-981-19-9331-2_35

Assoreira Almendra, R. (2025). *Proximity in Design Research; People, Processes, Products, Philosophy* (1st ed.). Routledge. https://doi.org/10.4324/9781003509653

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2012). Thematic analysis. In *APA handbook of research methods in psychology, Vol 2: Research designs: Quantitative, qualitative, neuropsychological, and biological.* (pp. 57–71). American Psychological Association. https://doi.org/10.1037/13620-004

Briner, R. B., & Denyer, D. (2012). Systematic Review and Evidence Synthesis as a Practice and Scholarship Tool. In D. M. Rousseau (Ed.), *The Oxford handbook of evidence-based management* (pp. 112–129). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199763986.013.0007

Diaz Schery, C. A., Caiado, R. G. G., Corseuil, E. T., Ivson, P., & Bueno, A. (2025). A novel BIM maturity model integrating Industry 4.0 and sustainability: a design science research approach. *Engineering, Construction and Architectural Management*. Advance online publication. https://doi.org/10.1108/ECAM-10-2024-1333

Estany, A. (2020). Design epistemology as innovation in public health research. *European Journal of Public Health*, *30*(Supplement_5). https://doi.org/10.1093/eurpub/ckaa165.647

Goecks, L. S., Souza, M. de, Librelato, T. P., & Trento, L. R. (2021). Design Science Research in practice: A review of applications in Industrial Engineering. *Gestão & Produção*, *28*(4). https://doi.org/10.1590/1806-9649-2021v28e5811

Goldkuhl, G. (2020). *Design Science Epistemology. A pragmatist inquiry*. https://aisel.aisnet.org/sjis/vol32/iss1/2

Gomera, W. C., & Mramba, N. R. (2023). Deploying design science research in sparse resource settings: Some lessons from design projects in Tanzania. *African Journal of Science, Technology, Innovation and Development*, *15*(6), 705–719. https://doi.org/10.1080/20421338.2023.2178786

Gregor, S. Diane., & Hart, D. N. (2010). *Information systems foundations: the role of design science*. ANU Press.

Gregor, S., & Hevner, A. R. (2013). Positioning and presenting design science research for maximum impact. *MIS Quarterly*, *37*(2), 337–355. https://doi.org/10.25300/MISQ/2013/37.2.01

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research 1. In *Design Science in IS Research MIS Quarterly* (Vol. 28, Number 1).

Holopainen, J., Mattila, O., Pöyry, E., & Parvinen, P. (2020). Applying design science research methodology in the development of virtual reality forest management services. *Forest Policy and Economics*, *116*, 102190. https://doi.org/10.1016/j.forpol.2020.102190

Iivari, J. (2015). Distinguishing and contrasting two strategies for design science research. *European Journal of Information Systems*, *24*(1), 107–115. https://doi.org/10.1057/ejis.2013.35

Iivari, J., & Venable, J. R. (2009). *Association for Information Systems AIS Electronic Library (AISeL) Action research and design science research-Seemingly similar but decisively dissimilar*. Retrieved http://aisel.aisnet.org/ecis2009/73

Johannesson, P., & Perjons, E. (2021). *An Introduction to Design Science*. Springer International Publishing. https://doi.org/10.1007/978-3-030-78132-3

Kitchenham, B. (2004). *Procedures for Performing Systematic Reviews*. Keele University and National ICT Australia.

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: a comparative analysis. *Scientometrics*, *106*(1), 213–228. https://doi.org/10.1007/s11192-015-1765-5

Muntean, M., & Militaru, F. D. (2022). Design Science Research Framework for Performance Analysis Using Machine Learning Techniques. *Electronics*, *11*(16), 2504. https://doi.org/10.3390/electronics11162504

Johannesson, P., & Perjons, E. (2021). Research strategies and methods. In *An introduction to design science* (pp. 69–96). Springer. https://doi.org/10.1007/978-3-030-78132-3_4.

Pedersen Zari, M., & Hecht, K. (2020). Biomimicry for Regenerative Built Environments: Mapping Design Strategies for Producing Ecosystem Services. *Biomimetics*, *5*(2), 18. https://doi.org/10.3390/biomimetics5020018

Peffers, J. (2006). *The Design Science Research Process : A Model for Producing and Presenting Information Systems Research*. http://rightsstatements.org/page/InC/1.0/?language=en

Peffers, K., Tuunanen, T., Gengler, C. E., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2007). *The design science research process: A model for producing and presenting information systems research. Journal of Management Information Systems, 24(3), 45–77.* https://doi.org/10.2753/MIS0742-1222240302.

Peffers, K., Tuunanen, T., & Niehaves, B. (2018). Design science research genres: introduction to the special issue on exemplars and criteria for applicable design science research. In *European Journal of Information Systems* (Vol. 27, Number 2, pp. 129–139). https://doi.org/10.1080/0960085X.2018.1458066

Phillips, M. J. (2023). Towards a social constructionist, criticalist, Foucauldian-informed qualitative research approach: Opportunities and challenges. *SN Social Sciences*, *3*(10), 184. https://doi.org/10.1007/s43545-023-00774-9

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students* (8th ed.). Pearson.

Simon, H. A. (2019). *The Sciences of the Artificial*. The MIT Press. https://doi.org/10.7551/mitpress/12107.001.0001

Simon, J. (2023). Augmented Reality Application Development using Unity and Vuforia. *Interdisciplinary Description of Complex Systems*, *21*(1), 69–77. https://doi.org/10.7906/indecs.21.1.6

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Stoecker, R., & Avila, E. (2021). From mixed methods to strategic research design. *International Journal of Social Research Methodology*, *24*(6), 627–640. https://doi.org/10.1080/13645579.2020.1799639

Tarhan, A., Turetken, O., & Reijers, H. A. (2016). Business process maturity models: A systematic literature review. *Information and Software Technology*, *75*, 122–134. https://doi.org/10.1016/j.infsof.2016.01.010

Tommelein, I. D. (2020). Design science research in construction management: multi-disciplinary collaboration on the SightPlan system. *Construction Management and Economics*, *38*(4), 340–354. https://doi.org/10.1080/01446193.2020.1718723

Toyin, J. O., Sattineni, A., Wetzel, E. M., Fasoyinu, A. A., & Kim, J. (2025). Augmented reality in U.S. Construction: Trends and future directions. *Automation in Construction*, *170*, 105895. https://doi.org/10.1016/j.autcon.2024.105895

Tranfield, D. (2002). Formulating the Nature of Management Research. *European Management Journal*, *20*(4), 378–382. https://doi.org/10.1016/S0263-2373(02)00057-9

van Rensburg, J. T. J., & Goede, R. (2019). A Model for Improving Knowledge Generation in Design Science Research through Reflective Practice. *Electronic Journal of Business Research Methods*, *17*(4), 194-206. https://doi.org/10.34190/JBRM.17.4.001

Vijay K. Vaishnavi. (2007). *Design Science Research Methods and Patterns* (1st ed.).CRC Press.

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. In *Energy and Buildings* (Vol. 135, pp. 286–301). Elsevier Ltd. https://doi.org/10.1016/j.enbuild.2016.11.042

Kadirappulige, I.R.., Karunasena, G., Udawatta, N., Gurmu, A., 2026. Risk perceptions in circular economy adoption in the Australian construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1498-1511. DOI: https://doi.org/10.31705/WCS.2026.109. Available from: https://ciobwcs.com/papers/

# RISK PERCEPTIONS IN CIRCULAR ECONOMY ADOPTION IN THE AUSTRALIAN CONSTRUCTION INDUSTRY

**Isuri Ridmika Kadirappulige[1], Gayani Karunasena[2], Nilupa Udawatta[3] and Argaw Gurmu[4]**

## *ABSTRACT*

*Risk refers to the uncertainty associated with achieving a particular objective. Innovative approaches often involve greater risk because they are not fully realised or widely validated in real-world contexts. The Circular Economy (CE) represents such an innovation, replacing traditional linear material flows with regenerative principles. Given its transformative nature and the conservative characteristics of the construction industry, CE adoption in Australia involves considerable uncertainty. This can lead to risk aversion among decision-makers, particularly clients who act as project initiators and investors. Therefore, how these decision-makers perceive risk is critical, as it strongly influences the initial decision to adopt CE. Therefore, this study examines the perceived risks faced by decision-makers in the Australian commercial construction industry. Eleven industry experts were interviewed, and the data were analysed using content and thematic concurrence analysis in NVivo. The findings show that financial ambiguity, material quality, supply chain reliability, stakeholder coordination, end-of-life planning and longer construction time are perceived as critical risks shaping early-stage decision-making. Experts explained that perceptions even exceed objective risk realities, consistent with the principles of Prospect Theory, which highlight the divergence between perceived and actual risk. In contrast, uncertain regulatory changes, corruption and health and safety concerns were generally not considered decisive in the initial decision-making process. The study highlights that perceived risks, rather than objective risks, dominate decision-makers in the early stages of CE adoption, underscoring the need to address perception gaps to facilitate effective implementation of circular practices in Australian commercial construction projects, leading to future research.*

***Keywords:*** *Circular Economy; Client; Commercial Construction Projects; Decision-makers; Perceived Risk.*

## 1. INTRODUCTION

In Australia, the built environment contributes substantially to environmental degradation, particularly through its generation of C&D waste (Feldman et al., 2024). The National Waste Report 2022 recorded 25.2 million tonnes of such waste in 2020–21,

[1] PhD Candidate, School of Architecture and Built Environment (SABE), Deakin University, Australia, i.kadirappulige@deakin.edu.au
[2] Senior Lecturer, SABE, Deakin University, Australia, gayani.karunasena@deakin.edu.au
[3] Senior Lecturer, SABE, Deakin University, Australia, nilupa.udawatta@deakin.edu.au
[4] Senior Lecturer, SABE, Deakin University, Australia, argaw.gurmu@deakin.edu.au

almost one-third of Australia's total waste output. Although the resource recovery rate is relatively high (approximately 81%), the scale of waste highlights the persistence of a linear construction model that prioritises virgin material extraction, short building lifespans, and demolition over circular practices (Department of Climate Change Energy, the Environment and Water [DCCEEW], 2022). A 39% increase in C&D waste per capita over the past 15 years illustrates the growing environmental strain on Australia's resource systems (DCCEEW, 2024). These trends indicate continued dependence on virgin materials, intensive energy use, and high disposal rates, all of which contribute to resource depletion and emissions burdens in the built environment. In response, the industry is increasingly incorporating sustainable practices to reduce its environmental impact (Amudjie et al., 2023). Approaches such as green construction, net-zero buildings, smart construction technologies, sustainable supply chains, and the Circular Economy (CE) are being adopted to improve sustainability (Amudjie et al., 2023; Ho et al., 2023). CE is particularly transformative, focusing on the full lifecycle of materials through strategies such as maintenance, reuse, refurbishment, remanufacture, and recycling (Ellen MacArthur Foundation [EMF], 2024). However, adoption remains limited; as of 2019, only 4% of construction practices in Australia incorporated circular principles, leaving a 96% gap (DCCEE, 2024). The adoption of CE represents a significant innovation within a conservative industry, creating uncertainties that influence decision-makers' willingness to initiate, invest, or support CE practices.

Risk perception plays a critical role in shaping such decisions. Unlike objective risk, which is measurable and data-driven, perceived risk is subjective, shaped by cognitive biases, heuristics, and emotional responses (Vasvári, 2015). Prospect Theory (Kahneman & Tversky, 1979) and Dual Process Theory (Kahneman, 2011) explain that decision-makers often weigh potential losses more heavily than gains, and rely on intuitive rather than analytical reasoning in early-stage decisions. There are numerous decision-makers, such as clients, government representatives, research and development institutes, designers, contractors, and suppliers, involved in initiating, supporting, and investing in CE-oriented strategies (Ho et al., 2023; Tan et al., 2022; Vasvári, 2015). Without proactive leadership from these groups, individual-level engagement is insufficient to drive systemic change (Tan et al., 2022). Yet existing studies consistently highlight limited commitment from decision-makers across key stakeholder groups (AlJaber, 2023; Circle Economy Foundation [CEF], 2024; Tan et al., 2022). Evidence suggests that designers, contractors, and suppliers are more likely to adopt CE practices when clients, R&D organisations, and governments demonstrate clear commitment (Adabre et al., 2024), while the success of CE-focused business models critically depends on clients' awareness and interest (Bertassini et al., 2021). Therefore, understanding how these risk perceptions affect decision-makers, particularly clients, is essential to accelerating CE adoption. Consequently, perceived risk may exceed objective risk, creating barriers to innovation adoption, particularly in client-led commercial construction projects where financial stakes, regulatory complexity, and multiple stakeholders intensify decision uncertainty (AlJaber et al., 2023; Tan et al., 2022). Hassan et al. (2023), Berglund-Brown et al. (2024), Tam (2024), and Wuni and Abankwa (2023) examined the objective risks associated with CE adoption in construction projects. Nevertheless, their analyses largely focused on risk identification and assessment, without distinguishing between objective risks and the perceptions of decision-makers who ultimately influence CE adoption decisions. Therefore, this study aims to examine the perceived risks of client, developer, and investor decision-makers in Australian commercial construction projects, with a

focus on understanding what are the different perceptions influences initial CE adoption decisions.

## 2. LITERATURE REVIEW

In natural ecosystems, every output becomes an input to another process, forming a continuous, regenerative cycle in which waste does not exist (Braungart & Braungart, 1990; Rim et al., 2025). By contrast, modern economies**,** including construction**,** have historically followed a linear "take–make–dispose" model, contributing to resource depletion and environmental degradation (Winans et al., 2017). As pressures from climate change and finite resources intensified (Baldassarre, 2025; CEF, 2024; United Nations, 2015), the need for an alternative system emerged: the circular economy. CE gained substantial global recognition in the late 2000s and early 2010s, driven largely by the work of the Ellen MacArthur Foundation (EMF) and reinforced by policymakers (e.g., European Union, World Economic Forum), multinational corporations (e.g., Renault, Philips), and consulting organisations (e.g., Deloitte, Circle Economy). These actors broadened CE's visibility by framing it as a closed-loop economic system centred on waste minimisation, resource optimisation, and sustainability across product lifecycles (Pauli, 2010; Winans et al., 2017). EMF provided one of the most widely adopted definitions in 2012, describing CE as: "*an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts toward renewable energy, eliminates toxic chemicals that impair reuse, and aims for the elimination of waste through superior design of materials, products, systems, and business models*" (p. 7). Its updated 2024 definition states: "*a system where materials never become waste and nature is regenerated. Products and materials are kept in circulation through maintenance, reuse, refurbishment, remanufacture, recycling, and composting*." Efforts in waste reduction, reuse, and recycling are already in place in construction projects, though not to their full potential (Feldman et al., 2024). Furthermore, the regenerative closed-loop supply chain, in which materials continuously circulate without losing value, is not encompassed in the construction industry (CEF, 2024; EMF, 2024; Wanaguru et al., 2022). Therefore, CE adoption is yet considered an innovation in the Australian construction industry.

Traditional economic models, such as Utility Theory, assume that decision-makers evaluate risk rationally, focusing on those objective risks and making choices that maximise their expected utility. Prospect Theory (Kahneman & Tversky, 1979) challenges this notion by demonstrating that individuals evaluate risk differently depending on whether they perceive a situation as a gain or a loss. Accordingly, perceived risk, as explained through Prospect Theory (Kahneman & Tversky, 1979), is a subjective concept shaped by how individuals evaluate gains and losses under conditions of uncertainty. Unlike objective risk, which relies on empirical data, perceived risk is influenced by cognitive biases, heuristics, and framing effects (Vasvári, 2015). Dual Process Theory (Kahneman, 2011) defines human behaviour as the decision-maker using two thinking systems: System 1 (fast, intuitive, and emotional) and System 2 (slow, analytical, and rational). Often, System 1 dominates, leading to subjective risk assessments influenced by emotions and heuristics (Kahneman, 2011; Kahneman & Tversky, 1979). When making decisions at the initiation stages of innovations, perceived risk often outweighs actual risk, as decision-makers might rely on System 1, which is influenced by biases and immediate perceptions of uncertainty, even when the objective

risk is low (Kahneman, 2011). Therefore, each innovation carries a set of risks, which creates resistance to adopting it among individuals. Adopting CE practices, such as material reuse, recycling, or innovative design for deconstruction, introduces new operational, financial, regulatory, and technological uncertainties that may deviate from established conventional methods (Adabre et al., 2023; AlJaber et al., 2023; Charef et al., 2021).

Through a Systematic Literature Review (SLR), 22 risk realities for CE adoption in the construction industry were identified shown in Table 2 (Refer Findings and Discussion), and findings indicated that only a limited number of studies specifically address risk in CE adoption within construction, with most research treating risks and barriers interchangeably (Lee et al., 2023; Wuni & Abankwa, 2023). International Standard 31000: 2018 (2018, p.1) defined "*risk as the effect of uncertainty on objectives.*" Renowned risk experts Murray-Webster and Hillson (2021) defined risk as the uncertainty that matters. Accordingly, risks are uncertainties that may or may not happen but require proactive management (Murray-Webster & Hillson, 2021). Risks are dynamic and uncertain, whereas barriers are static obstacles; unresolved barriers can exacerbate risk exposure (Murray-Webster & Hillson, 2021). This study adopts the definition of risk as "uncertainty that matters" and distinguishes between risks and barriers in CE adoption. Although objective risks can be measured, individuals often perceive them differently due to presentation, cognitive biases, and emotional responses (Vasvári, 2015). Prospect Theory (Kahneman & Tversky, 1979) and related studies (Edwards, 1996) indicate that for each objective risk, decision-makers develop a corresponding risk perception, which may not align with reality. Empirical studies (Lee et al., 2023) confirm that perceived risks often accompany objective risks, but misinterpretation and lack of awareness can cause perceived risks to exceed actual risks (Vasvári, 2015). Despite this, existing research has focused primarily on identifying and measuring objective risks in CE adoption, with limited attention to how decision-makers actually perceive those risks. Understanding these perceptions is particularly critical in Australian commercial construction projects, where clients, developers, and investors play key roles in initiating and supporting CE adoption. Therefore, this study will investigate different risk perceptions that influence the initial decision-making process for adopting CE in the construction industry, particularly in the context of Australian commercial construction projects, among client-side decision makers.

## 3. RESEARCH METHODOLOGY

A qualitative research approach was adopted to capture the complexity, nuance, and diversity of risk perceptions among decision-makers in the Australian construction industry (Hsieh & Shannon, 2005). Unlike quantitative methods, which are suited to testing predefined hypotheses, a qualitative approach enables rich, context-specific insights into why certain risks are emphasised, contested, or dismissed. Given that CE adoption involves uncertainty, trade-offs, and judgment-based decision-making, qualitative inquiry is particularly suitable for understanding the underlying reasoning processes of clients, developers, and investors (Hsieh & Shannon, 2005). The study used semi-structured expert interviews to access the strategic and experiential knowledge of senior decision-makers in the commercial construction industry. This format balanced consistency with flexibility, allowing exploration of predefined risk categories while enabling participants to discuss issues they deemed important. The interview guide, based

on CE and construction risk literature, focused on financial, regulatory, organisational, technological, and operational risks, with open-ended questions encouraging reflection on experiences and perceptions while allowing unanticipated themes to emerge. All interviews were audio-recorded with participant consent and transcribed to ensure accuracy and analytical transparency.

Purposive sampling is a nonprobability sampling technique in which researchers deliberately select participants based on specific characteristics, expertise, or knowledge relevant to the research objective (Rai & Thapa, 2015). Purposive sampling has been used because it allows the selection of experts (Tongco, 2007) with specialised knowledge and experience in CE adoption in the construction industry. These include "professionals in the client team, either internal or external professionals, such as consultants, project managers, architects, who play a central role in making decisions about adopting CE strategies in the planning stage (including feasibility and project brief) of a construction project". Their insights are crucial for understanding how risk perceptions form and how they might be managed in real project settings. Participants were selected based on having at least 15 years of industry experience and involvement in CE commercial projects in Australia, ensuring their input is grounded in practical knowledge and expertise. The sample size was followed by data saturation, and accordingly, 11 interviews were conducted. Table 1 shows the profile of the interviewees.

*Table 1: Profile of interviewees*

| Interviewee Code | Profession Category | Organisation Type | Construction Industry Experience in Years | CE Experience in Years |
|---|---|---|---|---|
| I1 | Sustainability Advisor | Consultant | 30 | 10 |
| I2 | Project Manager | Client/ Developer | 23 | 10 |
| I3 | Sustainability Advisor | Consultant | 20 | 10 |
| I4 | Sustainability Advisor | Client/ Developer | 15 | 3 |
| I5 | Client-Side Project Manager | Consultant | 17 | 8 |
| I6 | Sustainability Advisor | Client/ Developer | 15 | 5 |
| I7 | Development Manager | Client/ Developer | 25 | 10 |
| I8 | Sustainability Manager | Consultant | 20 | 10 |
| I9 | Sustainability Manager | Client/ Developer | 16.5 | 7 |
| I10 | Sustainability Advisor | Client/ Developer | 26 | 5 |
| I11 | Sustainability Advisor | Consultant | 15 | 10 |

The interview data were analysed using qualitative content analysis supported by NVivo to ensure a systematic, transparent, and rigorous examination of expert explanations. An initial deductive coding framework was developed from literature-derived risk categories associated with CE adoption in construction and implemented in NVivo as parent nodes representing the identified risk perceptions. Each transcript was read iteratively and coded to determine how these risks were recognised, contextualised, and validated by Australian client-side decision-makers in commercial construction projects. Beyond identifying individual risks, a thematic co-occurrence analysis was conducted using NVivo query functions to examine how multiple risks were discussed within the same narrative segments, revealing implicit perceived interrelationships among risks. Although participants were not directly asked about risk interdependencies, this analysis enabled the identification of concurrent themes that reflect how decision-makers link risks in CE

project environments. Together, content analysis and thematic co-occurrence analysis empirically validated literature-derived risks and uncovered the interconnected structure of perceived risks, providing a robust qualitative foundation for risk perceptions.

# 4. FINDINGS

Table 2 explains the perceived risk for client-side decision-makers in CE adoption in the Australian construction industry. The importance of a distinguished focus for perceived risk over risk reality has been emphasised by the experts; I10 stated, "*their perception of risk is really high, and probably higher than the reality of it in that sort of sense*". Experts have accepted the pre-assumptions of differences between perception and reality, as Prospect Theory (Kahneman & Tversky, 1979) explains, which are especially relevant to risks in CE adoption in the construction industry. Table 2 represents the objective risk realities identified through the SLR and accepted by the client as perceived risks in the Australian construction industry, whereas risks in *italic* letters were identified in the literature (SLR) but not accepted as perceived risks, and risks written in **bold** letters were newly identified by the client beyond the literature review.

CE projects are perceived as financially ambiguous because stakeholders are unsure whether the additional effort in reuse, recovery, and circular design will yield acceptable returns, and this is considered the main concern. I3 stated as "*cost is a big one*" in explaining the difference risk perceptions. I10 explained as "*They may not do it because they understand the old way of doing perfectly, and they understand the cost and the process in the old way of doing it. So even if they know that if they did this, they might actually save some time and, you know, material and what have you. They may not do it because they know exactly the cost and the time requirements of the previous methods or the previous materials, almost like on two fronts*". Wuni and Abnkwa (2023) explain that traditional investors or lenders may perceive circular construction as high risk due to its uncertain profitability, making it difficult to secure loans. However, experts (except I1 and I3), highlighted that uncertainty of funding strategy would not be a risk perception which will hinder the initial decision-making process, though it can be there at later stages. I1 and I3 emphasised this as a risk perception, particularly for small and medium enterprises (SMEs) and new clients in the Australian construction industry. Although the literature has identified material price fluctuations as a potential risk in construction projects, 60% of the interviewees in this study did not perceive it as a significant risk during initial decision-making for CE adoption in Australia. As I6 explained, "*Material prices can change…but that's something we can manage later; it doesn't usually stop us from moving forward in the first place.*" The remaining 40% of participants, however, noted that price volatility could pose a risk for SMEs or new entrants in the industry, who may have less capacity to absorb unexpected cost changes.

Regulatory-related risks in circular construction arise from the possibility of future policy changes rather than current regulatory gaps. While the absence of clear guidance acts as a barrier to CE adoption, uncertainty about potential changes constitutes a true risk, defined as "uncertainty that matters". Wuni and Abnkwa (2023) note that shifts in government policies or incentives may create uncertainty about whether CE-related regulations, targets, or rebates will remain stable throughout a project's lifecycle. This risk stems from potential changes, not from the current absence of incentives.

*Table 2: Summary of the survey findings: perceived risks by client-side decision makers in Australian commercial construction projects*

| **Perceived Risk of Client Side Decision Makers for CE Adoption in the Australian Construction Industry** | | **I 1** | **I 2** | **I 3** | **I 4** | **I 5** | **I 6** | **I 7** | **I 8** | **I 9** | **I 10** | **I 11** | **Accepted By** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Financial risks | Uncertain investment returns in circular construction projects | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| | Uncertain funding strategies | √ | x | √ | x | x | x | x | x | x | x | x | 18.2% |
| | Uncertainty in market demand for circular construction projects | √ | √ | √ | √ | √ | √ | x | √ | √ | √ | √ | 90.9% |
| | Price fluctuation of circular material | √ | √ | x | x | √ | √ | x | x | x | x | √ | 45.5% |
| Regulatory risks | *Changes in government policies for circular construction projects* | x | x | x | x | x | x | x | x | x | x | x | 0.0% |
| | *Changes in incentives for circular construction projects* | x | x | x | x | x | x | x | x | x | x | x | 0.0% |
| | **Regulatory compliance risk** | x | √ | x | x | x | x | √ | x | x | x | √ | 27.3% |
| Quality Risk | Uncertainty about the performance of recycled and reused construction materials | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| Supply chain risks | Uncertainty about the circular material supply chain for building projects | √ | √ | √ | √ | √ | x | x | √ | x | √ | √ | 81.8% |
| | Uncertainty of sustained commitment and collaboration across the supply chain | √ | x | √ | √ | x | x | x | √ | x | √ | √ | 54.5% |
| | Uncertainty of time for resolving the conflicts among circular supply chain partners | √ | x | √ | x | x | x | x | x | x | x | √ | 27.3% |
| Design risks | Uncertainty in End-of-life planning | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| | *Changes in Design* | x | x | x | x | x | x | x | x | x | x | x | 0.0% |
| Technological risks | Uncertainty in Performance and Reliability of Technologies | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | x | 90.9% |
| | Technology integration risk | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | x | 90.9% |
| Organisational risks | Strategic misalignment | √ | x | x | √ | x | x | √ | √ | x | x | √ | 45.5% |
| | Loss of Competitive Advantage | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| Stakeholder risks | Uncertainty of the sufficiency of experts in implementing circular projects | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| | Uncertainty of the sufficiency of skilled labour in implementing circular projects | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | 100.0% |
| | Negative effect on employment | √ | x | √ | x | x | x | x | √ | √ | √ | √ | 54.5% |
| | *Corruption-associated practices* | x | x | x | x | x | x | x | x | x | x | x | 0.0% |
| Operational Risk | Longer construction time | √ | x | √ | √ | √ | √ | √ | √ | √ | √ | √ | 90.9% |
| Health and safety risk | *Uncertainty of the safety of recycled construction products and materials* | x | x | x | x | x | x | x | x | x | x | x | 0.0% |

However, Australian experts generally did not perceive regulatory uncertainty as a significant risk in early-stage CE adoption. I4 stated "*..not really concerns, it's more like hoping …the policy side or government side, they would be more regulatory around the clarity*" while I5 stated, *"first aspect should be considered is price,"* explaining that changes in regulatory concerns do not emerge as risks in the early stages. These findings suggest that, in practice, regulatory issues are experienced less as uncertainty about policy change or incentive withdrawal, and more as ambiguity in regulatory guidance. This vagueness functions as a barrier to CE adoption and may also act as an underlying condition shaping overall risk perception, rather than constituting a discrete regulatory risk based on uncertainty. However, I2 mentioned a few regulatory compliance risks in Victoria, reflecting project-specific obligations.

Before adoption, stakeholders imagine that reused, recycled, or recovered materials may not match the reliability and consistency of virgin materials. Even in the absence of evidence, there is a perception that such materials might compromise structural integrity, durability, or aesthetics. This perceived quality uncertainty affects confidence at the decision stage, as construction decision-makers are highly risk-averse to quality. However, I4 noted that at the building level, quality concerns focus mainly on high-cost structural materials such as concrete and reinforcing steel, whereas highly recyclable materials, such as steel, are perceived as low-risk. I7 raised a lesser weightage in describing the impact of quality risk in perception, "*Not normally that early…not normally until you get a bit deeper into it*". However, I7 still explained that if reuse and refurbishment are the CE initiative, the quality aspect is a main risk factor that will eventually become a risk perception.

The findings indicate that client-side decision-makers in circular construction perceive supply chain-related uncertainties at varying levels. Inconsistencies in the supply chain for materials and services emerged, suggesting strong stakeholder concern about procurement reliability in circular supply systems. I6 explained it as after thinking about what is needed, how it can be attained will be a concern, which shapes the perception as "*need to have access to those solutions, which becomes a little bit more of a supply chain. Is it available, commercially available in the supply chain?*. Relational and coordination-related issues, including the absence of long-term partnerships, inconsistent stakeholder engagement, and communication gaps, were suggested by 50% of experts, reflecting concerns about collaborative stability but with comparatively lower intensity. Conflicts among diverse circular supply chain actors were perceived at a substantially lower level (20%), indicating that although governance tensions are acknowledged, they are not uniformly regarded as a critical perceived threat at the initial stages of decision making

Changes in design were rejected by all interviewees as a CE-specific risk, as design changes were viewed as a common and inherent feature of construction projects rather than a distinctive challenge introduced by circular practices. In contrast, end-of-life planning was perceived as a salient risk, as it introduces new considerations related to future adaptability, disassembly, and material recovery that are not typically embedded in conventional project decision-making.

Uncertainty in the performance and reliability of circular construction technologies increases risk perception because decision-makers in the construction industry are typically risk-averse and rely heavily on proven, long-term performance data (Tam, 2024; Tan et al., 2022). I1 explained that "*technological advancement is definitely part of the*

*decision, but it's often seen through a time and risk lens, rather than just innovation*". Adding to this, I6 stated that, as well as the client may perceive it as a risk, while contractors and the suppliers will consider technological advancement related to CE adoption such as digital material banks or building asset tracking systems (i.e., digital logs of building components and documentation), as an opportunity.

Organisations may perceive CE adoption as potentially misaligned with their current business strategy. There is a perception that focusing on circular practices might divert attention from core operations or reduce short-term competitiveness. Decision-makers fear that investing in CE may not align with market expectations or could disadvantage the organisation if competitors do not follow similar practices. This perceived strategic misfit delays initial commitment. I1 stated it as "*because people feel like, if something, if they do take a risk on a new product, for example, and it goes wrong, it'll be their reputation on the line. So I think reputational thing, and certainly the biggest challenge*," I10 added, "*not just the costs of the business, but also the reputation of the business as well*."

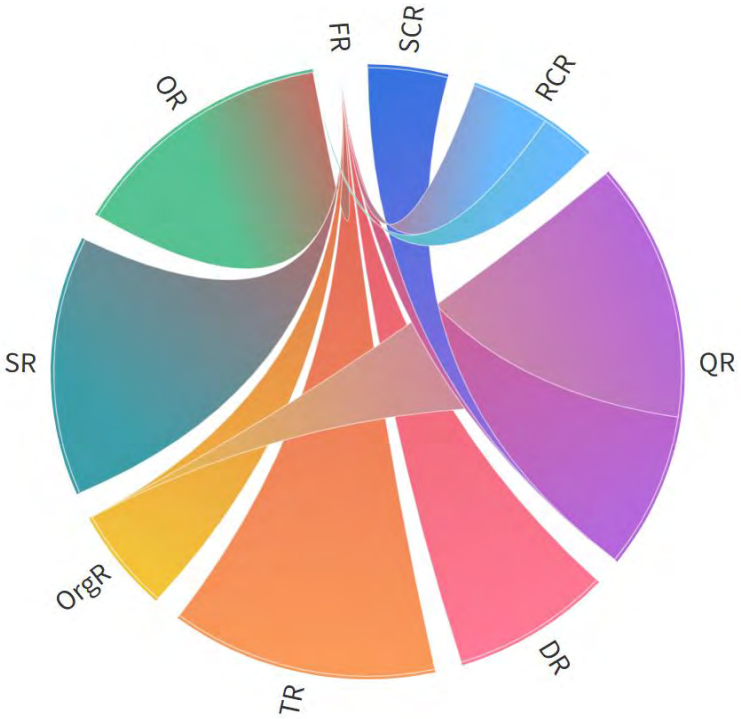
There is a perception that CE projects require specialised knowledge and skills that may not be readily available. Decision-makers fear difficulty in finding experts, trained labour, or consultants who understand circular construction. I5 illustrated that there is a risk of availability, and approaching required experts and skilled workforce will influence the initial decision-making process; "*You should be able to find qualified people, who know? Yeah, who knows how to deal with this equipment, how to adjust it, what parameters should be, how it should be, what should not be*" The uncertainty of negative impact on the existing employment, which was identified as a risk by Wuni and Abnkwa (2023) has gained 50% acceptance as a possible risk perception, as I3 explained that CE adoption can create new employment opportunities, but certain professions may face reduced demand, particularly affecting local or regional economies, requiring a just transition. However, the other 50% has not accepted it as a risk, stating, I8, "*it's not necessarily a risk in the sense of lack of jobs, it's just a shift of practices and behaviour".* Furthermore, Hassan et al. (2023) identified corrupt practices as a potential risk to the adoption of CE strategies in the Pakistani construction industry. However, the interviewees in this study did not consider future corruption as a perceived risk during initial decision-making regarding CE adoption in the Australian construction industry.

I1 illustrated adopting a circular solution means new or unfamiliar technology, learning new systems, or relying on untested tools, then decision makers immediately think about extra time, extra coordination, and potential delays. Accordingly, longer operational time is considered a key risk perception among client-side decision-makers in the Australian commercial construction industry. However, I9 added "*it definitely takes more time, and you have to be doing it for a reason"* while emphasising that "*prefabrication, or modular construction, which actually does reduce the time being few strategies in circular economy adoption*".

Experts indicated that health and safety issues were not perceived as a determining risk when deciding whether to pursue CE strategies, as these concerns typically arise later during detailed design, specification, or construction phases. As one interviewee (I9) explained, "*Not really, no, at least not in the initial decision-making. Health and safety around secondary materials might come up later in the process, once you're actually getting into specifications or construction. But at the early stages, when decisions about*

*whether to pursue circular options are being made, it's not seen as a major risk*." This suggests that health and safety considerations do not significantly drive or impede early CE adoption decisions, with respondents instead prioritising risks related to cost, market demand, and delivery certainty.

Experts explained the interdependencies among some risk perceptions as shown in Figure 1. Experts emphasised that these marked interdependencies always trigger the other risk perception. The perceived financial risk is influenced by most of the other risk perceptions. As an example, I3 "*If something has an impact on… the time frame… that has an impact on construction costs*" as a longer construction time, which is perceived as a risk in the early decision-making process by the experts. When I2, I7 and I11 emphasise the regulatory compliance risks, their impact on the project cost and time frame has also been stated. Though it has not been separately questioned, every expert has highlighted that financial risk often becomes the central outcome, as design changes, technological uncertainty, organisational capability gaps, stakeholder misalignment, operational inefficiencies, and quality issues ultimately translate into cost overruns or budget uncertainty.




FR – Financial Risk, RCR – Regulatory Compliance Risk, SCR – Supply Chain Risk, QR – Quality Riks, SR – Stakeholder Risk, TR – Technological Risk, DR – Design Risk, OrgR – Organisational Risk, OR – Operational Risk

*Figure 1: Interdependencies of perceived risks through thematic concurrence analysis*

Furthermore, the expert highlighted that quality risk is often closely linked to organisational reputation, noting that "*if they do take a risk on a new product, for example, and it goes wrong, it'll be their reputation on the line*" (I1), which can directly lead to a loss of competitive advantage, which shapes the initial risk perception. Quality of materials and supply chain-related risks are likely discussed by the experts as issues in the supply chain, such as unreliable suppliers, delayed deliveries, or substandard materials, that directly threaten the quality of the final product. I11 emphasised that this quality-related risk perception would not only represent a quality failure but could also

escalate into regulatory non-compliance risk perception and reputational damage, which leads risk perception around to the loss of competitive advantage, which was categorised under organisational risk.

The findings from this study highlight that perceived risks, rather than objective risks, predominantly shape early decision-making in CE adoption within the Australian commercial construction sector. In practice, these findings suggest that decision-makers approach CE adoption cautiously, with perceived risks shaping the threshold for initial commitment, even when objective risks may be lower or manageable.

## 5. DISCUSSION

The study confirms the importance of focusing on perceived risk rather than risk reality, as it influences the risk aversion of client-side decision-makers in the early stages of adopting CE in construction projects, as also emphasised by Tan et al. (2022) and Kazancoglu (2020) in other industries. Similar to prior studies on risk realities (Hassan et al., 2023; Tam, 2024; Wuni & Abnkwa, 2023), financial uncertainty, quality concerns, supply chain instability, technological uncertainty, and capability-related risks emerged as dominant perceived risks influencing early-stage CE adoption decisions. The findings reinforce that client-side decision-makers prioritise cost certainty, delivery reliability, and reputational outcomes at early decision stages (Berglund-Brown et al., 2024; Bertassini et al., 2021). This reflects the Australian commercial construction context, which is shaped by structured procurement systems, developer-led financing, and performance-driven contracts (Rahmani et al., 2016). In cities such as Melbourne and Sydney, investment expectations further emphasise predictable delivery, stable leasing outcomes, and return-on-investment requirements (Ellison et al., 2026). As a result, stakeholders prioritise cost certainty, programme reliability, and proven material performance in feasibility assessments. Nevertheless, as circular supply systems and secondary markets in Australia remain relatively immature and less integrated than conventional construction supply chains, CE adoption is often viewed as carrying higher uncertainty than linear approaches (Commonwealth Scientific and Industrial Research Organisation, 2024; Feldman et al., 2024). On the other hand, previous studies often frame regulatory uncertainty, policy instability, health and safety concerns, corruption-associated practices, and design changes as CE-related risks (Hassan et al., 2023; Tam, 2024; Wuni & Abnkwa, 2023). In contrast, these factors were not perceived as major risks during the initial decision-making stage in Australia. Instead, regulatory issues were interpreted more as barriers arising from unclear guidance rather than uncertainty regarding future policy changes. Similarly, design changes were viewed as inherent characteristics of construction projects rather than CE-specific risks. Corruption-related concerns, which are emphasised in studies conducted in developing economies (Hassan et al., 2023), were not identified as a risk factor influencing initial decision-making. Australia's comparatively stable governance system, mature regulatory environment, and established construction standards may explain why corruption and regulatory instability were not strongly perceived as risks at the initial stages of the decision-making process (Iyer-Raniga et al., 2023). Instead, participants were more concerned with practical implementation uncertainties, particularly those affecting project feasibility, quality assurance, and competitive positioning. These exceptions suggest that risk perceptions are highly context-dependent and shaped by institutional maturity, governance quality, and industry culture, as explained in the Psychometric paradigm (Slovic, 1987), Cultural

theory of risks (Douglas & Wildavsky, 1982) and Prospect theory (Kahneman & Tversky, 1979).

Although this study is based on the Australian commercial construction sector, the findings may be cautiously applicable to other developed construction industries undergoing CE transition, particularly where regulatory systems, procurement practices, and project delivery structures are similar (Iyer-Raniga et al., 2023). Similar patterns have also been identified in other industries. For example, Kazancoglu et al. (2020) found that CE adoption decisions in the e-waste sector were influenced by concerns regarding financial, reputational, and material-related uncertainty, consistent with Prospect Theory (Kahneman & Tversky, 1979). Similar concerns were evident in this study, indicating that risk perceptions associated with CE adoption may extend beyond industry boundaries where circular practices challenge conventional operational systems and established decision-making routines (Tan et al., 2022). Nevertheless, the applicability of these findings should be considered with caution, as the nature and intensity of perceived risks are likely to differ across regions depending on institutional stability, market maturity, technological capability, and the cultural acceptance of innovation and sustainability practices (Douglas & Wildavsky, 1982; Kahneman & Tversky, 1979; Tan et al, 2022).

## 6. CONCLUSIONS

This study underscores the importance of distinguishing between perceived and objective risks in the adoption of circular economy strategies within the construction industry. Through interviews with client-side decision-makers in the Australian commercial construction sector, it was observed that perceived financial risk dominates the adoption calculus, strongly influenced by interlinked perceptions of material quality, design complexity, stakeholder capability, and operational time. Conversely, risks commonly cited in literature, such as regulatory uncertainty, health and safety concerns, and corruption, were either minimally perceived or deferred to later project stages. These insights highlight that misalignment between perceived and objective risks can impede initial CE adoption, particularly for SMEs and projects with limited experience in circular practices. Addressing these perception-driven barriers will reframe CE adoption as a strategic opportunity rather than a speculative threat, ultimately supporting broader and more confident implementation of circular construction practices. Therefore, this study will extend to identify the causes of those risk perceptions among client-side decision-makers in Australian commercial construction projects and thereby provide actionable strategies to manage them. The study is limited by its small purposive sample of 11 client-side experts, which, although sufficient to achieve data saturation, may reduce the generalisability of findings to broader contexts. The study focuses exclusively on client-side decision-makers, excluding contractors, suppliers, regulators, or end-users, whose risk perceptions could differ and influence CE adoption decisions.

## 7. REFERENCE

Adabre, M. A., Chan, A. P., Darko, A., Edwards, D. J., Yang, Y., & Issahaque, S. (2024). No stakeholder is an island in the drive to this transition: Circular economy in the built environment. *Sustainability*, *16*(15), 6422. https://doi.org/10.3390/su16156422

AlJaber, A., Martínez-Vázquez, P., & Baniotopoulos, C. (2023). Barriers and enablers to the adoption of circular economy concept in the building sector: A systematic literature review. *Buildings*, *13*(11), 2778. https://doi.org/10.3390/buildings13112778

Amudjie, J., Agyekum, K., Adinyira, E., Amos-Abanyie, S., & Kumah, V. M. A. (2023). Awareness and practice of the principles of circular economy among built environment professionals. *Built Environment Project and Asset Management*, *13*(1), 140-156. https://doi.org/10.1108/BEPAM-11-2021-0135

Baldassarre, B. (2025). Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. *Ecological Economics*, *227*, 108345. https://doi.org/10.1016/j.ecolecon.2024.108345

Berglund-Brown, J., Pandey, A., Duarte, F., Ganitsky, R., Kirchain, R., & Zheng, S. Q. (2024). Stakeholders' perceptions of and willingness to pay for circular economy in the construction sector. *npj Urban Sustainability*, *4*(1), 46. https://doi.org/10.1038/s42949-024-00182-9

Bertassini, A. C., Ometto, A. R., Severengiz, S., & Gerolamo, M. C. (2021). Circular economy and sustainability: The role of organizational behaviour in the transition journey. *Business Strategy and the Environment*, *30*(7), 3160-3193. https://doi.org/10.1002/bse.2796

Braungart, M. M., & Braungart, R. G. (1990). The life-course development of left-and right-wing youth activist leaders from the 1960s. *Political Psychology*, *11*(2), 243-282. https://doi.org/10.2307/3791689

Charef, R., Morel, J.C., & Rakhshan, K. (2021). Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability*, *13*(23), 12989. https://doi.org/10.3390/su132312989

Circle Economy Foundation. (2024). *The circularity gap report*. https://www.circularity-gap.world/2024

*Commonwealth Scientific and Industrial Research Organisation*. (2024). Advancing the circular economy. Retrieved 10 October, 2025, from https://www.csiro.au/en/research/environmental-impacts/sustainability/Circular-Economy

Ellison, S., Crawford, L., McKinnon, J., Rose-Nokes, J., Lee, L., Swamy, P., & Brown, D. (2026). *Australia outlook 2026*. Cushman & Wakefield https://digital.cushmanwakefield.com/link/773894/2/ .

Department of Climate Change, Energy, the Environment and Water. (2022). *National waste report 2022*, Retrieved from https://www.dcceew.gov.au/sites/default/files/documents/national-waste-report-2022.pdf

Department of Climate Change, Energy, the Environment and Water. (2024). *Australia's circular economy framework*. Retrieved from https://www.dcceew.gov.au/sites/default/files/documents/australias-circular-economy-framework.pdf

Douglas, M., & Wildavsky, A. (1982). *Risk and culture: An essay on the selection of technological and environmental dangers*, Berkeley, CA. https://www.jstor.org/stable/10.1525/j.ctt7zw3mr

Edwards, K. D. (1996). Prospect theory: A literature review. *International review of financial analysis*, *5*(1), 19-38. https://doi.org/10.1016/S1057-5219(96)90004-6

Ellen Macarthur Foundation. (2024). *Building prosperity: Unlocking the potential of a nature-positive, circular economy for Europe*. https://content.ellenmacarthurfoundation.org/m/62e7613596a2d12f/original/Building-Prosperity-July-2024.pdf

Feldman, J., Seligmann, H., King, S., Flynn, M., Shelley, T., Helwig, A., & Burey, P. (2024). Circular economy barriers in Australia: How to translate theory into practice?. *Sustainable Production and Consumption*, *45*, 582–597. https://doi.org/10.1016/j.spc.2024.02.001

Hassan, M. S., Ali, Y., Petrillo, A., & De Felice, F. (2023). Risk assessment of circular economy practices in construction industry of Pakistan. *Science of The Total Environment*, *868*, 161418. https://doi.org/10.1016/j.scitotenv.2023.161418

Ho, O. T.-K., Gajanayake, A., & Iyer-Raniga, U. (2023). Transitioning to a state-wide circular economy: Major stakeholder interviews. *Resources, Conservation & Recycling Advances*, *19*, 200163. https://doi.org/10.1016/j.rcradv.2023.200163

Hsieh, H.-F., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative health research*, *15*(9), 1277-1288. DOI: 10.1177/1049732305276687

International Organization for Standardization. (2018). *ISO 31000:2018 Risk management — Guidelines*. https://www.iso.org/standard/65694.html

Iyer-Raniga, U., Gajanayake, A., & Ho, O. T.K. (2023). The transition to a circular built environment in Australia: An analysis of the jurisdictional policy framework. *Environmental Policy and Law*, *53*(4), 233-246. https://journals.sagepub.com/doi/full/10.3233/EPL-220073

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263-292. https://doi.org/10.2307/1914185

Kazancoglu, Y., Ozkan-Ozen, Y. D., Mangla, S. K., & Ram, M. (2020). Risk assessment for sustainability in e-waste recycling in circular economy. *Clean Technologies and Environmental Policy*, *24*(4), 1145–1157. https://link.springer.com/article/10.1007/s10098-020-01901-3

Lee, K.T., Park, S.J., & Kim, J.H. (2023). Comparative analysis of managers' perception in overseas construction project risks and cost overrun in actual cases: A perspective of the Republic of Korea. *Journal of asian architecture and building engineering*, *22*(4), 2291-2308. DOI: 10.1080/13467581.2022.2116940

Murray-Webster, R., & Hillson, D. (2021). *Making risky and important decisions: A leader's guide*. Auerbach Publications.

Pauli, G. A. (2011, January). The blue economy. *Japan Spotlight*, *4*, pp. 14-17. https://www.jef.or.jp/journal/pdf/175th_cover04.pdf

Rahmani, F., Khalfan, M. M., & Maqsood, T. (2016). Lessons learnt from the use of relationship-based procurement methods in Australia: Clients' perspectives. *Construction Economics and Building*, *16*(2), 1-13. https://doi.org/10.5130/AJCEB.v16i2.4634

Rai, N., & Thapa, B. (2015). A study on purposive sampling method in research. *Kathmandu School of Law*, *5*(1), 8-15. https://www.academia.edu/download/48403395/A_Study_on_Purposive_Sampling_Method_in_Research.pdf

Rim, G.N., An, C.J., Jang, H.S., Jong, C.-S., & Jo, C.-S. (2025). A study on the types and their characteristics of the circular economy. *Journal of the Knowledge Economy*, *17*, 1818–1846. https://doi.org/10.1007/s13132-024-02422-w

Slovic, P. (1987). Perception of risk. *Science*, *236*(4799), 280-285. https://doi.org/10.1126/science.3563507

Tam, N. V. (2024). Mitigating digital transformation risks for circular construction in emerging economies: An empirical investigation in Vietnam. *International Journal of Construction Management*, *25*(10), 1130–1140. https://doi.org/10.1080/15623599.2024.2397628

Tan, J., Tan, F. J., & Ramakrishna, S. (2022). Transitioning to a circular economy: A systematic review of its drivers and barriers. *Sustainability*, *14*(3), 1757. https://doi.org/10.3390/su14031757

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications*, *5*, 147–158. http://hdl.handle.net/10125/227

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981

Vasvári, T. (2015). Risk, risk perception, risk management - A review of the literature. *Public Finance Quarterly Pénzügyi Szemle*, *60*(1), 29-48. https://unipub.lib.uni-corvinus.hu/8850/

Wanaguru, K., Mallawaarachchi, H., & Vijerathne, D. (2022). Circular Economy (CE) based material selection: Development of a CE-based '10R'evaluation framework for building construction projects in Sri Lanka. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (Eds), *Proceedings of the 10th World Construction Symposium* (pp. 208-219) .https://doi.org/10.31705/WCS.2022.18

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825-833. http://dx.doi.org/10.1016/j.rser.2016.09.123

Wuni, I. Y., & Abankwa, D. A. (2023). Understanding the key risks in circular construction projects: From systematic review to conceptual framework. *Construction Innovation*. *25*(4), 1085-1107. https://doi.org/10.1108/CI-04-2023-0068

Fernando, M.K.L.I.C. and Wimalaratne, P.L.I., 2026. Robotic systems for closed-loop construction: A bibliometric analysis of construction demolition waste management. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1512-1526. DOI: https://doi.org/10.31705/WCS.2026.110. Available from: https://ciobwcs.com/papers/

# ROBOTIC SYSTEMS FOR CLOSED-LOOP CONSTRUCTION: A BIBLIOMETRIC ANALYSIS OF CONSTRUCTION DEMOLITION WASTE MANAGEMENT

**M.K.L.I.C. Fernando[1] and P.L.I. Wimalaratne[2]**

## *ABSTRACT*

*Robotic and automated systems present transformative potential for addressing construction and demolition waste (CDW) challenges through enhanced sorting, deconstruction, and material recovery. However, research at the intersection of robotics and closed-loop construction remains fragmented, lacking a comprehensive synthesis of trends, collaboration patterns, and technological evolution. This study conducts a bibliometric analysis of 36 peer-reviewed articles (2015-2026) retrieved from Scopus and Web of Science following PRISMA guidelines, employing VOSviewer for keyword co-occurrence, bibliographic coupling, and collaboration network analysis. Results reveal exponential publication growth since 2021, with peak output in 2024-2025 driven by advances in artificial intelligence and computer vision. China, Australia, and Hong Kong emerge as leading contributors within Asia-Pacific and European collaborative networks. Keyword analysis identifies five primary research clusters: robotic sorting and grasping technologies, computer vision for waste recognition, deconstruction and disassembly systems, digital enablers (BIM, digital twins, IoT), and circular economy frameworks. Despite significant progress, critical gaps persist in perception robustness under real-world conditions, manipulation of heterogeneous materials, and deconstruction system integration for component reuse, human-robot collaboration frameworks, and economic validation. This review provides researchers, practitioners, and policymakers with a systematic foundation for advancing robotic closed-loop construction toward sustainable, intelligent waste management.*

***Keywords:*** *Automation; Bibliometric Analysis; Closed-Loop Construction; Construction and Demolition Waste; Robotics*

## 1. INTRODUCTION

The construction industry faces an unprecedented crisis of resource depletion and waste generation, with construction and demolition waste (CDW) constituting approximately 36% of total waste in the European Union and exceeding 10 billion tons annually worldwide (Dodampegama et al., 2024; Moschen-Schimek et al., 2023). Traditional waste management approaches, characterised by manual sorting and conventional

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, lisdaireshi@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, indraniw@uom.lk

demolition, prove increasingly inadequate due to occupational health risks, human error, and limited recovery rates (Ku et al., 2020; Chen et al., 2023).

Robotic and automated systems have emerged as transformative enablers of circular construction, offering consistent, precise material handling capabilities through advanced configurations incorporating computer vision, hyperspectral imaging, and deep learning (Xiao et al., 2020; Prasad & Arashpour, 2024). Integration with digital technologies, including building information modelling (BIM), digital twins, and the Internet of Things (IoT), creates unprecedented opportunities for closed-loop material management across the building lifecycle (Abd El-Hameed, 2025; Thakuri et al., 2024).

Despite technological enthusiasm, the literature remains fragmented, with isolated studies examining specific applications lacking a comprehensive synthesis of research trends and collaboration networks (Heuer et al., 2025; Ostapska et al., 2025). This study addresses this gap through a bibliometric analysis of robotic closed-loop construction systems for onsite recycling and material reuse. The objectives are: (i) to identify evolutionary publication patterns; (ii) to reveal primary research themes through keyword co-occurrence analysis; (iii) to map collaborative networks; and (iv) to identify future research directions.

# 2. METHODOLOGY

This study employs a comprehensive methodological approach, applying bibliometric analysis to identify the literature pertaining to robotic and automated systems for onsite recycling and material reuse in construction and demolition waste management. According to De Oliveira et al. (2019), bibliometric analysis constitutes a statistical instrument that represents the current state of scientific knowledge by analysing citations, authors, institutions, countries, and journals, thereby identifying research opportunities, trends, and voids while facilitating the development of scientific projects. The methodology followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and rigour (Page et al., 2021). Scopus and Web of Science were employed due to their extensive coverage and high quality (Thelwall & Sud, 2022). The combination of Scopus and Web of Science follows the multi-database approach recommended by Abioye et al. (2021) and Kokkalis et al. (2025), serving to mitigate the risk of overlooking pertinent literature that might be indexed in only one database.

## 2.1 SEARCH STRATEGY DEVELOPMENT

The search strategy was structured around the following search string (Figure 1), in line with the methodologies established by Balogun et al. (2024), Shao et al. (2022), and Abd El-Hameed (2025).

(“robot*” OR “automation” OR “computer vision” OR “AI” OR “deep learning”)
AND
(“construction and demolition waste” OR “construction waste” OR “demolition waste” OR “CDW” OR “waste sorting” OR “deconstruction”)
AND
(“circular economy” OR “closed-loop” OR “recycling” OR “reuse” OR “material recovery”)

*Figure 1: Search string (By Authors)*

This approach ensured that retrieved articles addressed the intersection of robotics, construction waste, and circular economy principles. The search was applied to "Article title, Abstract, Keywords" fields across both databases. The search was conducted in February 2026, capturing the state of knowledge up to that date, with a focus on studies published between 2015 and 2026 to capture recent technological developments in this rapidly evolving field (Prasad & Arashpour, 2025a; Wang et al., 2020; Xiao et al., 2020).

## 2.2 SCREENING PROCESS

The screening process followed a systematic, multi-stage approach consistent with PRISMA guidelines (Page et al., 2021). Figure 2 presents the PRISMA flow diagram documenting the number of studies at each stage and the reasons for exclusion. Moreover, Table 1 represents the Exclusion and inclusion criteria established for article selection.

Initial database searches retrieved a total of 1,233 records (976 articles from Scopus and 257 articles from Web of Science). After removal of 216 duplicate records using reference management software (Mendeley), 1,017 unique records remained for screening. Titles and abstracts were screened against the inclusion and exclusion criteria. Articles were categorised based on their primary focus: robotic-related papers (137), construction-related papers (323), and papers addressing both areas (47), yielding 507 articles selected for full abstract review. The 507 articles underwent detailed abstract screening against all inclusion and exclusion criteria. This stage resulted in 139 articles selected for full-text retrieval.

Full-text articles were retrieved for all 139 studies passing abstract screening. Reasons for exclusion at this stage were documented, including insufficient technical detail on robotic systems (42 articles), lack of onsite applicability (31 articles), absence of closed-loop material flow considerations (18 articles), and focus on non-construction applications (10 articles). Following the full-text screening, 36 articles were selected for inclusion in the bibliometric analysis.

*Table 1: Inclusion and exclusion criteria*

| Criteria | Inclusion criteria | Exclusion criteria |
|---|---|---|
| **Year** | Publication years from 2015 to 2026 | Publications before 2015 |
| **Document Type** | Articles and Conference Papers | Books, book chapters, reviews, notes, and editorials |
| **Language** | English language | Languages other than English |
| **Subject Areas** | Construction technology, computer science, | All other subject areas |

## 2.3 DATA EXTRACTION AND BIBLIOMETRIC ANALYSIS

This study conducted a variety of bibliometric analyses using both manual techniques and VOSviewer software (version 1.6.20). The manual analysis concentrated on examining annual publishing patterns and identifying the most impactful journals and conferences in the sector. Additionally, keyword co-occurrence analysis was conducted using VOSviewer to reveal significant research topics and emerging areas of interest. Bibliographic coupling analysis was performed among journals, authors, and countries to identify influential publications and research groups, map the intellectual structure of the field, and visualise collaborative networks across geographic regions. Citation analysis

was employed to examine citation networks, identify seminal works, and track the evolution of key concepts in robotic closed-loop construction (Balogun et al., 2024; Oluleye et al., 2023). Figure 2 illustrates the PRISMA flow diagram which summarises the process of identifying, screening, assessing eligibility, and selecting studies for inclusion in the bibliometric analysis.

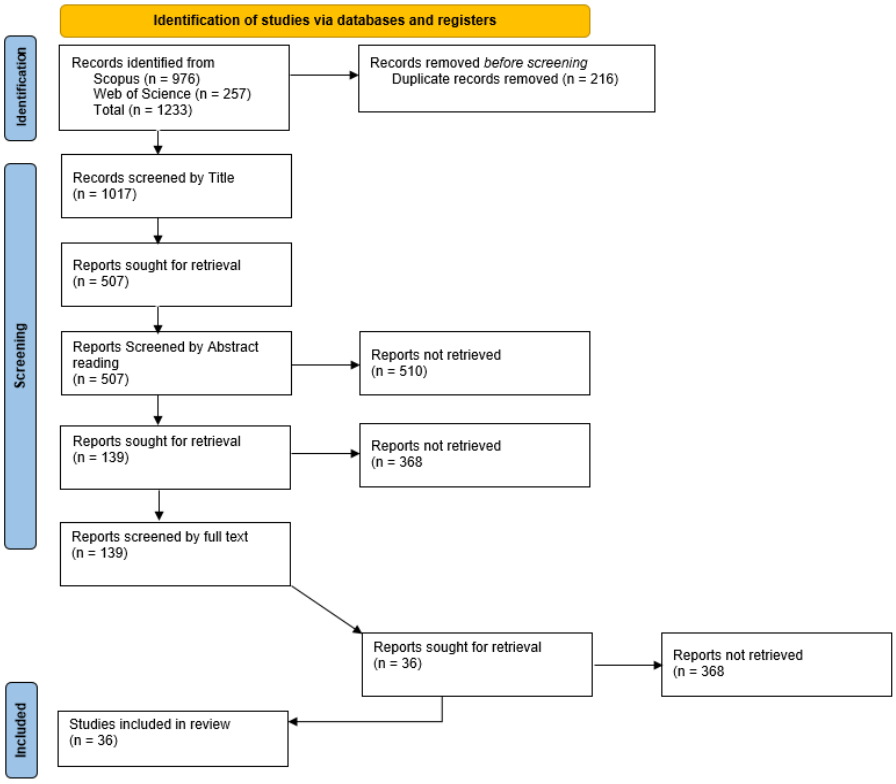



*Figure 2: PRISMA FLOW diagram (By authors)*

## 3. RESULTS AND DISCUSSION

This section presents the results of the bibliometric analysis with relevant interpretations while addressing the objectives of the study.

For keyword co-occurrence analysis, a minimum threshold of four occurrences for keywords was established. In the generated networks, the diameter of each circle represents the frequency of the term, while the thickness of the connecting lines denotes the strength of the association between keywords. Furthermore, the closeness of nodes demonstrates the extent of linkage, with nearer nodes indicating more closely connected phrases. These analyses jointly facilitated a qualitative interpretation of the bibliometric data, providing significant insights into the developing research landscape of robotic closed-loop construction in the context of CDW management.

Figure 3 presents the keyword co-occurrence network generated through the VOSviewer. The central positioning of terms such as “construction and demolition waste”, “robotic sorting” and “computer vision” indicates that the field remains strongly technology driven. However, the peripheral position of terms such as “human-robot collaboration” and “generative AI” suggests that socio-technical integration and advanced AI-enabled decision-making are still emerging rather than mature research areas.

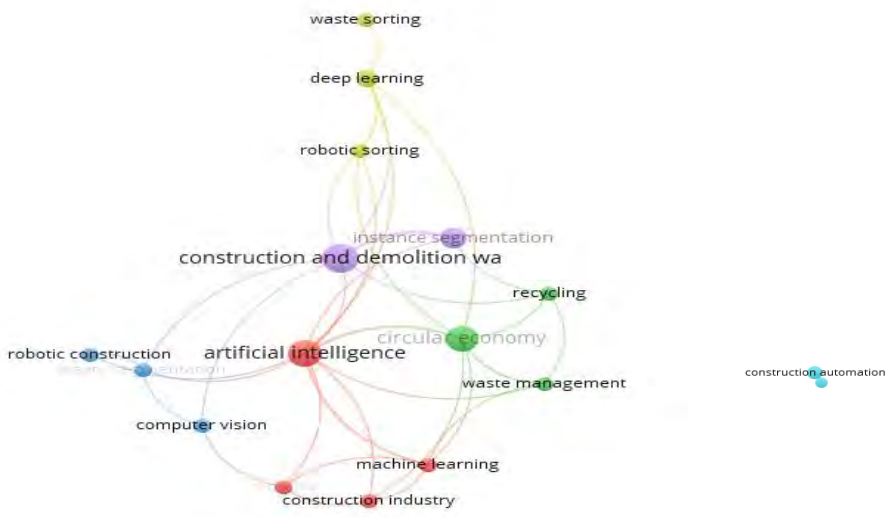



*Figure 3-Keyword co-occurrence*

The network therefore implies that future research should move beyond technical recognition accuracy and examine how robotic systems can be safely, economically and practically integrated into real construction waste environments.

## 3.1 EVOLUTION OF PUBLICATIONS AND TOP CONTRIBUTING SOURCES

Moreover, Figure 4 represents the analysis of publication trends from 2015 to 2026. During the initial period of 2015-2018, publications remained minimal, with only two contributions in 2015, including foundational works on robot-oriented construction management (Bock & Linner, 2015) and framework development for robot-assisted deconstruction (Lee et al., 2015). No publications were recorded between 2016 and 2019.

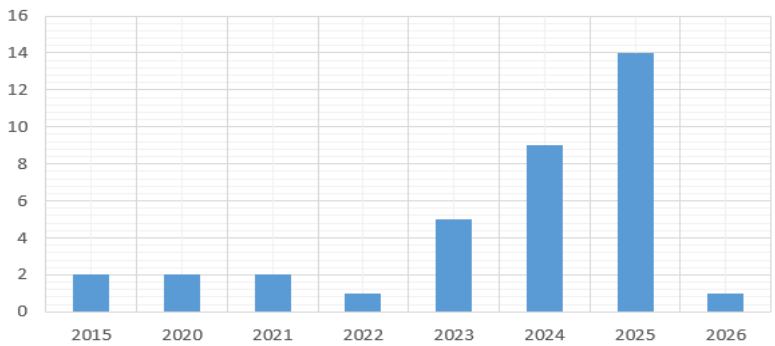



*Figure 4: Annual publication trend*

The period 2020-2021 witnessed gradual growth. Notable contributions included vision-based robotic systems for onsite CDW sorting (Wang et al., 2020), deep learning approaches for grasping detection (Ku et al., 2020), and automatic sorting robots employing hyperspectral imaging (Xiao et al., 2020). A significant inflexion point occurred in 2022-2023, with publications increasing from one to five annually. This acceleration coincided with advances in deep learning architectures substantially improving waste recognition capabilities (Chen et al., 2022; Lu et al., 2022), the

emergence of human-robot collaboration frameworks (Chen et al., 2023), and increased digital technology integration (Abd El-Hameed, 2025).

The years 2024-2025 represent peak research activity, with nine and fourteen publications, respectively. This rapid increase after 2021 can be linked to wider advances in artificial intelligence, computer vision and automated material recognition. However, the relatively small number of studies before 2020 indicates that robotic CDW management is still an emerging research niche rather than a fully established field.

Table 2 presents the top contributing sources in the domain. The concentration of publications in Automation in Construction, Journal of Building Engineering and Waste Management demonstrates that robotic closed loop construction is interdisciplinary, requiring integration across construction engineering, environmental management, computer vision and circular economy research.

*Table 2: Top contributing sources*

| Source Name | No of publications |
|---|---|
| **Automation in Construction** | 5 |
| **Journal of Building Engineering** | 4 |
| **Waste Management** | 3 |
| **Buildings** | 2 |
| **Journal of Environmental Management** | 2 |

The distribution implies that future progress will depend on stronger collaboration between technical robotics researchers and construction waste management specialists.

## 3.2 LEADING COUNTRIES UNDERTAKING RESEARCH ON ROBOTIC CLOSED-LOOP CONSTRUCTION

Figure 5 illustrates the geographic distribution of research contributions advancing robotic closed-loop construction. Australia leads with six documents, demonstrating high research intensity and international collaboration. Hong Kong and China contribute four documents each, reflecting significant investment in construction automation driven by rapid urbanisation and policy support for circular economy initiatives (Chen et al., 2022, 2023; Ku et al., 2020; Xiao et al., 2020). Germany also contributes four documents, while the United Kingdom follows with three publications. The United States, despite substantial research infrastructure, contributes only one document, suggesting a domestically focused approach.

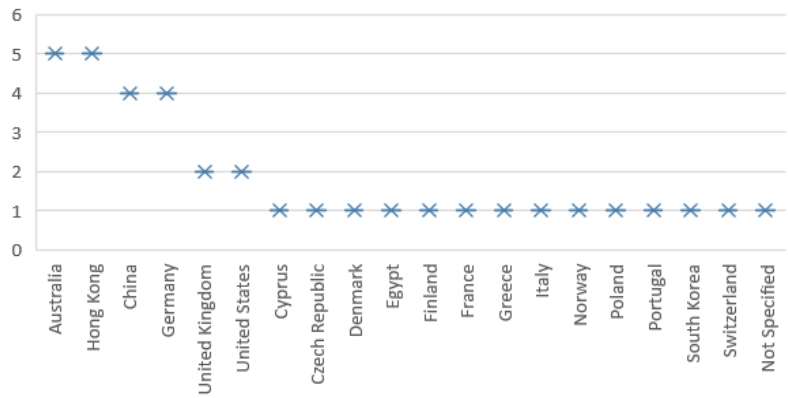



*Figure 5: Global research frontier (Publication trend over geographical locations)*

The collaborative landscape reveals two primary research clusters: the Asia-Pacific cluster centred on Australia, China and Hong Kong, and the European cluster encompassing diverse nations with dense collaborative networks. However, the limited representation of developing countries indicates a geographical research gap. This is important because CDW generation and informal recycling practices are significant in many developing economies, where low-cost and adaptable robotic solutions may offer considerable practical value.

## 3.3 TERMS CO-OCCURRENCE ANALYSIS

Figure 6 illustrates the results of terms co-occurrence analysis conducted using VOSviewer software, with a minimum threshold of four occurrences per term. Terms co-occurrence analysis is essential in academic research as it illustrates linkages between study subjects, uncovers temporal patterns, and assists researchers in comprehending the evolution of knowledge domains, thereby informing future research paths (Zhao, 2024).

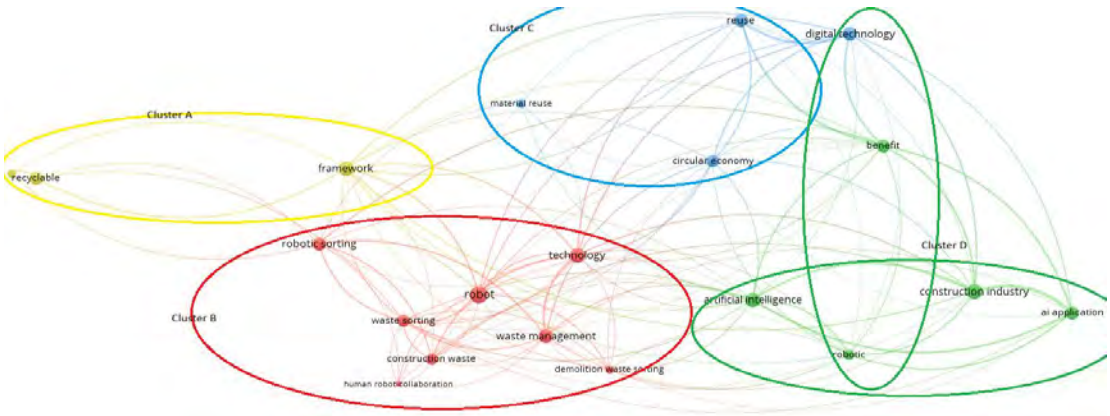



*Figure 6-Terms Co-occurrence network*

The network visualisation identifies four distinct research clusters (Table 3) in robotic closed-loop construction, each representing a coherent thematic area with characteristic terminology and conceptual focus.

*Table 3: Summary of Terms Co-Occurrence Analysis*

| Cluster | Thematic Focus | Key Terms | Research Emphasis |
|---|---|---|---|
| **A** | Robotic sorting and HR collaboration | Recyclable, robot sorting, waste sorting, framework, human-robot collaboration | Development of structured sorting frameworks integrating robotic automation with human expertise to improve efficiency, safety, and adaptability in waste sorting processes. |
| **B** | Circular economy and intelligent technologies | Material reuse, circular economy, artificial intelligence, robotic technology, demolition waste sorting | Application of AI-driven robotic systems to enable sustainable material recovery and support circular construction practices. |
| **C** | Construction industry implementation | Construction industry, AI application, robotics | Translation of robotic and AI technologies into real-world construction environments highlights limited but growing implementation-oriented research. |
| **D** | Foundational perception technologies | Deep learning, computer vision | Core enabling technologies for automated waste recognition, classification, and robotic manipulation across closed-loop construction systems. |

The four thematic clusters show that the literature has progressed from basic robotic sorting towards more integrated themes involving artificial intelligence, circular economy, and construction implementation. Nevertheless, the separation between technology-focused terms and implementation-focused terms suggests that many studies remain at the prototype or laboratory level. This highlights the need for field-based validation, standardised datasets, and operational studies that evaluate performance under unstructured site conditions.

## 3.4 APPLICATION OF ROBOTIC SYSTEMS IN CDW MANAGEMENT

The bibliometric analysis reveals substantial diversity in robotic system configurations, perception technologies, and application contexts within CDW management.

Selected studies reveal substantial diversity in robotic system configurations, perception technologies, and application contexts within construction and demolition waste management. The analysis identifies distinct evolutionary trajectories in robotic CDW research. Early systems (2019-2021) focused on demonstrating technical feasibility through proof-of-concept prototypes, establishing baseline capabilities for automated sorting and grasping with impressive accuracies approaching 100% (Xiao et al., 2020; Wang et al., 2020). Mid-period research (2022-2023) addressed challenges of material heterogeneity, occlusion, and adhesion through deep learning-based grasping optimisation (Ku et al., 2020) and human-robot collaboration frameworks (Chen et al., 2023). Recent studies (2024-2026) demonstrate maturation through vision foundation models for robust waste segmentation (Heo & Na, 2024), robot-agnostic planning frameworks (Kokkalis et al., 2025), and field-validated deconstruction systems (Heuer et al., 2025).

## 3.5 END-EFFECTOR TECHNOLOGIES AND GRASPING STRATEGIES FOR ROBOTIC CDW MANIPULATION

End-effector design emerges as a critical determinant of robotic construction and demolition waste (CDW) system performance. The reviewed literature identifies two primary gripper categories dominating waste sorting applications.

1. Finger grippers with force control offer versatility for irregular, heavy materials including concrete fragments, bricks, and timber sections (Ku et al., 2020; Xiao et al., 2020).
2. Vacuum grippers provide gentle handling for lightweight materials with smooth surfaces but face limitations with porous construction materials (Chen et al., 2023; Raptopoulos et al., 2020).

Emerging research integrates sensor-based adaptive control with global information-based strategies (Ku et al., 2020) and boundary-guided grasp detection (Prasad & Arashpour, 2025a), substantially improving performance with cluttered, heterogeneous waste streams.

## 3.6 INTEGRATION WITH DIGITAL TECHNOLOGIES

The synthesis of the reviewed literature, as reflected in Figure 7, demonstrates that the effectiveness of construction robotics in achieving circular economy objectives is fundamentally contingent upon its integration with advanced digital technologies. Rather than operating as isolated systems, robotic applications are increasingly embedded within a broader digital ecosystem that enables data-driven decision-making, real-time coordination, and closed-loop material management. In this context, BIM emerges as a foundational platform, providing structured representations of building geometry and material attributes while enabling the development of material passports that support reuse, remanufacturing, and lifecycle tracking (Abd El-Hameed, 2025; Honic et al., 2019).

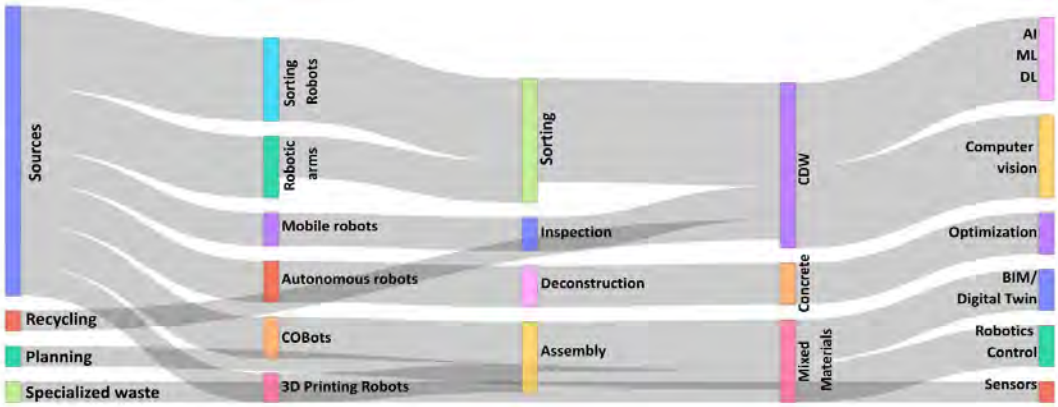



*Figure 7: Robotics in construction*

Beyond static data environments, Digital Twin technologies extend BIM capabilities by integrating real-time sensor inputs, thereby enabling dynamic monitoring of material conditions and predictive decision-making for deconstruction and recovery processes (Thakuri et al., 2024). IoT and Radio Frequency Identification (RFID) systems provide the necessary data infrastructure to support continuous tracking, identification, and

provenance verification of materials across the construction lifecycle, ensuring traceability within circular value chains (Bock et al., 2015; Santos et al., 2024).

At a higher level of integration, the convergence of robotics with digital systems gives rise to Cyber-Physical Systems (CPS), where AI-driven computer vision systems are combined with robotic manipulators to enable autonomous material identification, segmentation, and handling (Konstantinidis et al., 2023; Sirimewan et al., 2025).

Furthermore, digital marketplaces, supported by BIM, IoT and blockchain can support the matching of reclaimed material supply with demand while improving quality assurance, certification and trust in secondary material markets (Çetin et al., 2022; Abd El-Hameed, 2025). Despite these advancements, the literature indicates that the integration of robotics with digital technologies remains uneven. While BIM and digital twins are widely adopted in design and planning stages, their linkage with physical robotic execution is still limited, reflecting a persistent gap between digital modelling and on-site implementation (Abioye et al., 2021; Abd El-Hameed, 2025). Additionally, challenges such as high implementation costs, interoperability issues, and the lack of standardised datasets constrain large-scale deployment, particularly in complex and unstructured on-site environments (Balogun et al., 2024; Dodampegama et al., 2024).

Among the 36 studies considered 50% were on site, 22.2% were off site and the rest were conducted focusing both on site and off site context. For instance, 53.8% of the studies were closed loop status, and the rest were in open loop robotic stage. Moreover, a clear academic evolution towards the integration of robotics within a digitally enabled construction ecosystem is driving the transition from conventional linear construction practices to intelligent, closed-loop material systems, wherein CDW is not treated as waste but as a valuable resource stream governed through interconnected digital and robotic infrastructures.

## 3.7 GAPS IN THE EXISTING BODY OF KNOWLEDGE

Figure 8 summarises six interrelated gaps that currently restrict the transition from isolated robotic applications to fully integrated circular construction systems: deconstruction, perception, manipulation, policy, integration and human-robot collaboration. Robotic deconstruction remains limited because most studies focus on sorting after waste has already been generated rather than selective dismantling for component reuse. Perception systems have improved through computer vision and deep learning, but real CDW streams remain dusty, damaged, heterogeneous and visually cluttered.

Manipulation also remains challenging because construction waste varies widely in size, weight, shape, texture and fragility. Policy gaps are equally important because quality assurance standards, liability arrangements and certification procedures for recovered materials remain underdeveloped. Integration gaps persist because BIM, digital twins, IoT, RFID and blockchain are often discussed separately from physical robotic execution. Finally, human-robot collaboration requires further investigation because construction sites are dynamic and safety-critical environments where full autonomy may not yet be feasible.

## 4. CONCLUSIONS

This bibliometric analysis systematically maps the research landscape of robotic closed-loop construction, revealing exponential growth since 2021 driven by advances in artificial intelligence, computer vision, and robotic technologies. Publication output peaked at 12 articles in 2025, with China, Australia, and Hong Kong emerging as leading contributors within Asia-Pacific and European collaborative networks.

Keyword co-occurrence analysis identifies five primary research clusters: robotic sorting and grasping technologies, computer vision for waste recognition, deconstruction and disassembly systems, digital enablers (BIM, digital twins, IoT), and circular economy frameworks. Despite substantial progress, significant challenges impede widespread adoption. Perception systems remain vulnerable to real-world variability, robotic manipulation struggles with material heterogeneity, deconstruction systems for component reuse remain experimental, and economic validation across diverse contexts is limited.

Future research should prioritise large-scale datasets for robust perception, adaptive manipulation strategies for heterogeneous waste, comprehensive deconstruction systems for component reuse, human-robot collaboration frameworks, and integrated economic-environmental assessment. The convergence of robotics, computer vision, and circular economy principles offers transformative potential for transitioning from linear disposal to closed-loop resource systems, requiring sustained investment and cross-disciplinary collaboration.

*Figure 8: Gaps in the existing literature*

# 5. REFERENCES

Abd El-Hameed, A. K. (2025). Digital technologies as supporting tools for resource circularity in the construction industry: A review reflecting on the building lifecycle. *Journal of Building Engineering*, *114*, Article 114420. https://doi.org/10.1016/j.jobe.2025.114420

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Delgado, D., J. M., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*, Article 103299. https://doi.org/10.1016/j.jobe.2021.103299

Amirthalingam, K. (2010). Indirect taxation in Sri Lanka: The development challenge. *Economic Review*, *36*(7–8), 11–15. https://www.researchgate.net/publication/294729165_Sri_Lanka_Indirect_Taxation_in_Sri_Lanka_The_Development_Challenge

Amirthalingam, K. (2013). Importance and issues of taxation in Sri Lanka. *Colombo Business Journal*, *4*(1), 13–22. https://doi.org/10.4038/cbj.v4i1.30

Ashworth, A., & Perera, S. (2010). *Cost studies of buildings* (5th ed.). Routledge. https://doi.org/10.4324/9781315847122

Balogun, H., Alaka, H., Demir, E., Egwim, C. N., Olu-Ajayi, R., Sulaimon, I., & Oseghale, R. (2024). Artificial intelligence for deconstruction: Current state, challenges, and opportunities. *Automation in Construction*, *166*, Article 105641. https://doi.org/10.1016/j.autcon.2024.105641

Bird, R. M., Martinez-Vazquez, J., & Torgler, B. (2004). *Societal institutions and tax effort in developing countries* (CREMA Working Paper No. 2004-21). Center for Research in Economics, Management and the Arts (CREMA). https://www.econstor.eu/bitstream/10419/214307/1/2004-21.pdf

Bock, T. (2015). The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*, *59*, 113–121. https://doi.org/10.1016/j.autcon.2015.07.022

Bock, T., & Linner, T. (2015). *Robot-oriented design: Design and management tools for the deployment of automation and robotics in construction*. Cambridge University Press. https://doi.org/10.1017/CBO9781139924146

Central Bank of Sri Lanka. (2024). *Annual economic review 2024*. https://www.cbsl.gov.lk/en/publications/economic-and-financial-reports/annual-economic-review/annual-economic-review-2024

Central Bank of Sri Lanka. (2025). *Sri Lanka socio-economic data 2025*. Statistics Department, Central Bank of Sri Lanka. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/publications/otherpub/publication_sri_lanka_socio_economic_data_folder_2025_e.pdf

Central Bank of Sri Lanka. (2026). *Monthly economic indicators: January 2026*. https://www.cbsl.gov.lk/en/statistics/economic-indicators/monthly-indicators

Çetin, S., Rukanova, B. D., De Wolf, C., Gruis, V. H., & Tan, Y. (2022). A conceptual framework for a digital circular built environment: The data pipeline, passport generator and passport pool. In S. Shahnoori & M. Mohammadi (Eds.), *The state of circularity: The content of the 2nd International Conference on Circular Systems for the Built Environment* (pp. 97–106). Technische Universiteit Eindhoven. https://www.researchgate.net/publication/359802247

Chandrasekera, A. D. D. J., Waidyasekara, K. G. A. S., & Sirimewan, D. C. (2021). The impact of frequent tax reforms on construction industry in Sri Lanka. *Sri Lankan Journal of Banking and Finance*, *4*(1), 124–140. https://www.researchgate.net/publication/354393588

Chen, J., Fu, Y., Lu, W., & Pan, Y. (2023). Augmented reality-enabled human-robot collaboration to balance construction waste sorting efficiency and occupational safety and health. *Journal of Environmental Management*, *348*, Article 119341. https://doi.org/10.1016/j.jenvman.2023.119341

Chen, X., Huang, H., Liu, Y., Li, J., & Liu, M. (2022). Robot for automatic waste sorting on construction sites. *Automation in Construction*, *141*, Article 104387. https://doi.org/10.1016/j.autcon.2022.104387

Dassanayake, D. R. S., & Rathnayake, L. (2023). Cost of construction update for the year 2022: Position of Sri Lanka (Colombo) within the South Asian region. In P. S. Dissanayaka (Ed.), *IQSSL technical*

*research proceedings 2023* (pp. 23–27). Institute of Quantity Surveyors Sri Lanka. https://iqssl.lk/docs/publications/publication-iqssl-2023-08-28-uid454.pdf

De Oliveira, O. J., da Silva, F. F., Juliani, F., Barbosa, L. C. F. M., & Nunhes, T. V. (2019). Bibliometric method for mapping the state-of-the-art and identifying research gaps and trends in literature: An essential instrument to support the development of scientific projects. In S. Kunosic & E. Zerem (Eds.), *Scientometrics recent advances*. IntechOpen. https://doi.org/10.5772/intechopen.85856

De Silva, N., Rajakaruna, R. W. D. W. C. A. B., & Bandara, K. A. T. N. (2008). Challenges faced by the construction industry in Sri Lanka: Perspective of clients and contractors. In *Proceedings of the CIB W107 International Symposium on Innovation in Architecture, Engineering and Construction* (pp. 1–12). CIB. https://www.irbnet.de/daten/iconda/CIB11344.pdf

De Silva, S. S., Wijekoon, W. M. C. L. K., & Kalugala, C. (2023). Impact of economic crisis on employees of contractors' organisations in the Sri Lankan construction industry. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, & K. A. T. O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium* (pp. 557–568). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2023.46

Department of National Planning. (2024). *Annual performance report*. Ministry of Finance, Economic Stabilization and National Policies. https://npd.treasury.gov.lk/files/3.%20PP%20English.pdf

Dodampegama, S., Hou, L., Asadi, E., Zhang, K., & Setunge, S. (2024). Revolutionising construction and demolition waste sorting: Insights from artificial intelligence and robotic applications. *Resources, Conservation and Recycling*, *202*, Article 107375. https://doi.org/10.1016/j.resconrec.2023.107375

Engen, E. M., & Skinner, J. (1996). Taxation and economic growth. *National Tax Journal*, *49*(4), 617–642. https://doi.org/10.1086/NTJ41789231

Gangodawilage, D. (2015). *Business taxation*. The Institute of Chartered Accountants of Sri Lanka. https://www.casrilanka.com/casl/images/stories/EDBA/study%20text%20business%20taxation%20m1%204.pdf

Heo, S., & Na, S. (2024). Developing WasteSAM: A novel approach for accurate construction waste image segmentation to facilitate efficient recycling. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *43*(7), 1048–1059. https://doi.org/10.1177/0734242x241290743

Heuer, C., Jung, V., Kamp, C., & Brell-Cokcan, S. (2025). Deconstruction system for the reuse of concrete building parts in circular automated construction. *Journal of Building Engineering*, *114*, Article 113952. https://doi.org/10.1016/j.jobe.2025.113952

Honic, M., Kovacic, I., Sibenik, G., & Rechberger, H. (2019). Data- and stakeholder management framework for the implementation of BIM-based Material Passports. *Journal of Building Engineering*, *23*, 341–350. https://doi.org/10.1016/j.jobe.2019.01.017

James, S., & Edwards, A. (2008). Developing tax policy in a complex and changing world. *Economic Analysis and Policy*, *38*(1), 35–53. https://doi.org/10.1016/S0313-5926(08)50005-1

Kelegama, S. (Ed.). (2017). *Tax policy in Sri Lanka: Economic perspectives*. Institute of Policy Studies of Sri Lanka. https://www.ips.lk/wp-content/uploads/2017/10/Tax-Policy-in-Sri-Lanka-Economic-Perspectives_E_Book.pdf

Kokkalis, K., Konstantinidis, F. K., Koskinopoulou, M., Tsimiklis, G., Amditis, A., & Frangos, P. (2025). RaapWaste: Robot- and application-agnostic planning for efficient construction and demolition waste sorting. *Sustainability*, *17*(16), Article 7293. https://doi.org/10.3390/su17167293

Konstantinidis, F. K., Sifnaios, S., Tsimiklis, G., Mouroutsos, S. G., Amditis, A., & Gasteratos, A. (2023). Multi-sensor cyber-physical sorting system based on Industry 4.0 principles: A multi-functional approach. *Procedia Computer Science*, *217*, 227–237. https://doi.org/10.1016/j.procs.2022.12.218

Ku, Y.-D., Yang, J.-H., Fang, H.-Y., Xiao, W., & Zhuang, J.-T. (2020). Optimisation of grasping efficiency of a robot used for sorting construction and demolition waste. *International Journal of Automation and Computing*, *17*(5), 691–700. https://doi.org/10.1007/s11633-020-1237-0

Lee, S., Pan, W., Linner, T., & Bock, T. (2015). A framework for robot assisted deconstruction: Process, sub-systems and modelling. In *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2015)* (pp. 1–8). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2015/0093

Lu, W., Chen, J., & Xue, F. (2022). Using computer vision to recognise composition of construction waste mixtures: A semantic segmentation approach. *Resources, Conservation and Recycling*, *178*, Article 106022. https://doi.org/10.1016/j.resconrec.2021.106022

McNabb, K. (2018). Tax structures and economic growth: New evidence from the government revenue dataset. *Journal of International Development*, *30*(2), 173–205. https://doi.org/10.1002/jid.3345

Ministry of Finance. (2022). *Fiscal management report 2023*. https://www.treasury.gov.lk/api/file/f3256b98-539f-4645-85a6-6fe50a7a865f

Moschen-Schimek, J., Kasper, T., & Huber-Humer, M. (2023). Critical review of the recovery rates of construction and demolition waste in the European Union: An analysis of influencing factors in selected EU countries. *Waste Management*, *167*, 150–164. https://doi.org/10.1016/j.wasman.2023.05.020

Oluleye, B. I., Chan, D. W. M., & Antwi-Afari, P. (2023). Adopting Artificial Intelligence for enhancing the implementation of systemic circularity in the construction industry: A critical review. *Sustainable Production and Consumption*, *35*, 509–524. https://doi.org/10.1016/j.spc.2022.12.002

Ostapska, K., Hingorani, R., Tecław, W., Kaufmann, F., Gradeci, K., & Rüther, P. (2025). Automated robotic deconstruction sequence planning from scan-to-BIM data for reinforced concrete structure reuse. *Automation in Construction*, *180*, Article 106548. https://doi.org/10.1016/j.autcon.2025.106548

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, Article n71. https://doi.org/10.1136/bmj.n71

Panagodage, T. L., & De Silva, P. (2022). Critical supply chain problems in contractor - Subcontractor interface of Sri Lankan building construction projects. *Proceedings of the SLIIT International Conference on Engineering and Technology*, 57–68. https://doi.org/10.54389/cjfm8214

Patel, M., & Patel, N. (2019). Exploring research methodology: Review article. *International Journal of Research and Review*, *6*(3), 48–55. https://www.ijrrjournal.com/IJRR_Vol.6_Issue.3_March2019/IJRR0011.pdf

Prasad, V., & Arashpour, M. (2024). Real-time instance segmentation of recyclables from highly cluttered construction and demolition waste streams. *Journal of Environmental Management*, *372*, Article 123365. https://doi.org/10.1016/j.jenvman.2024.123365

Prasad, V., & Arashpour, M. (2025a). Enhancing sorting efficiency in cluttered construction and demolition waste streams via boundary-guided grasp detection. *Waste Management*, *207*, 115123. https://doi.org/10.1016/j.wasman.2025.115123

Prasad, V., & Arashpour, M. (2025b). ShARP-WasteSeg: A shape-aware approach to real-time segmentation of recyclables from cluttered construction and demolition waste. *Waste Management*, *195*, 231–239. https://doi.org/10.1016/j.wasman.2025.02.006

Ranasinghe, S. R. S. H., & Kulathunga, K. M. M. C. B. (2016). Impact of the income tax system on tax payers' satisfaction: With special reference to Kegalle district income tax payers. *International Journal of Accounting and Business Finance*, *2*(2), 24–37. https://www.maco.jfn.ac.lk/ijabf/wp-content/uploads/2017/11/vol2_issue2_3.pdf

Raptopoulos, F., Koskinopoulou, M., & Maniadakis, M. (2020). Robotic pick-and-toss facilitates urban waste sorting. In *16th IEEE International Conference on Automation Science and Engineering (CASE 2020)* (pp. 1149–1154). IEEE. https://doi.org/10.1109/CASE48305.2020.9216746

Santos, P., Cervantes, G. C., Zaragoza-Benzal, A., Byrne, A., Karaca, F., Ferrández, D., Salles, A., & Bragança, L. (2024). Circular material usage strategies and principles in buildings: A review. *Buildings*, *14*(1), Article 281. https://doi.org/10.3390/buildings14010281

Shao, Z., Li, M., & Yu, D. (2022). Bibliometric analysis of construction and demolition waste recycling: Review and prospects. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *175*(6), 283–292. https://doi.org/10.1680/jensu.21.00089

Sirimewan, D., Kineber, A. F., Raman, S., Garcia, R., & Arashpour, M. (2025). Leveraging large-scale vision foundation models for automated construction and demolition waste recognition. *Advanced Engineering Informatics*, *68*, Article 103593. https://doi.org/10.1016/j.aei.2025.103593

Taherdoost, H. (2022). What are different research approaches? Comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Thakuri, P. K., Alkki, L., & Stenroos, L. A. (2024). Digital technologies enabling component reuse in circular value chains: Using digital twin, internet of things and robots in construction and manufacturing sectors. *R&D Management*, *55*(4), 1161–1216. https://doi.org/10.1111/radm.12744

Thelwall, M., & Sud, P. (2022). Scopus 1900–2020: Growth in articles, abstracts, countries, fields, and journals. *Quantitative Science Studies*, *3*(1), 37–50. https://doi.org/10.1162/qss_a_00177

Vickneswaran, A. (2014). *Tax policy changes, tax revenue and budget deficit: A case in Sri Lanka* [Unpublished manuscript]. University of Jaffna. https://www.researchgate.net/publication/314116840

Wang, Z., Li, H., & Yang, X. (2020). Vision-based robotic system for on-site construction and demolition waste sorting and recycling. *Journal of Building Engineering*, *32*, Article 101769. https://doi.org/10.1016/j.jobe.2020.101769

Waidyasekera, D. D. M. (2016). *Taxation in Sri Lanka: Current trends and perspectives* (Research Studies Series No. 25). Institute of Policy Studies of Sri Lanka. https://www.ips.lk/wp-content/uploads/2017/01/Taxation-in-Sri-Lanka.pdf

Xiao, W., Yang, J., Fang, H., Zhuang, J., Ku, Y., & Zhang, X. (2020). Development of an automatic sorting robot for construction and demolition waste. *Clean Technologies and Environmental Policy*, *22*(9), 1829–1841. https://doi.org/10.1007/s10098-020-01922-y

Zhao, X. (2024). Evolution of construction risk management research: Historiography and keyword co-occurrence analysis. *Engineering, Construction and Architectural Management*, *31*(4), 1408–1428. https://doi.org/10.1108/ECAM-09-2022-0853

Attanayaka, S.M.S.S., Illeperuma, I.E. and Abeynayake, M.D.T.E., 2026. Role of regulations and governance in the circular economy for construction: A comparative analysis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1527-1540. DOI: https://doi.org/10.31705/WCS.2026.111. Available from: https://ciobwcs.com/papers/

# ROLE OF REGULATIONS AND GOVERNANCE IN THE CIRCULAR ECONOMY FOR CONSTRUCTION: A COMPARATIVE ANALYSIS

**S.M.S.S. Attanayaka[1], I.E. Illeperuma[2] and M.D.T.E. Abeynayake[3]**

## *ABSTRACT*

*The construction sector is among the largest global consumers of raw materials and generators of waste, making regulatory governance a decisive factor in the circular economy (CE) transition. This paper presents findings of a comprehensive document analysis examining CE-relevant regulatory frameworks across six Asian jurisdictions, China, Japan, South Korea, Hong Kong, Singapore, India and Sri Lanka's (SL's) national regulatory landscape, comprising eleven instruments. Applying a structured analytical framework consistently across all documents, the study interrogates legislative intent, compliance mechanisms, enforcement architecture and identified limitations. The Asian analysis reveals stratification across three governance tiers, i) advanced statutory architectures with mandatory waste separation, ii) quantified recovery targets and multi-instrument enforcement, and iii) framework legislation with variable subnational implementation and early-stage disposal-oriented regulation. SL's framework is characterised by a pre-CE legislative inheritance, institutional fragmentation and a systematic implementation deficit. The Construction Industry Development Authority (CIDA) Regulations 2018 represent the only operative mandatory CE-adjacent obligation in the national framework, yet threshold, monitoring and penalty provisions limit their effectiveness. The paper concludes by identifying governance pathways informed by Asian regulatory experience and germane to SL's institutional context.*

***Keywords:*** *Circular Economy; Governance; Policy Frameworks; Regulations; Sri Lanka.*

## 1. INTRODUCTION

The construction industry (CI) has long been recognised as a dominant consumer of natural resources, accounting for over 40% of global resource usage (Weerakoon et al., 2023). Buildings account for nearly 40% of global energy consumption and solid waste generation, 30% of raw material use and nearly 33% of greenhouse gas emissions (Gowsiga et al., 2023). Construction and demolition waste (C&DW) is one of the most substantial waste streams worldwide representing 30 - 40% of total waste production and

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, attanayakasmss.21@uom.lk
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, isurii@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk

causing landfill congestion, soil contamination and greenhouse gas emissions (Gowsiga et al., 2023). Addressing these impacts requires a fundamental shift from the traditional linear take-make-dispose model towards a circular economy (CE) which is a viable pathway to sustainable development (Gowsiga et al., 2023; Kuzma et al., 2022).

Regulations define behavioural expectations, establish accountability and align collective action toward systemic transformation (Kyriakopoulos, 2021). Strong regulatory enforcement provides the essential top-down mechanism to accelerate CE adoption (Yu et al., 2022). Unlike standard sustainability or waste management instruments, which typically target end-of-pipe disposal or energy efficiency in isolation, CE-specific regulations mandate the systemic retention of material value across the full construction lifecycle, integrating design, procurement, use and end-of-life stages within a single governance logic (Kyriakopoulos, 2021; Calisto Friant et al., 2021). CE regulations are specifically designed to close material loops retaining resources at their highest value through reuse, remanufacturing and recycling across the construction value chain (Kyriakopoulos, 2021; Calisto Friant et al., 2021). Members of the European Union (EU) have been leading legislative efforts (Ballardini et al., 2020; Steenmans & Lesniewska, 2023). Asia presents a particularly instructive governance landscape for CE regulatory analysis. The region encompasses some of the world's most advanced CE statutory architectures alongside regulatory systems in early formative stages, operating within distinctive institutional cultures, economic contexts and governance capacities (Ghisellini & Ulgiati, 2020; Kyriakopoulos, 2021). Asian applications tend to prioritise material efficiency at the industrial level, reflecting manufacturing-based economies and centralised governance (Ghisellini & Ulgiati, 2020). Besides, developing nations face implementation challenges that go beyond resource constraints, with institutional fragmentation, limited enforcement capacity and competing development priorities constraining circular governance transitions (De Melo et al., 2022; Torgautov et al., 2021; Victar & Waidyasekara, 2024).

SL’s CI demonstrated notable economic contribution, accounting for 1.20% of GDP growth in 2024 (Central Bank of Sri Lanka [CBSL], 2024) and 0.69% in the first quarter of 2025 (CBSL, 2025), reflecting its consistent role as a key driver of economic recovery. However, it lacks enforceable regulatory frameworks that facilitate CE transition (Bimsara et al., 2024; Weerakoon et al., 2023). Existing environmental and waste management regulations are outdated and poorly enforced, resulting in inadequate governance of C&DW and limited incentives for circular practices (Bimsara et al., 2024; Weerakoon et al., 2023). Understanding the range of regulatory approaches adopted across Asian jurisdictions provides a comparative basis for SL to assess how countries at differing stages of regulatory development might configure their own CE governance systems (Calisto Friant et al., 2021; Yu et al., 2022).

Therefore, this study addresses the research question, “how to bridge the regulatory deficiencies that constrain CE transition in SL's CI?”. The study aims to strengthen the SL's regulatory framework for CE in the CI through a comparative analysis of CE governance approaches across jurisdictions. Accordingly, the objectives of the study are (1) to examine CE-relevant regulatory landscapes across selected Asian jurisdictions in relation to the CI, and (2) to identify governance pathways for regulatory reforms in SL.

# 2. LITERATURE REVIEW

## 2.1 ROLE OF REGULATIONS IN CE TRANSITION

Reduced. Regulatory approaches to CE span a spectrum from prescriptive command-and-control measures to flexible performance-based regulations (Kyriakopoulos, 2021). Command-and-control instruments such as material recovery mandates provide clarity and ensure minimum compliance but may constrain innovation (Calisto Friant et al., 2021). Performance-based regulations, by contrast, set defined outcome targets without prescribing specific methods of compliance, allowing firms to meet the standards through the most cost-effective pathway (Kyriakopoulos, 2021). Market-based instruments, as a form of performance-based regulation, include Extended Producer Responsibility (EPR) schemes and material taxes that internalise environmental costs, using price signals to drive behavioural change without prescriptive control (Ballardini et al., 2020). Informational regulations and mandatory environmental disclosure enable market driven transformation without direct control over private decision making (Charef, 2024).

Regulatory instruments for CE implementation span several categories, each with different mechanisms and institutional requirements. Regulatory instruments establishing mandatory requirements, economic instruments internalising environmental externalities, informational tools addressing gaps and informational asymmetries and collaborative tools building consensus toward circular goals (De Melo et al., 2022; Kyriakopoulos, 2021). The effectiveness of any instrument is strongly conditioned by institutional capacity, market maturity, stakeholder characteristics and cultural norms (De Melo et al., 2022; Yu et al., 2022).

Effective regulatory regimes typically combine instrument types that address different dimensions. Overly prescriptive rules impose disproportionate compliance burdens on small firms and regulatory fragmentation hinder market development for recovered materials (Ahmed et al., 2024; Ballardini et al., 2020; Kyriakopoulos, 2021; Steenmans & Lesniewska, 2023). Effective regulatory strategies combine instrument types to reinforce one another. Regulations set minimum requirements, economic incentives make compliance financially beneficial, informational programmes build implementation capacity and collaborative mechanisms ensure buy-in (Ahmed et al., 2024; Yu et al., 2022). The appropriate combination, however, depends on local institutional capabilities, development priorities and available resources (De Melo et al., 2022).

## 2.2 INTERNATIONAL REGULATORY DIVERSITY

The EU's multi-level governance framework (Calisto Friant et al., 2021; Kyriakopoulos, 2021) and the United Kingdom’s (UK's) performance-based strategy (Kyriakopoulos, 2021) demonstrate comprehensive legislative approaches, while Singapore's centralised enforcement model (Yu et al., 2022; Ghisellini & Ulgiati, 2020) and Japan's material-specific phasing (Ghisellini & Ulgiati, 2020; Yu et al., 2022) illustrate targeted sector-specific regulation. China's framework legislation with variable provincial implementation (Ghisellini & Ulgiati, 2020) and South Korea's economic instrument integration (Ghisellini & Ulgiati, 2020; Yu et al., 2022) reflect distinct institutional traditions. This diversity demonstrates that there is no single optimal regulatory path. The relative effectiveness of each model depends on its alignment with local governance capacity, institutional traditions and economic context rather than on the sophistication of the instruments themselves (Ballardini et al., 2020; Corvellec et al., 2022).

International evidence indicates that simple yet consistently enforced regulations achieve greater impact than comprehensive frameworks that outpace implementation capacity (Torgautov et al., 2021; Yu et al., 2022).

The regulations of developed economies cannot be directly transplanted to developing countries without substantial modifications (Abeynayake & Perera, 2025). Comprehensive regulatory systems assume monitoring infrastructure, multi-agency coordination and legal precedents are absent in developing economies (De Melo et al., 2022). For example, high recycling targets may be technically feasible but economically unviable without sufficient market demand and processing capacity (Victar & Waidyasekara, 2024). Enforcement credibility outweighs regulatory comprehensiveness in determining CE outcomes in developing countries (De Melo et al., 2022). Sequencing of interventions is equally critical, attempting wholesale regulatory transformation can overwhelm limited institutional capacity, necessitating phased approaches that lay foundational elements before advancing to more sophisticated requirements (Yu et al., 2022). Piloting on larger projects, where monitoring is manageable and demonstration effects are visible, provides evidence for subsequent expansions (Torgautov et al., 2021).

## 2.3 REGULATORY LANDSCAPE IN ASIA

Reduced. Infrastructure deficits, technical resource gaps, institutional fragmentation and financial constraints are recurrent barriers. Yet developing economies simultaneously lack the lock-in effects associated with entrenched linear infrastructure and deeply embedded supply chains prevalent in more advanced contexts (De Melo et al., 2022; Torgautov et al., 2021). Rapid urbanisation, while placing pressure on resources, creates windows to embed circular principles in new infrastructure rather than retrofitting existing systems (Torgautov et al., 2021; Victar & Waidyasekara, 2024).

China's CE Promotion Law illustrates the governance risks of national framework legislation with variable subnational implementation. India's governance trajectory further demonstrates how bilateral commitments and state-level fragmentation constrain the translation of national CE regulatory aspirations into consistent field-level compliance when regulatory authority is dispersed across jurisdictions of variable capacity (Corvellec et al., 2022; De Melo et al., 2022). Across Asian contexts, institutional fragmentation, limited enforcement capacity and competing development priorities collectively constrain circular governance transitions (De Melo et al., 2022; Torgautov et al., 2021).

## 2.4 REGULATORY CONTEXT IN SL

SL's regulatory framework for circular construction consists of a multi-layered system with varied legal force and enforcement capacity (Abeynayake & Perera, 2025). Authority is distributed among CIDA, the Central Environmental Authority (CEA), the Urban Development Authority (UDA), provincial councils and local government authorities, creating coordination challenges and potential regulatory gaps between institutional mandates (Victar & Waidyasekara, 2024; Weerakoon et al., 2023). Persistent disconnect characterises this landscape, progressive policy language articulates sustainability goals broadly consistent with global best practice (Ministry of Housing & Construction and CIDA, 2020), yet these remain untranslated into binding requirements, enforcement mechanisms and accountability systems (Abeynayake & Perera, 2025).

Guidelines are predominantly voluntary, carrying advisory rather than legal authority, which allows progressive regulatory intent to coexist with business-as-usual behaviour as there are no material consequences for disregarding sustainability provisions (Weerakoon et al., 2023; Wijesinghe et al., 2022). SL currently requires no design provisions for future disassembly, material recovery or building adaptability in either design requirements or permitting processes (Wijewansha et al., 2021). This creates path dependency in which early design decisions permanently foreclose circularity options over a building's entire lifecycle (Anastasiades et al., 2023). Further deficiencies include the absence of quantified material recovery targets, no legally binding waste hierarchy and a near complete absence of digital tracking infrastructure for material flows (Abeynayake & Perera, 2025; Victar & Waidyasekara, 2024).

# 3. RESEARCH METHODOLOGY

This study forms part of a broader study that followed a mixed-method approach. Accordingly, this paper adopted the qualitative approach and the document review technique for data collection and the content analysis technique for data analysis (Kagioglou et al., 1998).

Document analysis is particularly suited to regulatory research where the operative content of formal instruments must be assessed on its own terms rather than through practitioner interpretation (Bowen, 2009). Documents were selected based on four criteria applied consistently: (1) formal promulgation by a recognised governmental, intergovernmental or statutory authority, (2) current or recent operative status, (3) direct relevance to construction activities, waste management, material flows or the built environment and (4) accessibility through official legislative repositories or governmental publications. For the international component, jurisdictions were selected to represent Asia's principal governance typologies, across East Asia, Southeast Asia and South Asia.

Each instrument was evaluated against five analytical criteria: (1) legislative objectives and policy intent, (2) regulatory instruments and compliance mechanisms, (3) alignment with CE principles, (4) enforcement architecture and accountability provisions and (5) practical implications for construction actors. Identified limitations were documented to guard against attributing CE relevance based on superficial classification rather than substantive content review.

# 4. RESEARCH FINDINGS AND DISCUSSION

## 4.1 ASIAN CE REGULATORY FRAMEWORKS

The document analysis identified CE-relevant regulatory instruments across six Asian jurisdictions. Table 1 presents a comparative overview, structured by governance region.

### 4.1.1 East Asia

China's CE Promotion Law - 2008 establishes a national statutory basis for CE transition, mandating C&DW management plans, quantified resource utilisation targets and clean production audits for large enterprises. However, extreme geographic variation between coastal cities and interior areas produces a dual regulatory reality. Utilisation targets have been met primarily through aggregate crushing rather than high-value component recovery. Japan's Construction Material Recycling Law - 2000 mandates on-site separation, pre-demolition notification, material-specific recovery targets with named

professional liability and a manifest tracking system, though material quality enforcement at receiving facilities varies by prefecture. South Korea's Framework Act on Resources Circulation - 2016 combines mandatory reporting, resource circulation charges and mandatory recycled aggregate use in public construction, though downcycling to fill applications predominates over high-value structural use. Hong Kong's Construction Waste Disposal Charging Scheme - 2005 addresses disposal behaviour through fiscal disincentives but lacks a corresponding incentive for upstream material recovery.

#### 4.1.2 Southeast Asia: Singapore

Singapore's CE governance architecture is the most comprehensively integrated system in the analysis. Green Mark Certification is mandatory for all new buildings and major renovations exceeding 5,000 m² gross floor area, with material efficiency and C&DW reduction as building permit conditions. The Carbon Pricing Act - 2019 creates a pricing signal favouring lower embodied carbon construction, the Resource Sustainability Act - 2019 underpins a national C&DW monitoring infrastructure and the Zero Waste Masterplan - 2019 commits to a 70% C&DW recycling rate by 2030. Limitations include recycling rate targets that aggregate volume recovery without distinguishing high-value reuse from low-grade crushing and coverage thresholds that exclude smaller projects.

#### 4.1.3 South Asia: India

India's EU-India Joint Declaration on Resource Efficiency and Circular Economy - 2017 signals a bilateral CE governance reform commitment. However, governance aspirations diverge substantially from construction practice dominated by small contractors outside regulatory visibility, with no binding domestic CE legislation enacted for the CI at the time of analysis. C&DW governance remains fragmented across state-level instruments of variable coverage and enforcement.

#### 4.1.4 Cross-Jurisdictional Analytical Observations

The international regulatory landscape reflects considerable diversity in legislative philosophy and implementation maturity (Calisto Friant et al., 2021; Kyriakopoulos, 2021). Jurisdictions differ according to whether their regulatory approach is anchored in product-level lifecycle obligations, waste management mandates or sector-specific construction requirements. The most sophisticated frameworks Japan, Singapore and South Korea exhibit multi-instrument architecture operating at complementary points along the construction value chain (Ghisellini & Ulgiati, 2020; Yu et al., 2022). Developing contexts reveal alternative models characterised by national framework legislation with variable subnational implementation (Corvellec et al., 2022).

Three cross-cutting observations emerge from the Asian analysis. First, regulatory effectiveness correlates not with the breadth of policy ambition but with the specificity and enforceability of individual instruments consistently enforced regulations achieve greater impact than comprehensive frameworks that outpace implementation capacity (Torgautov et al., 2021; Yu et al., 2022). Second, a persistent disjunction exists across all jurisdictions between recycling rate metrics and genuine material quality outcomes, volume-based statistics aggregate high-value component reuse and low-grade aggregate crushing into a single indicator, risking perverse optimisation. Third, the most successful governance models Japan, South Korea and Singapore address institutional coordination through systematic instrument stacking, with multiple regulatory mechanisms operating at complementary intervention points along the construction value chain.

*Table 1: Comparative Overview of Asian CE Regulatory Frameworks for Construction*

| Jurisdiction | | Instrument / Legislation | CE-Relevant Provisions | Identified Limitations |
|---|---|---|---|---|
| East Asia | China | Circular Economy Promotion Law 2008 (amended 2013) | Mandatory C&DW management plans, quantified resource utilisation targets, clean production audit obligations, CE demonstration city/industrial park programmes | Extreme geographic variation between coastal and interior provinces, enforcement inconsistency across jurisdictions |
| | | C&DW Management Regulations (provincial and municipal) | Source separation requirements, licensed processing facilities, demolition waste management plans, recycled aggregate use in public works | Regulatory variation across provinces creates market fragmentation, secondary material quality certification inconsistent |
| | | Law on Promoting Clean Production 2003 | Mandatory clean production audits for large enterprises, material efficiency requirements, hazardous substance reduction, lifecycle documentation | Less systematic application to construction than manufacturing, audit frequency and quality variable across provinces |
| | | 12th 5-Year Plan Guidance on Comprehensive Utilisation of Resources 2015 | Quantified C&DW utilisation rate targets, central government demonstration programme for circular construction sites, processing infrastructure investment | Targets met primarily through aggregate crushing rather than high-value recovery, recovered material quality insufficiently verified |
| | Japan | Construction Material Recycling Law 2000 (Kensetsu Recycle Ho) | Mandatory on-site separation of concrete, asphalt, wood and metal, pre-demolition notification, material-specific recovery targets, manifest tracking system | Coverage limited to four designated streams, multi-decade implementation horizon required to achieve current compliance |
| | | Building Standards Law (Kenchiku Kijunho) | Structural and material standards, building lifetime extension requirements, documentation for major structural elements, basis for recycled content requirements | Primary focus on structural safety, CE-specific provisions require supplementary secondary regulations to become operative |
| | | Waste Management and Public Cleansing Law (Haikibutsu Shoriho) | Duty of care obligations, industrial waste manifest system for C&DW, licensed carrier requirements, processing facility certification | Enforcement of material quality at receiving facilities varies, recycled material verification infrastructure differs by prefecture |
| | South Korea | Framework Act on Resources Circulation 2016 | Resource circulation performance assessment indicators, mandatory reporting for large producers, targets for reducing final disposal rates, resource circulation charges | Performance assessment applies principally to large enterprises, SMEs in construction largely outside systematic monitoring |
| | | Construction Waste Recycling Promotion Act | Mandatory recycled aggregate use in public sector projects, source separation at demolition sites, licensed C&DW processor registration, permit-linked compliance | Mandatory recycled aggregate creates demand but does not address quality differentiation, downcycling to fill applications predominates |

| Jurisdiction | | Instrument / Legislation | CE-Relevant Provisions | Identified Limitations |
|---|---|---|---|---|
| South-East Asia | Hong Kong | EPR Schemes and Deposit-Refund Mechanisms | EPR obligations for diverse product categories, deposit systems incentivising material return, construction material EPR under development, industrial symbiosis platforms | Construction material EPR presents design challenges distinct from packaging EPR, long service lives measured in decades not months |
| | | Construction Waste Disposal Charging Scheme 2005 | Levy on C&DW disposed at government facilities, fiscal disincentive for unnecessary waste generation, licensed disposal facility system, project-linked waste account | Addresses disposal behaviour only, no upstream material efficiency incentive, no corresponding support for material recovery investment |
| | | Blueprint for Sustainable Use of Resources 2013 | Strategic framework identifying C&DW as priority resource stream, landfill diversion targets, pilot recycled aggregate use in public works | Binding force limited to specific charging and licensing provisions, circular design and material reuse provisions remain aspirational |
| | Singapore | Sustainable Construction Masterplan and Green Mark Certification | Mandatory Green Mark for new buildings and major renovations >5,000 m², material efficiency and C&DW reduction criteria, permit conditional on Green Mark compliance | Primarily addresses operational and energy performance, material circularity criteria not weighted equivalently to energy metrics |
| | | Resource Sustainability Act 2019 | Mandatory waste reporting for large construction projects, national C&DW monitoring data foundation, authority for NEA to impose sector-wide waste reduction obligations | Reporting thresholds exclude smaller projects with cumulatively significant volumes, enforcement relies on self-reported data |
| | | Carbon Pricing Act 2019 | Economy-wide carbon price for large emitters, financial signal favouring lower-embodied-carbon materials, revenue supports CE transition initiatives | Applies at enterprise level, project-level carbon cost not systematically internalised in contract pricing without supplementary mechanisms |
| | | Zero Waste Masterplan 2019 | 0% C&DW recycling target by 2030, prefabrication adoption targets, circular design guidelines, mandatory waste management plans for significant projects | Recycling rate target measures aggregate volume recovery, does not distinguish high-value component reuse from low-grade aggregate crushing |
| South Asia | India | EU-India Joint Declaration on Resource Efficiency and CE 2017 | Bilateral CE governance reform commitment, policy orientation toward CE principles, technical cooperation for regulatory capacity building and knowledge transfer | CE aspirations substantially diverge from construction practice dominated by small contractors, no binding domestic CE legislation in CI enacted |

## 4.2 CE REGULATORY FRAMEWORK IN SL

SL's regulatory landscape relevant to CE in the CI comprises a range of Acts and Laws promulgated across more than four decades. These instruments were designed to achieve specific sectoral or environmental objectives that, in most cases, predate the CE paradigm. Their relevance to circular construction governance, therefore, derives from incidental overlap with CE principles rather than deliberate circular design. Table 2 presents the analytical assessment of the seven primary legislative instruments examined.

### 4.2.1 Environmental and Planning Legislation

The National Environmental Act No. 47 of 1980 and its EIA Regulations (1993) provide the primary environmental governance gateway for major construction projects. However, CE dimensions including Design for Disassembly (DfD), material passports and secondary material specifications are absent in EIA assessment criteria and C&DW is not classified as scheduled waste. The UDA Law No. 41 of 1978 operates a development permit system, yet permit review contains no CE criteria. The Town and Country Planning Ordinance provides a statutory basis for area-wide material flow planning, yet CE provisions are not systematically applied and capacity differentials between urban and peri-urban authorities further constrain its operative effect.

### 4.2.2 Construction Related Legislation

The Construction Industry Development Act No. 33 of 2014 contains no CE content in its primary legislation. Its Section 41 secondary regulation-making powers, which could mandate CE practices, remain unexercised. The Coast Conservation Act No. 57 of 1981 governs coastal construction through a permit system addressing coastal ecology only, with C&DW management entirely absent from assessment criteria. The Municipal Councils, Urban Councils and Pradeshiya Sabhas Acts govern building approval across SL's 341 local authorities, with bylaws covering structural safety, fire and sanitation only. No CE content exists in any local authority framework, despite local approvals constituting the dominant category of construction by project number. The Chamber of Construction Industry Act No. 23 of 2019 establishes CCI as a self-regulation body with a CE knowledge dissemination role. However, its reach is limited to voluntary membership with no enforcement authority against non-members.

### 4.2.3 Governance Deficit and Reform Implications

A common pattern emerges in all legislative instruments. All three environmental and planning instruments hold significant untapped potential for CE integration through existing amendment and permit condition mechanisms that have not been activated to date. The governance deficit is therefore not the absence of suitable legislative architecture but the systematic failure to exercise existing powers: a governance implementation deficit (Abeynayake & Perera, 2025) paralleled across developing countries (De Melo et al., 2022; Yu et al., 2022). No agency exercises comprehensive oversight of C&DW flows, reflecting the institutional fragmentation as a critical barrier to CE transition (Charef, 2022; Weerakoon et al., 2023). The most productive near-term reform pathway lies within the existing legislative framework. CIDA's secondary regulation-making powers, EIA terms of reference and UDA permit conditions each represent actionable instruments for CE integration without requiring primary legislative change (Abeynayake & Perera, 2025; Hossain et al., 2020; Ahmed et al., 2024).

*Table 2: Sri Lankan Legislative Instruments - CE Governance Assessment*

| Instrument | Responsible Authority | CE-Relevant Provisions | | Identified Limitations |
|---|---|---|---|---|
| **National Environmental Act No. 47 of 1980** | CEA | Sec 23 | ✓ - Section 23Z is part of the Environmental Protection License (EPL) framework designed to regulate pollution. Mandatory EIA for all prescribed construction undertakings CE assessment gateway, currently addressed through project approval process. | Standard EIA terms of reference address construction-phase disturbance, CE dimensions (DfD, material passports, secondary material use) absent from prescribed assessment criteria<br>CDW not classified as scheduled waste<br>Enforcement resources stretched across all sectors |
| | | Sec 24 | ✗ - Pollution discharge standards. Regulates environmental discharge from construction activities, relevant but C&DW and secondary material-use standards not incorporated. | |
| | | First Schedule | ✗ - Prescribed undertakings. Lists project categories triggering EIA, can be expanded to include CE-specific thresholds (DfD, material passports). Not yet done. | |
| **Construction Industry Development Act No. 33 of 2014** | CIDA | Sec 5 & 7 | ✗ - Contractor registration & grading. Registration system provides leverage for CE capability requirements potential exists but CE competencies not yet embedded in grading criteria. | Primary legislation contains no sustainability, environmental, or CE content<br>No inter-agency coordination mandate<br>CE-relevant use of secondary regulation powers not exercised to date |
| | | Sec 41 | ✗ - Power to make secondary regulations. Authority to promulgate secondary regulations on technical standards, can be exercised to mandate CE practices. Not yet exercised for CE purposes. | |
| **Urban Development Authority Law No. 41 of 1978** | UDA | Sec 8 | ✗ - Development permit system. Covers highest intensity urban construction permit conditions mechanism is available for attaching CE requirements. CE criteria not yet included. | Current permit review contains no CE criteria<br>Assessment confined to planning, land use, structural and safety compliance<br>Amendment or implementing regulations required to incorporate CE conditions |
| | | Sec 14 | ✗ - Implementing Regulations. Empowers UDA to issue implementing regulations, amendment or new regulation required to incorporate CE permit conditions. | |
| **Coast Conservation Act No. 57 of 1981** | Coast Conservation & Coastal Resource | Sec 14 | ✗ - Coastal zone permit system. Permit system covers all coastal construction including tourism, residential and port facilities. Coastal ecology addressed, &CDW and secondary material requirements absent. | Permit conditions address only coastal ecology, no C&DW management, secondary material, or DfD requirements imposed |

| Instrument | Responsible Authority | CE-Relevant Provisions | | Identified Limitations |
|---|---|---|---|---|
| | Management Dept. (CCCRMD) | Sec 16 | ✗ - Permit conditions. Conditions may be imposed on coastal construction permits. Mechanism available to embed CE requirements but not yet utilised for this purpose. | CE dimensions entirely absent from prescribed permit assessment criteria |
| **Town and Country Planning Ordinance & Amendment Act No. 49 of 2000** | National Physical Planning Department, Provincial/Local authorities | Sec 3 | ✗ - Development scheme preparation. Planning framework determines where and what development may occur, potential instrument for area-wide material flow and CE infrastructure planning. CE provisions not applied. | CE-relevant planning provisions (material flow assessments, processing facility zones, waste infrastructure requirements) not systematically applied<br>Capacity differential between urban and peri-urban authorities limits consistent application |
| | | Sec 10 | ✗ - Development control. Development approvals under the planning framework can be conditioned to require CE assessments. No such conditions issued to date. | |
| **Municipal Councils Act, Urban Councils Act & Pradeshiya Sabhas Act** | Local Authorities (341 bodies) | Building Plan Approval Provisions | ✗ - Local approval authority covering all residential and smaller commercial projects, numerically the largest approval class. CE content absent from all local building bylaws. | Building bylaws exclusively address structural safety, fire, sanitation and dimensional compliance<br>No CE content in any local authority building bylaw framework<br>No national standards for local CDW management<br>Extreme variation in capacity across 341 local authorities |
| | | Waste Management Service Provisions | ✗ - Mandate for local solid waste management services, C&DW could be incorporated into local waste management frameworks. National standards for local CDW management absent. | |
| **Chamber of Construction Industry Act No. 23 of 2019** | CCI Sri Lanka | Statutory Incorporation Provisions | ✓ - Establishes CCI as formalised self-regulation body, CE knowledge dissemination and standard development role recognised. Currently facilitative and normative only. | Limited regulatory authority, voluntary membership<br>No enforcement against non-members<br>Effectiveness dependent on voluntary engagement<br>Formalised coordination with CIDA is still developing |
| | | Standard Development Powers | ✗ - Authority to develop professional standards and best practice guidance, can be directed toward CE standards development. Effectiveness dependent on voluntary engagement. | |

### 4.3 GOVERNANCE PATHWAYS: LESSONS FROM ASIA FOR SL

Regulatory progression in CE construction governance follows a discernible path from disposal management through material recovery optimisation to upstream circular design integration (Calisto Friant et al., 2021; Kyriakopoulos, 2021). SL's current condition aligns with the first stage, addressing C&DW through waste classification and licensed disposal requirements without interrogating the material efficiency or design decisions that determine C&DW generation rates. The qualitative leap to upstream integration, exemplified by Japan's pre-demolition notification systems and Singapore's Green Mark material efficiency criteria, requires a reorientation of regulatory philosophy from end-of-pipe waste management toward circular material governance (Yu et al., 2022).

In the medium term, CIDA's secondary regulation-making powers should be exercised to incorporate CE competence requirements into contractor registration, reaching across the project scale spectrum that the LKR 500 million threshold excludes. In the long term, dedicated CE framework legislation would provide the statutory basis for mandatory C&DW recovery targets, EPR for construction materials and a national material information infrastructure for which no current SL instrument provides adequate legal authority (Abeynayake & Perera, 2025).

## 5. CONCLUSIONS AND RECOMMENDATIONS

This paper presents findings of a comprehensive document review of CE-relevant regulatory frameworks across six Asian jurisdictions and SL's national regulatory landscape. Asian jurisdictions exhibit a pronounced stratification across three governance tiers: (i) advanced statutory architectures with mandatory waste separation, quantified recovery targets and multi-instrument enforcement, (ii) framework legislation with variable subnational implementation and (iii) early-stage disposal-oriented regulations. Japan, Singapore and South Korea demonstrate that mandatory obligations, quantified recovery targets, multi-instrument enforcement and design-stage integration are achievable outcomes of sustained regulatory development. China's framework legislation illustrates the governance risks of delegation to lower-capacity jurisdictions without accompanying institutional capacity building. India's early-stage CE governance demonstrates how bilateral policy commitments and state-level fragmentation can constrain the translation of CE aspirations into operative regulatory provisions.

SL's regulatory framework is characterised by a pre-CE legislative inheritance, institutional fragmentation and a systematic implementation deficit. The CIDA Regulations 2018 represent the only operative mandatory CE-adjacent obligation, but threshold, content orientation and monitoring provisions collectively limit governance effectiveness. The most technically sophisticated instrument the Guidelines for Green Rating of Construction Materials has negligible regulatory impact due to its voluntary character and isolation from procurement and permitting systems.

Regulatory effectiveness in CE construction governance depends not on the breadth of policy articulation but on the specificity, enforceability and institutional coherence of individual instruments. SL's existing framework contains architectural elements that could be progressively activated through regulatory amendment to close identified governance gaps, drawing on the graduated implementation models the Asian evidence base validates. As a priority, the CIDA Regulations 2018 should be reformed to lower the SWMP threshold, mandate circular material hierarchy compliance within SWMP content,

establish a national C&DW data registry and introduce meaningful penalties. CIDA's secondary regulation-making powers should be exercised to incorporate CE capability requirements into contractor registration. Finally, SL requires dedicated CE framework legislation to establish the statutory basis for mandatory C&DW recovery targets and EPR for construction materials. In establishing targets, SL should avoid pitfalls evident in China and Singapore, where volumetric recycling rates conflate high-value component reuse with aggregate crushing; recovery targets should therefore be quality-differentiated to ensure rates reflect genuine material circularity rather than perverse optimisation towards volume alone. Collectively, these governance reforms carry implications beyond SL, offering transferable lessons for developing economies where the gap between CE policy ambition and operative regulatory implementation remains a pervasive challenge.

The international comparative analysis is limited to six Asian jurisdictions, limiting the generalisability of findings beyond Asia. Within the SL analysis, the scope is restricted to Acts and Laws, excluding regulations, policies, codes and guidelines, which may contain additional CE relevant provisions. As this paper forms a part of a broader study the identified limitations directly inform the relevant phases of that research. It will extend the analytical scope to encompass the full spectrum of SL regulatory instruments and will develop a structured implementation framework for the identified governance pathways. It will also identify specific regulations, policies, codes and guidelines for enactment or amendment in SL, derived from the international instruments examined.

## 6. REFERENCES

Abeynayake, M. D. T. E., & Perera, B. A. K. S. (2025). Comparison of legislation of UK and Sri Lanka for better implementation of circular economy in Sri Lankan construction industry. In K. G. A. S. Waidyasekara, H. S. Jayasena, P. L. I. Wimalaratne, & G. A. Tennakoon (Eds.), *Proceedings of the 13th World Construction Symposium* 15-16 August 2025, Sri Lanka. (pp. 424–437). https://doi.org/10.31705/WCS.2025.32

Ahmed, S., Majava, J., & Aaltonen, K. (2024). Implementation of circular economy in construction projects: a procurement strategy approach. *Construction Innovation, 24*(7), 204–222. https://doi.org/10.1108/CI-12-2022-0327

Anastasiades, K., Dockx, J., van den Berg, M., Rinke, M., Blom, J., & Audenaert, A. (2023). Stakeholder perceptions on implementing design for disassembly and standardisation for heterogeneous construction components. *Waste Management and Research, 41*(8). https://doi.org/10.1177/0734242X231154140

Ballardini, R. M., Kaisto, J., & Similä, J. (2020). Developing novel property concepts in private law to foster the circular economy. *Journal of Cleaner Production, 279, 1372-1381*. https://doi.org/10.1016/j.jclepro.2020.123747

Bimsara, K. D. M., Abenayake, D. N., Lingasabesan, V., & Shanika, V. G. (2024). Adopting circular economy practices in major building materials and elements to minimise waste in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, & H. Chandanie (Eds.), *12th World Construction Symposium* 9-10 August 2024, Sri Lanka. (pp. 105–118). https://doi.org/10.31705/WCS.2024.9

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal, 9*(2), 27–40. https://doi.org/10.3316/QRJ0902027

Calisto Friant, M., Vermeulen, W. J. V., & Salomone, R. (2021). Analysing European Union circular economy policies: Words versus actions. *Sustainable Production and Consumption, 27*, 337–353. https://doi.org/10.1016/j.spc.2020.11.001

CBSL. (2024). GDP - National Accounts Estimates - 2024. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/statistics/national_account_estimates_2024_annual_e.pdf

CBSL. (2025). GDP - National Accounts Estimates - 1st Quarter 2025. https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/about/national_accounts_estimates_2025_q1.pdf

Charef, R. (2022). Supporting construction stakeholders with the circular economy: A trans-scaler framework to understand the holistic approach. *Cleaner Engineering and Technology*, *8*. https://doi.org/10.1016/j.clet.2022.100454

Charef, R. (2024). A digital framework for the implementation of the circular economy in the construction sector: Expert opinions. *Sustainability (Switzerland)*, *16*(14). https://doi.org/10.3390/su16145849

Corvellec, H., Stowell, A. F., & Johansson, N. (2022). Critiques of the circular economy. *Journal of Industrial Ecology*, *26*(2), 421–432. https://doi.org/10.1111/jiec.13187

De Melo, T. A. C., De Oliveira, M. A., De Sousa, S. R. G., Vieira, R. K., & Amaral, T. S. (2022). Circular economy public policies: A systematic literature review. *Procedia Computer Science*, *204*, 652–662. https://doi.org/10.1016/j.procs.2022.08.079

Ghisellini, P., & Ulgiati, S. (2020). Circular economy transition in Italy: Achievements, perspectives and constraints. *Journal of Cleaner Production*, *243*. https://doi.org/10.1016/j.jclepro.2019.118360

Gowsiga, M., Ramachandra, T., Sridarran, P., & Thurairajah, N. (2023). Principles of circular economy for building sector: A systematic review. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, T. Ramachandra, & K. A. T. O. Ranadewa (Eds.), *Proceedings of the 11th World Construction Symposium*, 21-22 July 2023, Sri Lanka. (pp. 885-899). https://doi.org/10.31705/WCS.2023.71

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, *130*. https://doi.org/10.1016/j.rser.2020.109948

Kagioglou, M., Cooper, R., Aouad, G., Hinks, J., Sexton, M., & Sheath, D. (1998). A generic guide to the design and construction: Process protocol. University of Salford. https://pure.hud.ac.uk/en/publications/a-generic-guide-to-the-design-and-construction-process-protocol

Kuzma, E. L., Sehnem, S., Lopes de Sousa Jabbour, A. B., & Campos, L. M. S. (2022). Circular economy indicators and levels of innovation: An innovative systematic literature review. *International Journal of Productivity & Performance Management*, *71*(3), 952-980.https://doi.org/10.1108/IJPPM-10-2020-0549

Kyriakopoulos, G. L. (2021). Environmental legislation in european and international contexts: Legal practices and social planning toward the circular economy. *Laws*, *10*(1). https://doi.org/10.3390/laws10010003

Ministry of Housing & Construction, & Construction Industry Development Authority. (2020). National policy on construction. https://www.cida.gov.lk/content/files/acts/272)%20NATIONAL%20POLICY%20ON%20CONSTRUCTION%20ENGLISH.pdf

Steenmans, K., & Lesniewska, F. (2023). Limitations of the circular economy concept in law and policy. *Frontiers in Sustainability*, *4*. https://doi.org/10.3389/frsus.2023.1154059

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2021). Circular economy: Challenges and opportunities in the construction sector of Kazakhstan. *Buildings*, *11*(11). 501. https://doi.org/10.3390/buildings11110501

Victar, H. C., & Waidyasekara, K. G. A. S. (2024). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management and Research*, *42*(11), 953–976. https://doi.org/10.1177/0734242X231206988

Weerakoon, T. G., Wimalasena, S., & Zvirgzdins, J. (2023). Assessment of implementation of circular economy framework in the Sri Lankan construction sector. *Baltic Journal of Real Estate Economics and Construction Management*, *11*(1), 133–152. https://doi.org/10.2478/bjreecm-2023-0009

Wijewansha, A.S., Tennakoon, G.A., Waidyasekara, K.G.A.S., & Ekanayake, B. J. (2021). Implementation of circular economy principles during pre-construction stage: The case of Sri Lanka. *Built Environment Project and Asset Management*, *11*(4), 750–766. https://doi.org/10.1108/BEPAM-04-2020-0072

Wijesinghe, A., Jayasinghe, C., Jayasinghe, M. T. R., Perera, A., Rajapaksha, R. M. K. U., & Ranasinghe, W. M. D. N. (2022). Guidelines for green rating of construction materials in Sri Lanka. https://www.cida.gov.lk/content/files/publications/directives/Guidelines%20for%20Green%20Rating%20of%20Construction%20Materials%20in%20sri%20lanka.pdf

Yu, Y., Junjan, V., Yazan, D. M., & Iacob, M. E. (2022). A systematic literature review on circular economy implementation in the construction industry: A policy-making perspective. *Resources, Conservation and Recycling*, *183*. https://doi.org/10.1016/j.resconrec.2022.106359

Mendis, E., Thayaparan, M. and Lellupitiya, D., 2026. Schoolyards as built infrastructure: A feasibility framework for closing environmental education implementation gaps. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1541-1555. DOI: https://doi.org/10.31705/WCS.2026.112. Available from: https://ciobwcs.com/papers/

# SCHOOLYARDS AS BUILT INFRASTRUCTURE: A FEASIBILITY FRAMEWORK FOR CLOSING ENVIRONMENTAL EDUCATION IMPLEMENTATION GAPS

**Eshadi Mendis[1], M. Thayaparan[2], Dumina Lellupitiya[3]**

## *ABSTRACT*

*Environmental education (EE) is widely promoted as a response to climate change, biodiversity loss, and sustainability challenges, with schools identified as critical settings for fostering children's engagement with nature. However, despite increasing policy attention and expanding initiatives, the implementation of school-based environmental education remains fragmented and difficult to sustain. This paper argues that these limitations are not primarily pedagogical, but structural, institutional, and spatial, rooted in the everyday built and institutional environments of schools. Drawing on a narrative literature review of school-based environmental education initiatives, the study synthesises reported implementation challenges and organises them into six systemic categories: Professional Capacity Gap, Institutional Integration Gap, Learning Design–Accessibility Gap, Socio-Cultural and Equity Gap, Programme Design–Context Gap, and Evaluation and Evidence Gap. These challenges reveal persistent gaps between environmental education ambitions and the operational, organisational, and spatial realities of schools. In response, the paper presents two connected conceptual frameworks. The first establishes a conceptual enabling conditions framework with six conditions: Realistic Time Demand, Embedded Whole-School Practice, Student-Friendly Learning Design, Context-Responsive Inclusion, Locally Feasible Programme Design, and Observable Practice-Based Evidence, which function as a feasibility filter. The second translates these conditions into built-environment applications, positioning schoolyards and everyday school spaces as strategic infrastructure for sustained engagement with nature. The paper offers a practical lens for educators, school leaders, built-environment professionals, and policymakers to plan, evaluate, and scale more feasible and context-responsive environmental education initiatives.*

***Keywords:*** *Built Environment; Environmental Education; Implementation Feasibility; Nature Engagement; Schoolyards*

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, mendisapen.25@uom.lk
[2] Professor in Building Economics, Department of Building Economics, University of Moratuwa, Sri Lanka, mthayaparan@uom.lk
[3] Senior Lecturer, Education Administration and Development, Faculty of Educational Leadership Development and Management, National Institute of Education, ddlellupitiya@nie.edu.lk

# 1. INTRODUCTION

Environmental education (EE) is increasingly positioned as a core response to climate change, biodiversity loss, and long-term sustainability challenges (Akinsemolu & Onyeaka, 2025; Olsson et al., 2016). Schools are frequently identified as critical settings for fostering environmental awareness and encouraging children's engagement with the natural world (Christ et al., 2022). In this context, schoolyards and outdoor spaces are highlighted for their potential to support experiential and place-based learning (Hamilton & Marckini-Polk, 2023).

Despite this recognised potential, environmental education initiatives in schools frequently remain fragmented, short-lived, or peripheral to core educational practice. Many EE programmes rely on external funding, individual champions, or short-term projects, limiting their ability to become embedded within routine school life (Hamalosmanoğlu & Varinlioğlu, 2019; Sulsberger, 2018). Although existing research documents a wide range of EE practices and learning outcomes, considerably less attention has been paid to why such initiatives struggle to persist within everyday school environments (Hamilton & Marckini-Polk, 2023).

From a built environment perspective, schools are not neutral spaces for learning (Arghiani & Shakeri, 2021). They are complex systems shaped by spatial layouts, infrastructure provision, timetabling constraints, and institutional routines. These conditions directly influence how spaces, including schoolyards, are used and prioritised. Environmental education is often treated as an add-on, insufficiently aligned with the physical and organisational systems that govern everyday school operations (Nabirye, 2025).

In this study, school-based environmental education is framed as a feasibility challenge grounded in schools' built and institutional environments. This focuses particularly on schoolyards as routinely accessible spaces. This study asks: Under what conditions can environmental education and children's engagement with nature be realistically embedded and sustained within everyday school contexts? By addressing this question, this paper positions the built environment as a central consideration in environmental education planning.

# 2. METHODOLOGY

A narrative literature review (Baethge et al., 2019) was conducted to examine implementation challenges in school-based environmental education (EE) involving school-aged populations. Narrative reviews are widely used across disciplines to synthesise existing knowledge, identify recurring patterns, and support the development of conceptual frameworks (Baethge et al., 2019). The purpose of this review was to develop a conceptually grounded understanding of the conditions that influence the feasibility of embedding environmental education within everyday school environments, particularly through schoolyards, which are routinely accessible learning spaces. In addition to identifying systemic implementation challenges, the review also aimed to translate these conditions into built-environment applications that could support the practical operationalisation of environmental education within everyday school settings.

The literature search was conducted using Scopus, Web of Science, and Google Scholar. These databases were selected to ensure broad disciplinary coverage across

environmental education, sustainability education, school-based learning, and built environment research. The review focused on literature published between 2015 and 2025 to ensure relevance to contemporary environmental education practices, particularly in the context of the adoption of the Sustainable Development Goals (SDGs) in 2015 (Cai & Wolff, 2023).

Searches were performed using combinations of keywords including "environmental education", "education for sustainable development", "school-based environmental education", "implementation challenges", "barriers", "feasibility", "schoolyards", "outdoor learning", "children's connection with nature", "schoolyard design", "learning infrastructure", and "built environment".

Studies were included where they explicitly discussed implementation-level challenges affecting environmental education practices within schools, including both formal curricular and non-formal school-based initiatives. Attention was given to constraints related to programme planning, delivery, adaptation, continuity, and institutionalisation. Studies focused exclusively on higher education, the preschool level, programs outside the school system or non-school-based were excluded. Articles not available in English were also excluded.

An inductive thematic coding approach (Braun & Clarke, 2006) was used to identify recurring implementation patterns across the selected studies. Initially, specific implementation challenges directly reported in the literature were coded and organised into six challenge categories (Table 1). These categories were subsequently interpreted as holistic implementation gaps as presented in Table 1. Building on these gaps, a set of conceptual enabling conditions (Figure 1) was developed to articulate how environmental education, particularly nature-based engagement through schoolyards, could be feasibly embedded within routine school environments.

A second stage of abductive conceptual synthesis (Awuzie & McDermott, 2017) was then undertaken to develop the second framework (Table 2), and each enabling condition was examined through a built-environment lens to identify the spatial and infrastructural characteristics most likely to support its practical implementation.

Accordingly, this review adopts a conceptual and design-oriented approach to identify the foundational conditions necessary for feasible and sustained environmental education within everyday school systems.

## 3. REPORTED IMPLEMENTATION CHALLENGES IN SCHOOL-BASED ENVIRONMENTAL EDUCATION

Across the global literature, implementation challenges in school-based environmental education (EE) are characterised by a layered set of structural, institutional, and learner-level constraints rather than isolated barriers. At the instructional level, many studies report insufficient teacher knowledge of environmental and climate issues, limited pedagogical preparation for experiential or inquiry-based learning, and low confidence in facilitating outdoor or action-oriented activities (Cudworth, 2020; Hartley et al., 2023). These capacity gaps are compounded by heavy workloads, administrative pressures, and exam-driven accountability systems, which significantly restrict the time and flexibility required for environmental and outdoor learning (Boeve-de Pauw et al., 2019; Heras et

al., 2020; Wellman et al., 2025). As a result, even where teacher motivation exists, EE is often deprioritised within everyday classroom practice.

These instructional constraints are reinforced by rigid curricular structures and inadequate school-level resources (Masson et al., 2025). Across contexts, curricula are frequently described as overcrowded, academically oriented, and resistant to cross-curricular integration (Aguilar-Jurado et al., 2019; Walshe et al., 2023). This limits opportunities to meaningfully embed EE. Many schools also lack the physical infrastructure, green spaces, equipment, laboratories, ICT access, or waste-management systems necessary to support hands-on, place-based, or citizen-science activities (Nursofah et al., 2025; Tan et al., 2024). Consequently, environmental education is often implemented as fragmented, extracurricular, or short-term interventions rather than as a sustained whole-school practice embedded within core teaching and institutional routines (Balundė & Poškus, 2025; Bissinger & Bogner, 2018).

At an organisational and policy level, the literature consistently highlights weak institutional support as a major constraint. Programmes commonly operate under unstable funding conditions, limited staffing, high staff turnover, and insufficient management capacity, undermining continuity and scalability (Hasriyanti et al., 2025; Mulders et al., 2025; Sulsberger, 2018). Policy-level gaps, including weak enforcement of environmental regulations, inconsistent national priorities, and limited commitment from education authorities, further constrain long-term integration (Trott, 2022; Zhan et al., 2019). These challenges are worsened by practical disruptions such as scheduling conflicts, examinations, school events, strikes, and shifting institutional timelines, which frequently interrupt planned activities (Collins & O'Riordan, 2022; Willis & Schmidt, 2018). Many initiatives also lack an explicit programme theory or theory of change, making it difficult to align activities with intended outcomes or to generate systematic learning from implementation (Eichinger et al., 2022; Salazar et al., 2024).

*Table 1: Mapping of the implementation challenges of environmental education practices in the global school context*

| Holistic Gaps | Implementation Challenges | Reference Examples |
|---|---|---|
| Professional Capacity Gap | IC01. Teacher Capacity Gaps | [1], [2], [3] |
| | IC02. Teacher Workload and Time Pressure | [4], [5], [6] |
| Institutional Integration Gap | IC03. Infrastructure and Resource Limitations | [7], [8] |
| | IC04. Curriculum Rigidity | [9], [10], [11] |
| | IC05. Fragmented Curriculum Integration | [12], [13] |
| | IC11. Institutional and Funding Instability | [14], [15], [16] |
| | IC22. Policy and Governance Gaps | [17], [18] |
| | IC23. Program Continuity and Logistics Disruptions | [19], [20] |
| | IC24. Weak Programme Theory | [21], [22] |
| Learning Design– | IC06. Student Cognitive and Language Barriers | [23], [24] |
| | IC07. Sustained Student Engagement Challenges | [25], [26] |

| Holistic Gaps | Implementation Challenges | Reference Examples |
|---|---|---|
| Accessibility Gap | IC19. Emotional and Affective Barriers | [27], [28], [29] |
| | IC25. Social Norms and Perceived Control Barriers | [30], [31], [32] |
| Socio-Cultural and Equity Gap | IC08. Family and Community Resistance | [33], [34] |
| | IC09. Socioeconomic Inequality and Access Gaps | [35], [36] |
| | IC10. Cultural and Power Constraints | [37], [38], [39] |
| | IC20. Knowledge System and Stakeholder Tensions | [40], [41] |
| | IC21. Limited Nature Access and Urbanisation | [42], [43] |
| Programme Design–Context Gap | IC12. Contextual Fit and Adaptation Challenges | [44], [45] |
| | IC13. Constraints on Outdoor and Field Learning | [46], [47] |
| | IC14. Technology Access and Reliability Barriers | [48], [49] |
| Evaluation and Evidence Gap | IC15. Evaluation and Data Collection Constraints | [50], [51] |
| | IC16. Impact Measurement Limitations | [52] |
| | IC17. Inconsistent Evidence Base | [53], [54] |
| | IC18. Behavioural Persistence Gaps | [55], [56] |

[1] (Díaz et al., 2020); [2] (Hartley et al., 2023); [3] (Cudworth, 2020); [4] (Wellman et al., 2025); [5] (Heras et al., 2020); [6] (Boeve-de Pauw et al., 2019); [7] (Tan et al., 2024); [8] (Nursofah et al., 2025); [9] (Masson et al., 2025); [10] (Walshe et al., 2023); [11] (Aguilar-Jurado et al., 2019); [12] (Bissinger & Bogner, 2018); [13] (Balundė & Poškus, 2025); [14] (Hasriyanti et al., 2025); [15] (Sulsberger, 2018); [16] (Mulders et al., 2025); [17] (Trott, 2022); [18] (Zhan et al., 2019); [19] (Willis & Schmidt, 2018); [20] (Collins & O'Riordan, 2022); [21] (Salazar et al., 2024); [22] (Eichinger et al., 2022); [23] (Robledo & Prudente, 2022); [24] (Repetto et al., 2024); [25] (Delmas et al., 2024); [26] (Ampuero et al., 2014); [27] (Waite et al., 2016); [28] (Cornelisse & Sagasta, 2018); [29] (Sarrasin et al., 2022); [30] (Christ et al., 2022); [31] (Kwan et al., 2017); [32] (Ampuero et al., 2013); [33] (Nahar, 2024); [34] (Phillips et al., 2024); [35] (Jaime et al., 2023); [36] (Stevenson et al., 2018); [37] (Zhang et al., 2019); [38] (Schneller et al., 2022); [39] (Hoare & Higgins, 2022); [40] (Demneh & Zackery, 2023); [41] (Collier et al., 2023); [42] (Barthel et al., 2018); [43] (Liang et al., 2025); [44] (Bergman, 2016); [45] (Ray et al., 2015); [46] (Rollwagen-Bollens et al., 2022); [47] (Chen et al., 2025); [48] (Hamdan et al., 2023); [49] (Roy et al., 2025); [50] (Nekaris et al., 2018); [51] (Hutasoit et al., 2024); [52] (Keller et al., 2022); [53] (Pongsophon, 2025); [54] (Whitburn et al., 2023); [55] (Moghadam et al., 2022); [56] (Isenaj et al., 2025)

Learner-level challenges intersect with these structural constraints. Students often struggle with abstract concepts, technical language, and unfamiliar outdoor or scientific settings, leading to reduced comprehension, confidence, and perceived relevance (Repetto et al., 2024; Robledo & Prudente, 2022). Sustaining engagement over time is particularly difficult in rural, low-income, or marginalised contexts, and during periods of disruption such as the COVID-19 pandemic (Ampuero et al., 2014; Delmas et al., 2024). Emotional responses, including climate anxiety, fear, hopelessness, and aversion to certain species, are repeatedly identified as barriers that can inhibit engagement rather than motivate action (Cornelisse & Sagasta, 2018; Sarrasin et al., 2022; Waite et al., 2016). In addition, social norms, peer dynamics, and perceived lack of control over family, community, or economic conditions often limit students' capacity to translate learning into action (Ampuero et al., 2013; Christ et al., 2022; Kwan et al., 2017).

Environmental education initiatives are further shaped by broader social and cultural contexts. Several studies report resistance or limited support from parents and local communities due to conflicting norms, misinformation, or practical constraints (Nahar, 2024; Phillips et al., 2024). Socioeconomic inequalities and long-standing underinvestment in schools reduce both the reach and equity of EE programmes (Jaime et al., 2023; Stevenson et al., 2018). Cultural beliefs, power structures, and traditional practices, such as patriarchal norms, elders' authority, hunting traditions, or consumerist values, conflict with conservation objectives and restrict youth agency (Hoare & Higgins, 2022; Schneller et al., 2022; Zhang et al., 2019). Tensions between formal and informal learning spaces, modern scientific approaches and indigenous knowledge systems, and differing stakeholder values further complicate programme design and legitimacy (Collier et al., 2023; Demneh & Zackery, 2023).

Contextual and logistical constraints also recur across regions. Urbanisation, reduced access to natural spaces, and changing lifestyles limit children's everyday contact with nature (Barthel et al., 2018; Liang et al., 2025). This weakens the baseline experiential connections. Designing programmes that are adaptable across diverse regions, cultures, age groups, and learning needs remains challenging, with materials often criticised as either too locally specific, overly theoretical, or excessively complex (Bergman, 2016; Ray et al., 2015). Outdoor and field-based activities are constrained by weather, safety concerns, travel logistics, and institutional risk aversion, while technology-based tools face barriers related to cost, device access, usability, digital literacy, and technical reliability (Chen et al., 2025; Hamdan et al., 2023; Rollwagen-Bollens et al., 2022).

Finally, the literature identifies persistent challenges in generating evidence and assessing impact. Data collection and evaluation are frequently constrained by cultural biases in instruments, delays in ethics approval, small sample sizes, weak methodological designs, and heavy analytical demands on educators and researchers (Hutasoit et al., 2024; Nekaris et al., 2018). Even where data are available, quantifying long-term impacts, such as sustained behaviour change, carbon reductions, or environmental outcomes, remains difficult (Keller et al., 2022). As a result, evidence on the effectiveness of school-based EE is often inconsistent. It often reports mixed or modest effects across knowledge, attitudes, behaviours, wellbeing, and connection to nature (Pongsophon, 2025; Whitburn et al., 2023). Many programmes struggle to move beyond short-term awareness toward durable, real-world pro-environmental practices (Isenaj et al., 2025; Moghadam et al., 2022). This underscores a persistent implementation gap in environmental education initiatives within formal school contexts globally.

# 4. CONCEPTUAL FRAMEWORK: ENABLING CONDITIONS FOR FEASIBLE ENVIRONMENTAL EDUCATION IN SCHOOLYARDS

## 4.1 FRAMEWORK OVERVIEW, SYSTEMIC LOGIC, AND FEASIBILITY LENS

To overcome the reported challenges in Chapter 3, the proposed framework conceptualises school-based environmental education as a built-environment and systems challenge rather than a programme-delivery problem. Reported implementation challenges are interpreted as manifestations of broader structural conditions that shape what schools can realistically initiate, sustain, and institutionalise within everyday practice. From this perspective, implementation difficulties are not isolated barriers but

indicators of systemic misalignments between environmental education ambitions and schools' spatial, institutional, and operational capacities.

To make these dynamics explicit, the framework synthesises reported implementation challenges into a set of holistic implementation gaps, recurring mismatches between environmental education initiatives and how schools function as routine environments. These gaps demonstrate that the persistence of implementation challenges is not due to a lack of environmental education activity but to insufficient alignment with school timetables, governance structures, pedagogical realities, socio-cultural contexts, and evaluation mechanisms (Figure 1). Rather than linking environmental education directly to learning or behavioural outcomes, the framework introduces conceptual enabling conditions as a feasibility filter. These conditions clarify the circumstances under which environmental education and routine engagement with nature can be embedded within everyday school environments, shifting attention from what environmental education aims to achieve to what schools are structurally able to sustain.

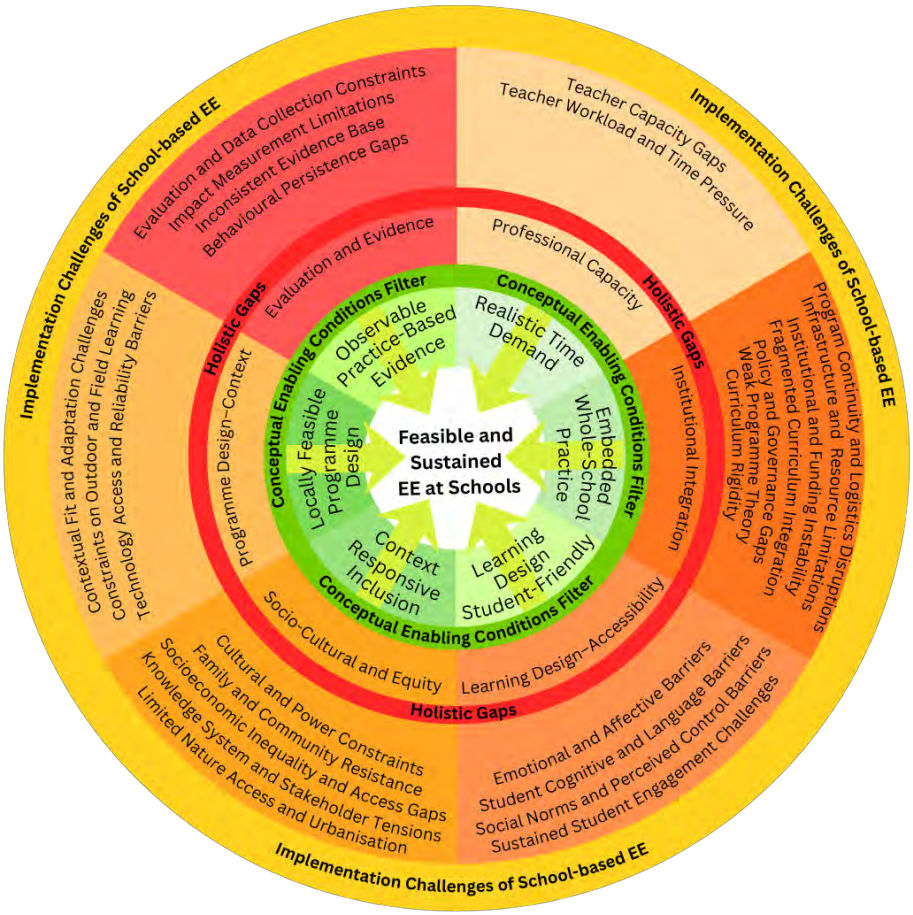



*Figure 1: Conceptual framework linking implementation challenges, systemic gaps, and enabling conditions*

Six systemic gaps were identified through the synthesis (Table 1). A Professional Capacity Gap reflects limitations in teacher knowledge, confidence, training, and workload capacity. An Institutional Integration Gap arises from rigid curricula, fragmented delivery, weak policy alignment, and limited organisational support. A Learning Design - Accessibility Gap is linked to cognitive, emotional, and engagement-

related barriers among students. A Socio-Cultural and Equity Gap is shaped by family expectations, community norms, cultural contexts, and structural inequalities. A Programme Design - Context Gap reflects poor alignment between intervention design and local spatial, infrastructural, and institutional realities. Finally, an Evaluation and Evidence Gap are associated with weak monitoring practices, inconsistent evidence, and limited feedback into decision-making processes. Together, these gaps indicate that implementation challenges persist not because environmental education is absent, but because initiatives are insufficiently aligned with the everyday functioning of schools as institutional and spatial systems.

In response, through the framework in Figure 1, this paper proposes, six corresponding conceptual enabling conditions: Realistic Time Demand, ensuring alignment with school schedules, routines, and workload constraints; Embedded Whole-School Practice, integrating environmental education into governance, culture, and daily operations rather than treating it as an add-on; Student-Friendly Learning Design, prioritising accessibility, developmental appropriateness, and emotional support; Context-Responsive Inclusion, recognising socio-cultural, ecological, and equity conditions; Locally Feasible Programme Design, aligned with available infrastructure and spatial resources; and Observable Practice-Based Evidence, generating visible outputs that support reflection, continuity, and institutional learning. These enabling conditions do not prescribe specific interventions. Instead, they articulate minimum feasibility requirements for embedding environmental education in routine school practice.

To achieve these enabling conditions, how the built environment in schools can support is worth investigating. By shifting the analytical focus from programme effectiveness to structural feasibility and offering a built-environment–informed lens for understanding, section 4.2 examines the conditions under which environmental education can be sustained within everyday school systems.

## 4.2 SCHOOLYARDS AS EVERYDAY BUILT INFRASTRUCTURE: A BUILT ENVIRONMENT TRANSLATION FRAMEWORK

The second framework (Table 2) was developed through a conceptual translation of the six enabling conditions identified in Figure 1 into built-environment applications. While Figure 1 explains the systemic conditions required for the feasibility of environmental education within formal school systems, Table 2 addresses how these conditions can be operationalised through the design, allocation, maintenance, and management of everyday school environments. This translation was informed by recurring spatial and infrastructural constraints identified across the reviewed literature.

Accordingly, Realistic Time Demand is strengthened when nature engagement is embedded within routine circulation and daily school movement rather than requiring additional travel or scheduling (Cenić et al., 2023). Embedded Whole-School Practice becomes more feasible when environmental education is integrated into maintenance systems, supervision patterns, and shared school operations (Karaarslan-Semiz & Sund, 2026). Student-Friendly Learning Design depends on safe, visible, shaded, and accessible spaces that support repeated use, while Context-Responsive Inclusion requires school environments that reflect local ecology, cultural relevance, equity, and learner diversity (Blanchet-Cohen & Reilly, 2013; van Dijk-Wesselius et al., 2020). Locally Feasible Programme Design depends on low-maintenance, infrastructure-compatible environmental learning spaces (van Dijk-Wesselius et al., 2020), while Observable

Practice-Based Evidence is strengthened by visible ecological change and student participation in environmental monitoring (Ballard et al., 2017).

Moreover, this paper argues that the schoolyards have the potential to simultaneously reduce multiple implementation barriers. As routinely accessible spaces, schoolyards minimise reliance on external logistics, reduce financial and administrative burdens, enable repeated low-cost use, and align with existing supervision arrangements and timetabling structures (van Dijk-Wesselius et al., 2020). This positions schoolyards particularly well-suited to supporting sustained engagement with natural elements within school settings (Andersen et al., 2015; Martin, 2003).

*Table 2: Conceptual built environment translation framework for feasible school-based environmental education*

| Enabling Condition | Built Environment Translation |
|---|---|
| Realistic Time Demand | Nature engagement embedded within routine circulation and daily school movement |
| Embedded Whole-School Practice | Environmental education integrated into maintenance systems, supervision patterns, and shared school operations |
| Student-Friendly Learning Design | Safe, visible, shaded, accessible, and developmentally appropriate learning spaces |
| Context-Responsive Inclusion | School spaces reflecting local ecology, cultural relevance, equity and learner diversity |
| Locally Feasible Program Design | Low-maintenance, infrastructure-compatible, and spatially practical environmental learning spaces |
| Observable Practice-Based Evidence | Visible ecological change and student participation in environmental monitoring |

In contrast to field trips, externally delivered programmes, or one-off environmental activities, which typically require additional time, funding, permissions, transport, and coordination, schoolyards function within existing institutional rhythms (Behrendt & Franklin, 2014; Bergin et al., 2024). Their integration into daily supervision, timetabling, and maintenance structures enables repetition, continuity, and cumulative learning, conditions that are difficult to achieve through sporadic interventions. Integrated green spaces and visible ecological functions also strengthen whole-school environmental practice by embedding sustainability within institutional planning, supervision, and maintenance systems (Blanc et al., 2025), while safe, shaded, and accessible outdoor environments improve student participation, emotional comfort, and developmental suitability for repeated engagement (Bergin et al., 2024; Waite et al., 2016).

However, the framework explicitly recognises that schoolyards or built environmental aspects alone are insufficient. Their capacity to support environmental education is realised only when the identified enabling conditions are in place, ensuring alignment with institutional routines, pedagogical design, socio-cultural contexts, and organisational capacity. As an example, visible biodiversity monitoring, restoration spaces, and student-led environmental observation may strengthen continuity and

institutional learning by making environmental education outcomes tangible within everyday school life (Christ et al., 2022; Howe et al., 2025; Masson et al., 2025). In this context, children's connection with nature is understood not as an abstract psychological outcome, but as regular exposure and repeated interaction with natural elements embedded within everyday school life, made possible through structurally aligned, spatially supportive, and context-responsive educational systems.

## 5. CONCLUSIONS

This paper demonstrates that the persistent challenges in school-based environmental education are not primarily pedagogical shortcomings, but reflections of deeper structural, institutional, and spatial misalignments within everyday school systems. By synthesising implementation challenges across the global literature, the study shows that environmental education often remains fragmented because it is insufficiently aligned with how schools function as built and organisational environments. In response, two connected conceptual frameworks are proposed. The first identifies six systemic implementation gaps and translates them into six enabling conditions that function as a feasibility filter for embedding environmental education and routine engagement with nature within daily school life. The second translates these enabling conditions into built-environment application principles, showing how schoolyards and everyday school spaces can support feasibility through accessible, low-maintenance, and institutionally integrated design. Positioning schoolyards as everyday built infrastructure offers a practical pathway for repeated, low-cost engagement with nature; however, their potential depends on alignment with institutional routines, pedagogical design, socio-cultural context, and organisational capacity. For the built environment field, this highlights the importance of recognising schoolyards as strategic educational assets. Future research should empirically test and refine both frameworks across diverse school contexts to support more durable and context-responsive environmental education.

## 6. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial assistance provided by the Senate Research Committee (SRC/LT/2025/07) of the University of Moratuwa, Sri Lanka, for the research on which this publication was based and for the conference presentation.

## 7. REFERENCES

Aguilar-Jurado, M. Á., Gil-Madrona, P., Ortega-Dato, J. F., & Zamorano-García, D. (2019). Effects of an educational glass recycling program against environmental pollution in Spain. *International Journal of Environmental Research and Public Health*, *16*(24), 5108. https://doi.org/10.3390/ijerph16245108

Akinsemolu, A. A., & Onyeaka, H. (2025). The role of green education in achieving the sustainable development goals: A review. *Renewable and Sustainable Energy Reviews*, *210*, 115239. https://doi.org/10.1016/j.rser.2024.115239

Ampuero, D. A., Miranda, C., & Goyen, S. (2014). Positive psychology in education for sustainable development at a primary-education institution. *Local Environment*, *20*(7), 745–763. https://doi.org/10.1080/13549839.2013.869199

Ampuero, D., Miranda, C. E., Delgado, L. E., Goyen, S., & Weaver, S. (2013). Empathy and critical thinking: primary students solving local environmental problems through outdoor learning. *Journal of Adventure Education & Outdoor Learning*, *15*(1), 64–78. https://doi.org/10.1080/14729679.2013.848817

Andersen, H. B., Pawlowski, C. S., Scheller, H. B., Troelsen, J., Toftager, M., & Schipperijn, J. (2015). Activating schoolyards: Study design of a quasi-experimental schoolyard intervention study. *BMC Public Health*, *15*, 523. https://doi.org/10.1186/s12889-015-1828-9

Arghiani, M., & Shakeri, M. (2021). The role of built environments in student interactions at school. *Armanshahr Architecture & Urban Development*, *13*(33), 1–12. https://doi.org/10.22034/AAUD.2019.155800.1734

Awuzie, B., & McDermott, P. (2017). An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, *17*(4), 356–372. https://doi.org/10.1108/QRJ-08-2016-0048

Baethge, C., Goldbeck-Wood, S., & Mertens, S. (2019). SANRA—a scale for the quality assessment of narrative review articles. *Research Integrity and Peer Review*, *4*(1), 5. https://doi.org/10.1186/s41073-019-0064-8

Ballard, H. L., Dixon, C. G. H., & Harris, E. M. (2017). Youth-focused citizen science: Examining the role of environmental science learning and agency for conservation. *Biological Conservation*, *208*, 65–75. https://doi.org/10.1016/j.biocon.2016.05.024

Balundė, A., & Poškus, M. S. (2025). Fostering interest in and support for climate change activism among adolescents. *Environmental Education Research*, *31*(12), 2609–2626. https://doi.org/10.1080/13504622.2025.2468513

Barthel, S., Belton, S., Raymond, C. M., & Giusti, M. (2018). Fostering children's connection to nature through authentic situations: The case of saving salamanders at school. *Frontiers in Psychology*, *9*, 928. https://doi.org/10.3389/fpsyg.2018.00928

Behrendt, M., & Franklin, T. (2014). A review of research on school field trips and their value in education. *International Journal of Environmental and Science Education*, *9*(3), 235–245. https://doi.org/10.12973/ijese.2014.213a

Bergin, M., Boyle, B., Lilja, M., & Prellwitz, M. (2024). Exploring with children, play in Irish primary schoolyards. *International Journal of Play*, *13*(2), 157–172. https://doi.org/10.1080/21594937.2024.2355443

Bergman, B. G. (2016). Assessing impacts of locally designed environmental education projects on students' environmental attitudes, awareness, and intention to act. *Environmental Education Research*, *22*(4), 480–503. https://doi.org/10.1080/13504622.2014.999225

Bissinger, K., & Bogner, F. X. (2018). Environmental literacy in practice: Education on tropical rainforests and climate change. *Environment, Development and Sustainability*, *20*(5), 2079–2094. https://doi.org/10.1007/s10668-017-9978-9

Blanc, N., Clauzel, C., About, C., Riché, A.-L., Gippet, M., & Bortolamiol, S. (2025). Schoolyards greening for connecting people and nature: An example of nature-based solutions? *npj Urban Sustainability*, *5*, 64. https://doi.org/10.1038/s42949-025-00252-6

Blanchet-Cohen, N., & Reilly, R. C. (2013). Teachers' perspectives on environmental education in multicultural contexts: Towards culturally-responsive environmental education. *Teaching and Teacher Education*, *36*, 12–22. https://doi.org/10.1016/j.tate.2013.07.001

Boeve-de Pauw, J., Van Hoof, J., & Van Petegem, P. (2019). Effective field trips in nature: The interplay between novelty and learning. *Journal of Biological Education*, *53*(1), 21–33. https://doi.org/10.1080/00219266.2017.1418760

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Cai, Y., & Wolff, L. A. (2023). Education and sustainable development goals. *Sustainability*, *15*, 643. https://doi.org/10.3390/su15010643

Cenić, D. S., Milosavljević Đukić, T. B., Stojadinović, A. M., & Spasić Stošić, A. D. (2023). Outdoor education: Perspectives of teachers and students in the context of school in nature as an innovative approach in education. *International Journal of Cognitive Research in Science, Engineering and Education*, *11*(3), 497–510. https://doi.org/10.23947/2334-8496-2023-11-3-497-510

Chen, C.C., Chai, M.H., & Lin, P.H. (2025). Exploring the impact of interactive multimedia e-books on the effectiveness of environmental learning, pro-environmental attitudes, and behavioural intentions

among primary school students. *Journal of Computer Assisted Learning*, *41*(4), 70087. https://doi.org/10.1111/jcal.70087

Christ, L., Hahn, M., Sieg, A. K., & Dreesmann, D. C. (2022). Be(e) engaged! How students benefit from an educational citizen science project on biodiversity in their biology classes. *Sustainability*, *14*(21), 14524. https://doi.org/10.3390/su142114524

Collier, K. M., McCance, K., Jackson, S., Topliceanu, A., Blanchard, M. R., & Venditti, R. A. (2023). Observing microplastics in the environment through citizen-science-inspired laboratory investigations. *Journal of Chemical Education*, *100*(5), 2067–2079. https://doi.org/10.1021/acs.jchemed.2c01078

Collins, C., & O'Riordan, R. (2022). Data triangulation confirms learning in the zoo environment. *Environmental Education Research*, *28*(2), 295–317. https://doi.org/10.1080/13504622.2021.1974351

Cornelisse, T. M., & Sagasta, J. (2018). The effect of conservation knowledge on attitudes and stated behaviors toward arthropods of urban and suburban elementary school students. *Anthrozoos*, *31*(3), 283–296. https://doi.org/10.1080/08927936.2018.1455450

Cudworth, D. (2020). Promoting an emotional connection to nature and other animals via forest school: Disrupting the spaces of neoliberal performativity. *International Journal of Sociology and Social Policy*, *41*(3–4), 506–521. https://doi.org/10.1108/IJSSP-09-2019-0188

Delmas, M. A., Giottonini, P., & Teng, G. (2024). Adolescents as energy conservation stewards. *Sustainable Environment*, *10*(1). https://doi.org/10.1080/27658511.2024.2408926

Demneh, M. T., & Zackery, A. (2023). You are not one, you are a thousand: Findings from a future-oriented participatory action research. *Futures*, *154*, *103245*. https://doi.org/10.1016/j.futures.2023.103245

Eichinger, M., Bechtoldt, M., Bui, I. T. M., Grund, J., Keller, J., Lau, A. G., Liu, S., Neuber, M., Peter, F., Pohle, C., Reese, G., Schäfer, F., & Heinzel, S. (2022). Evaluating the public climate school—a school-based programme to promote climate awareness and action in students: Protocol of a cluster-controlled pilot study. *International Journal of Environmental Research and Public Health*, *19*, 8039. https://doi.org/10.3390/ijerph19138039

Hamalosmanoğlu, M., & Varinlioğlu, S. (2019). The effects of argumentation activities on seventh grade students' environmental attitudes and their knowledge level. *Science Education International*, *30*(3), 158–168. https://doi.org/10.33828/sei.v30.i3.2

Hamdan, F. A., Lara-Sánchez, A. J., & Arufe-Giráldez, V. (2023). Critical thinking in environmental education through digital games among students. *Environment and Social Psychology*, *8*(2), 1725. https://doi.org/10.54517/esp.v8i2.1725

Hamilton, E., & Marckini-Polk, L. (2023). The impact of place-based education on middle school students' environmental literacy and stewardship. *Cogent Education*, *10*(1), 2163789. https://doi.org/10.1080/2331186X.2022.2163789

Hartley, J. M., Stevenson, K. T., Pereira, S. R., Peterson, M. N., Lawson, D. F., & Martinez, B. (2023). How a marine debris environmental education program plays to strengths of linguistically diverse learners. *Frontiers in Education*, *7*, *1058864*. https://doi.org/10.3389/feduc.2022.1058864

Hasriyanti, Ali, M. I., Malik, A., Dermawan, & Latief, M. M. (2025). Developing pro-environmental attitudes through integrated environmental education: Insights from a high school in Indonesia. *International Journal of Sustainable Development and Planning*, *20*(6), 2619–2626. https://doi.org/10.18280/ijsdp.200629

Heras, R., Medir, R. M., & Salazar, O. (2020). Children's perceptions on the benefits of school nature field trips. *Education 3-13*, *48*(4), 379–391. https://doi.org/10.1080/03004279.2019.1610024

Hoare, G., & Higgins, P. (2022). Wildlife and indigenous communities in Kenya: The influence of conservation education in supporting co-existence between wildlife and a Maasai community. *Southern African Journal of Environmental Education*, *38*, 43–60. https://doi.org/10.4314/sajee.v38i1.08

Howe, A. G., Nguyen, T. T. T., O'Connor, P., Woodward, A., Clarke, S., Ducker, N., Dilger, K., & Fagan-Jeffries, E. P. (2025). Catching 'the bug': Investigating insects through school-based citizen science increases intentions for environmental activities in students and teachers. *Austral Entomology*, *64*(2), 70004. https://doi.org/10.1111/aen.70004

Hutasoit, P. A., Saragih, R. A., Riyan, D., Christina, I., Yustiningtyas, R., Soler, J. A., & Cheyne, S. M. (2024). Communicating conservation: Evidence of knowledge gains through a children's conservation

club in Central Kalimantan, Indonesia. *Folia Primatologica*, *95*(4–6), 425–434. https://doi.org/10.1163/14219980-bja10023

Isenaj, Z. S., Moshammer, H., Berisha, M., & Weitensfelder, L. (2025). Effect of an educational intervention on pupil's knowledge, attitudes, perceptions, and behavior on air pollution in public schools in Pristina. *European Journal of Investigation in Health, Psychology and Education*, *15*(5), 69. https://doi.org/10.3390/ejihpe15050069

Jaime, M., Salazar, C., Alpizar, F., & Carlsson, F. (2023). Can school environmental education programs make children and parents more pro-environmental? *Journal of Development Economics*, *161*, 103032. https://doi.org/10.1016/j.jdeveco.2022.103032

Karaarslan-Semiz, G., & Sund, P. (2026). Whole-school approach to sustainability: an in-depth study of six green schools in Sweden and Türkiye. *Journal of Biological Education*, *60*(1), 60–83. https://doi.org/10.1080/00219266.2025.2452190

Keller, L., Riede, M., Link, S., Hüfner, K., & Stötter, J. (2022). Can education save money, energy, and the climate? Assessing the potential impacts of climate change education on energy literacy and energy consumption in the light of the EU energy efficiency directive and the Austrian Energy Efficiency Act. *Energies*, *15*(3), 1118. https://doi.org/10.3390/en15031118

Kwan, B. K. Y., Cheung, J. H. Y., Law, A. C. K., Cheung, S. G., & Shin, P. K. S. (2017). Conservation education program for threatened Asian horseshoe crabs: A step towards reducing community apathy to environmental conservation. *Journal for Nature Conservation*, *35*, 53–65. https://doi.org/10.1016/j.jnc.2016.12.002

Liang, Z., Chen, L., Ren, J., Liu, C., Zhou, K., Lee, T. M., & Hu, S. (2025). Fostering children's self-efficacy through nature education: Insights from a wildlife education program in rural China. *Integrative Conservation*, *4*(2), 154–164. https://doi.org/10.1002/inc3.70017

Martin, S. C. (2003). The influence of outdoor schoolyard experiences on students' environmental knowledge, attitudes, behaviors, and comfort levels. *Journal of Elementary Science Education*, *15*(2), 51–63. https://doi.org/10.1007/BF03173843

Masson, T., Siebert, J., Köhler, S., Fritsche, I., & Zabel, J. (2025). Citizen science goes to school: Intervention effects on biodiversity knowledge, nature relatedness, and biodiversity action in secondary school students. *Environment and Behavior*, *57*(5–6), 359–398. https://doi.org/10.1177/00139165251345383

Moghadam, N. R., Narafshan, M. H., & Anjomshoa, L. (2022). Education for sustainable development: Effects of sustainability education on English language learners' empathy and reading comprehension. *Journal of Environmental Education*, *53*(5), 280–289. https://doi.org/10.1080/00958964.2022.2107605

Mulders, M., Träg, K. H., & Kirner, L. (2025). Go green: Evaluating an XR application on biodiversity in German secondary school classrooms. *Instructional Science*, *53*(3), 429–455. https://doi.org/10.1007/s11251-024-09697-1

Nabirye, K. (2025). Integrating environmental education into school curricula. *Eurasian Journal of Humanities and Social Sciences*, *7*(3), 73–79. https://www.eejournals.org/

Nahar, L. (2024). Assessing the influence of a high school environmental project on teacher readiness across borders. In L. Nahar & N. Tayem (Eds.), *Cases on Collaborative Experiential Ecological Literacy for Education* (pp. 1–25). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-1710-5.ch001

Nekaris, K. A. I., McCabe, S., Spaan, D., Ali, M. I., & Nijman, V. (2018). A novel application of cultural consensus models to evaluate conservation education programs. *Conservation Biology*, *32*(2), 466–476. https://doi.org/10.1111/cobi.13023

Nursofah, N., Sari, E., & Supadi, S. (2025). Environmentally conscious schools through the implementation of Adiwiyata program at junior high schools in Jakarta. *Edelweiss Applied Science and Technology*, *9*(4), 2893–2904. https://doi.org/10.55214/25768484.v9i4.6697

Olsson, D., Gericke, N., & Chang Rundgren, S. N. (2016). The effect of implementation of education for sustainable development in Swedish compulsory schools – assessing pupils' sustainability consciousness. *Environmental Education Research*, *22*(2), 176–202. https://doi.org/10.1080/13504622.2015.1005057

Phillips, J. A., Rijal, B., & Tan, C. L. (2024). Changing Nepali children's attitudes toward conservation through a participatory education program. *Folia Primatologica*, *95*(4–6), 411–423. https://doi.org/10.1163/14219980-bja10035

Pongsophon, P. (2025). Cultivating environmental consciousness: Evaluating plant genetics conservation through school botany programs in Thailand. *Science & Education*, *34*(4), 2589–2616. https://doi.org/10.1007/s11191-024-00574-4

Ray, C., McKnight, D. M., Bidwell, M. D., Fourment, T., Pritz, C. F., & Rinehart, A. H. (2015). Children's book series and associated curricula support elementary education and outreach in water resources. *Plant Ecology and Diversity*, *8*(5–6), 795–804. https://doi.org/10.1080/17550874.2015.1050711

Repetto, M., Prevot, A. B., Brizio, A., Boldi, A., Talarico, M., Stanchi, S., Palma, D., & Maran, D. A. (2024). Digital escape rooms: A resource for environmental education. *Sustainability*, *16*(19), 8525. https://doi.org/10.3390/su16198525

Robledo, D. a. R., & Prudente, M. S. (2022). "A virtual fieldtrip": Effects of google earth learning activities on students' environmental values. In *IC4E 2022: 2022 13th International Conference on E-Education, E-Business, E-Management, and E-Learning* (pp. 1–8). https://doi.org/10.1145/3514262.3514293

Díaz, G., Gómez, B. C., Lomelí, D. G., & Mirón-Juárez, C. A. (2020). A Structural model of the teaching practice and Pro-Environmental behavior in Elementary Mexican students. *International Electronic Journal of Environmental Education*, *11*(1), 42–57. https://doi.org/10.18497/iejeegreen.781808

Rollwagen-Bollens, G., Holmlund, T., & Wait, J. (2022). Actively participating in university-sponsored ecological research increases high school students' knowledge of and attitudes about sciences. *Frontiers in Environmental Science*, *9*, 797769. https://doi.org/10.3389/fenvs.2021.797769

Roy, T., Sparra, H. J., Skripnikov, A., & Gilchrist, S. (2025). Fostering environmental responsibility with JellyBean: A Google Cardboard VR-based case study on cultivating awareness in middle and high school students about marine ecology and the impact of everyday pollutants. *Frontiers in Virtual Reality*, *6*, 1469409. https://doi.org/10.3389/frvir.2025.1469409

Salazar, C., Jaime, M., Leiva, M., & González, N. (2024). Environmental education and children's pro-environmental behavior on plastic waste. Evidence from the green school certification program in Chile. *International Journal of Educational Development*, *109*, 103106. https://doi.org/10.1016/j.ijedudev.2024.103106

Sarrasin, O., Henry, J. L. A., Masserey, C., & Graff, F. (2022). The relationships between adolescents' climate anxiety, efficacy beliefs, group dynamics, and pro-environmental behavioral intentions after a group-based environmental education intervention. *Youth*, *2*(3), 422–440. https://doi.org/10.3390/youth2030031

Schneller, A. J., Lacy, G., Kellogg, S., Pettigrew, S. M., Denny, C., Feldman-Schwartz, G., Beard, I., Rhodes, A., Wilson Radcliffe, B., Erickson, A., & Bardin, I. (2022). Urban ecojustice education: Transformative learning outcomes with high school service learners. *Journal of Environmental Education*, *53*(3), 127–140. https://doi.org/10.1080/00958964.2022.2063784

Stevenson, K. T., Peterson, M. N., & Bondell, H. D. (2018). Developing a model of climate change behavior among adolescents. *Climatic Change*, *151*(3–4), 589–603. https://doi.org/10.1007/s10584-018-2313-0

Sulsberger, M. J. (2018). Gathering, interpreting, and positioning children's narratives in environmental education research. *Cultural Studies of Science Education*, *13*(3), 707–732. https://doi.org/10.1007/s11422-018-9867-z

Tan, X. Y., Cheng, K. M., Chong, C. W., & Koo, A. C. (2024). Edcraft: Gamified handicrafts as an inspiration for teenagers to practice upcycling. *Australian Journal of Environmental Education*, *40*, 758–769. https://doi.org/10.1017/aee.2024.44

Trott, C. D. (2022). Climate change education for transformation: Exploring the affective and attitudinal dimensions of children's learning and action. *Environmental Education Research*, *28*(7), 1023–1042. https://doi.org/10.1080/13504622.2021.2007223

van Dijk-Wesselius, J. E., van den Berg, A. E., Maas, J., & Hovinga, D. (2020). Green schoolyards as outdoor learning environments: Barriers and solutions as experienced by primary school teachers. *Frontiers in Psychology*, *10*,2919. https://doi.org/10.3389/fpsyg.2019.02919

Waite, S., Goodenough, A., Norris, V., & Puttick, N. (2016). From little acorns.: Environmental action as a source of well-being for schoolchildren. *Pastoral Care in Education*, *34*(1), 43–61. https://doi.org/10.1080/02643944.2015.1119879

Walshe, N., Perry, J., & Moula, Z. (2023). Eco-capabilities: Arts-in-nature for supporting nature visibilisation and wellbeing in children. *Sustainability*, *15*(16), 12290. https://doi.org/10.3390/su151612290

Wellman, R. L., Henderson, A., Coleman, R., Hill, C., & Davey, B. T. (2025). Assessment of a youth climate empowerment program: Climate READY. *Geoscience Communication*, *8*(1), 1–46. https://doi.org/10.5194/gc-8-1-2025

Whitburn, J., Abrahamse, W., & Linklater, W. (2023). Do environmental education fieldtrips strengthen children's connection to nature and promote environmental behaviour or wellbeing? *Current Research in Ecological and Social Psychology*, *5*, 100163. https://doi.org/10.1016/j.cresp.2023.100163

Willis, A., & Schmidt, F. (2018). Amplifying John Muir's life: A third sector intervention in providing alternative narrative resources to secondary schools. *Environmental Education Research*, *24*(7), 1050–1061. https://doi.org/10.1080/13504622.2017.1344192

Zhan, Y., He, R., & So, W. W. M. (2019). Developing elementary school children's water conversation action competence: A case study in China. *International Journal of Early Years Education*, *27*(3), 287–305. https://doi.org/10.1080/09669760.2018.1548346

Zhang, W., Zhao, J., & Chen, J. (2019). Nature club programs promote adolescents' conservation behavior: A case study in China's biodiversity hotspot. *Journal of Environmental Education*, *50*(3), 192–207. https://doi.org/10.1080/00958964.2019.1604480

Kiridana, Y.M.W.H.M.R.R.L.J.B. and Abeynayake, M.D.T.E., 2026. Significance of joint venture enterprises for the development of the construction industry of Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1556-1568. DOI: https://doi.org/10.31705/WCS.2026.113. Available from: https://ciobwcs.com/papers/

# SIGNIFICANCE OF JOINT VENTURE ENTERPRISES FOR THE DEVELOPMENT OF THE CONSTRUCTION INDUSTRY OF SRI LANKA

**Y.M.W.H.M.R.R.L.J.B. Kiridana[1] and M.D.T.E. Abeynayake[2]**

## *ABSTRACT*

*Developing economies rely on technology acquisition and innovation to build capacity, yet Sri Lanka's construction industry lags due to an over-reliance on traditional procurement over equity-based Joint Venture Enterprises (JVEs). While firms use contractual joint ventures to execute large-scale infrastructure projects, the unique benefits of JVEs remain underutilized. This study explores the drivers, benefits, operational barriers, and selection criteria for implementing efficient JVEs in Sri Lanka. Using a mixed-method approach, the research contextualized international literature through three semi-structured expert interviews, followed by a quantitative survey of 30 industry professionals. Qualitative data were evaluated via Content Analysis, while quantitative data were ranked using the Relative Importance Index (RII). The analysis reveals that safeguarding investments (RII = 0.7633) is the primary motivator for choosing a JVE over a contractual alternative. The most significant industry benefits identified are making complex projects feasible (RII = 0.8333) and facilitating technology transfer (RII = 0.8133). However, the model faces severe headwinds: an unstable economic situation (RII = 0.807) and a lack of specific foreign investment laws (RII = 0.767) emerged as the top operational barriers. The study concludes that JVEs are highly effective instruments for expanding local capacity in the construction sector. To unlock this potential and encourage equity-based joint venture participation, the study recommends targeted legislative adjustments to protect and incentivize foreign and domestic investors.*

***Keywords:*** *Business Organizations; Construction Industry; Development Economy; Joint Venture Enterprises.*

## 1. INTRODUCTION

The construction industry is widely recognized as one of the most complex, dynamic, and unpredictable environments to manage effectively (Dushie, 2011). Globally, the sector has frequently been plagued by adversarial relationships, recurring disputes, and poor coordination among diverse stakeholders. These fragmented working relationships significantly disrupt the overall competitiveness, productivity, and delivery efficiency of construction projects (Rooke et al., 2014). Schaufelberger (2023) noted that primary

[1] Quantity Surveyor, Planning, HKN JV, Sri Lanka, ravindu.hkn@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, mabeynayake@uom.lk

drivers of construction firm failures include capital inadequacy, deficient managerial expertise, unfamiliarity with new operating environments, and inadequate cost-control mechanisms. Concurrently, the globalization of markets and the increasing centralization of procurement have expanded project scales, effectively restricting small and medium-sized enterprises (SMEs) from participating independently (Shen & Cheung, 2018).

To mitigate these risks and access emerging market opportunities, construction organizations are increasingly adopting collaborative procurement frameworks (Ozorhon & Altun, 2017). According to Mohamed (2001), the joint venture (JV) approach is an essential mechanism for construction firms aiming to enter foreign markets or undertake projects that exceed their individual capacities. The growing complexity, scale, and financial risk profiles of modern infrastructure projects require entities with distinct, complementary strengths to form alliances to bid and execute works collectively (Kumaraswamy et al., 2020). A joint venture represents a partnership, co-operation, or business enterprise established by two independent entities to pool resources, share risks, and generate long-term mutual profit (Kale et al., 2023).

While JVs offer substantial advantages, they are traditionally deemed high-risk structures due to the inherent uncertainties of the construction sector (Adnan, 2018). In developing countries, international construction JVs have experienced rapid growth as local industries attempt to build internal capabilities, absorb modern technology, and encourage domestic innovations (Ponomariov & Toivanen, 2014). However, the Sri Lankan construction industry has not progressed at the same pace as other developing nations. The adoption of progressive, alternative procurement systems has historically been neglected or underutilized (Rathnasabapathi & Rameezdeen, 2017). Furthermore, while project-specific, non-integrated contractual joint ventures are common in Sri Lanka, the establishment of permanent, integrated equity-based Joint Venture Enterprises (JVEs) remains virtually non-existent in the domestic construction sector.

Previous domestic research has predominantly focused on short-term project risk-sharing, basic technology transfer, or contractual disputes within project-specific JVs (Ozorhon & Altun, 2017). There is an explicit empirical gap concerning the strategic necessity, institutional benefits, and operational viability of formalized equity JVEs within Sri Lanka. To bridge this research gap, this study establishes the following Research Questions (RQs):

**RQ1:** What are the primary influential factors that drive construction organizations to select a formalized JVE structure over traditional contractual JVs in Sri Lanka?

**RQ2:** What clear benefits do JVEs offer to the local construction industry, and what primary barriers impede their operational success?

**RQ3:** What key criteria should guide partner selection and operational management for JVEs to achieve long-term viability?

Consequently, the Aim of this research is to investigate the strategic significance and operational feasibility of implementing efficient Joint Venture Enterprises (JVEs) to foster the long-term capacity development and sustainability of the construction industry in Sri Lanka.

# 2. LITERATURE REVIEW

## 2.1 TYPOLOGY AND DEFINITIONS OF JOINT VENTURES IN CONSTRUCTION

The construction sector is a core engine of macroeconomic growth, contributing substantially to a nation's Gross Domestic Product (GDP) and driving broader developmental goals such as infrastructure expansion, technical employment, and engineering modernization (Athukorla, 2024; Sivakumaran et al., 2025). Within this sector, a joint venture grouping is defined as a collaborative business partnership formed by two or more independent entities to combine engineering, consulting, procurement, and management expertise to deliver specialized project scopes (Yu et al., 2017). JVs function as strategic alliances that enable organizations to merge complementary assets, spread financial liabilities, and leverage shared experiences (Ozorhon, 2007).

Legally, joint venture arrangements are divided into three primary categories: contractual (or combination) JVs, partnership JVs, and corporate JVs, the latter involving the formal creation of an independent limited liability company (Kwok et al., 2016). In construction management literature, these are broadly categorized into two operational structures: integrated JVs and non-integrated JVs (Hong & Chan, 2014). Non-integrated or contractual JVs are short-term, project-specific alliances where partners remain independent and simply execute designated portions of the work. Conversely, integrated JVs—alternatively defined as Joint Venture Enterprises (JVEs) or equity JVs—involve the establishment of a legally distinct, jointly owned corporate entity where partners invest capital, share equity, and collectively manage long-term organizational decisions (Zhang & Zou, 2017).

## 2.2 GLOBAL DRIVERS AND STRUCTURAL CONFIGURATIONS OF JVES

JVEs as a highly effective entry strategy to penetrate restricted or foreign infrastructure markets (Chen & Messner, 2019; Sillars & Kangari, 2024). Compared to basic licensing agreements or loose contractual partnerships, JVEs provide a significantly more robust governance structure for transferring complex, tacit knowledge and advanced management frameworks between international and domestic partners (Famakin et al., 2012; Mellewigt & Das, 2020). Empirical studies demonstrate that the choice of a JV's governance structure is heavily influenced by the nationality and institutional backgrounds of the participating partners.. Alliances involving cross-border multi-national participants display a stronger propensity to formalize into equity-based JVEs to align asymmetric legal backgrounds, whereas firm age does not significantly alter this governance choice (Gulati, 1995).

A formalized JVE model arises when two or more legally independent entities co-invest capital, facilities, heavy machinery, intellectual property rights, and labor into a newly incorporated entity, participating actively in unified corporate governance (Ho et al., 2019). JVE configurations are classified based on equity distribution as majority-owned, equal-equity, or minority-owned enterprises; however, operational control and decision-making authority do not always correlate linearly with equity ownership percentages (Chen & Messner, 2009).

Historically, the strategic deployment of equity JVEs has yielded massive macroeconomic benefits. For example, Norwood and Mansfield (1999) documented that the structured implementation of JVE regulations in China was the foundational catalyst

that allowed the nation to attract unprecedented levels of Foreign Direct Investment (FDI). These corporate JVEs, structured as limited liability entities, protected international capital while ensuring that risks, profits, and technical knowledge were equitably shared on a platform of mutual economic benefit. Equity JVEs provide the stable organizational environment required to foster collaborative research and development, mitigate systemic market risks, and help emerging domestic contractors expand their operational scale by partnering with established multinational corporations (Contractor et al., 2012; Mathu, 2014; Oxley & Wada, 2019).

### 2.3 HOST-GOVERNMENT MOTIVES AND PROJECT PERFORMANCE: DRIVING ECONOMIC DEVELOPMENT IN SRI LANKA'S CONSTRUCTION SECTOR

In developing economies, the modernization of the construction sector is inextricably linked to socioeconomic progression (Kolbehdari & Sobhiyah, 2024). Governments frequently look to shape the institutional framework of joint ventures to achieve strategic economic outcomes, such as enhancing local productivity, updating local supply chains, and generating sustainable employment (Silah, 2017). Research indicates that from a contractor's perspective, JVE integration is heavily customer-driven. Client bodies increasingly favor equity-backed consortia because integrated operations deliver demonstrably higher rates of project success, improved cost-containment, superior safety compliance, and enhanced post-handover innovation compared to fragmented contractual combinations (Akintoye & Main, 2017).

Furthermore, from a risk management perspective, long-term infrastructure developments require highly stable collaborative structures. By housing major risks within a capitalized corporate entity, the long-term liabilities associated with complex or multigenerational construction concessions (such as Public-Private Partnerships) are effectively distributed and contained, protecting individual partner organizations from catastrophic single-project failures (Cheatham, 2024). Consequently, understanding the unique operational characteristics, partner selection parameters, and baseline institutional benefits of JVEs is a critical step toward implementing successful regulatory and corporate frameworks within a developing context like Sri Lanka (Mathu, 2014).

## 3. RESEARCH METHODLOGY

### 3.1 RESEARCH DESIGN AND SAMPLE JUSTIFICATION

To fulfill the research, aim and address the empirical questions comprehensively, this study adopted a mixed-method research design. Relying strictly on foreign literature was insufficient, as joint venture performance is highly dependent on regional socio-economic dynamics and local legal frameworks (Mathu, 2014; Tang et al., 2010). By combining qualitative and quantitative data, this study achieves methodological triangulation, which is highly recommended in construction management research to minimize individual method biases and capture the operational complexities of multi-partner projects (Creswell & Creswell, 2018; Fellows & Liu, 2015). Therefore, a two-stage empirical approach was implemented:

- **Stage 1: Qualitative Expert Interviews:** Structured around an interview guideline derived from the literature review, semi-structured interviews were conducted with three (3) hand-picked senior construction experts in Sri Lanka. The selection criteria required the experts to have a minimum of 15 years of

corporate experience in managing large-scale, multi-partner infrastructure projects or public procurement frameworks in Sri Lanka. This approach aligns with the principles of purposive expert sampling, where sample size is secondary to information richness; selecting elite participants with deep, specialized experience ensures the generation of high-quality data (Bogner et al., 2009; Patton, 2015). The primary purpose of these interviews was to scrutinize the factors identified in the global literature, contextualize them to the unique landscape of Sri Lankan procurement, and identify localized barriers.

- **Stage 2: Quantitative Questionnaire Survey:** The findings and validated factors resulting from the content analysis (Krippendorff, 2018) of the expert interviews were used to design a comprehensive survey questionnaire. The questionnaire was distributed via purposive sampling to industry professionals (project managers, client representatives, quantity surveyors, and directors) with direct experience in local or international joint venture projects within Sri Lanka. In specialized industrial research, targeting an "informed population" via purposive sampling is crucial to ensure that respondents possess genuine, direct operational exposure, thereby safeguarding data reliability (Tongco, 2007). A total of thirty (30) fully completed questionnaires were collected and used for quantitative statistical ranking. Under the tenets of the Central Limit Theorem, a sample size of $N \ge 30$ represents the recognized threshold where the distribution of sample means approaches normality, validating the statistical integrity of the descriptive ranking model within this niche domain (Field, 2018; Hogg et al., 2015).

### 3.2 DATA ANALYSIS: CONTENT ANALYSIS AND RELATIVE IMPORTANCE INDEX (RII)

The qualitative data gathered from the expert interviews were evaluated using Content Analysis to extract core contextual themes and refine the operational variables. For the quantitative data collected from the 30 survey respondents, statistical analysis was executed using Microsoft Excel. To determine the perceived importance and rank the variables across the categories (influencing factors, benefits, partner criteria, and operational barriers), the Relative Importance Index (RII) was calculated for each factor using a standard 5-point Likert scale. The RII formula applied is RII = Sum(W) / (A * N), where W represents the weighting given to each factor by the respondents (ranging from 1 for 'Very Low Importance' to 5 for 'Very High Importance'), A represents the highest weight available (i.e., 5 in this study), and N represents the total number of respondents within the sample size (i.e., 30). The resulting RII values range from 0 to 1, with higher values indicating greater significance and priority among the surveyed construction industry professionals.

## 4. DATA ANALYSIS AND DISCUSSION

The collection of data commenced with an expert survey, which is intended to accomplish the objectives of the study. The interviews were conducted with three professionals who are currently working in the construction industry in Sri Lanka. For the expert interview, data were collected using an interview guideline consisting of five sections. Finally, the findings of the expert interviews were analysed using content analysis. The questionnaire was generated based on the literature findings and the semi-structured interviews conducted. The collected data were analysed by the RII method using Microsoft Excel

spreadsheet software. A questionnaire survey collected data from 30 respondents who had knowledge and experience in joint venture projects in Sri Lanka.

The influencing factors for choosing JVEs in Sri Lanka were identified through a literature review and expert interviews. The comprehensive questionnaire survey was used to rank certain identified factors according to their level of significance. The five-point scale was used to determine the significance of the influencing factors identified. The findings of the questionnaire related to its significance are summarized in Table 1. According to the responses of professionals, Table 1 illustrates the influencing factors for choosing JVEs in Sri Lanka. As per RII values, the main influential factor in choosing JVEs is safeguarding the investments. Since JVEs have a formal structure, partners seek.

*Table 1: Significance of the influencing factors for choosing JVEs*

| Influencing Factors | RII | Rank |
|---|---|---|
| Partners seek to safeguard their investments through JVEs | 0.7633 | 1 |
| Foreign investment, which increases the foreign equity | 0.7123 | 2 |
| Technological experience of partners | 0.7123 | 2 |
| Partners' limited managerial skills and risk-sharing issues. | 0.6712 | 4 |
| Provides access to certain capabilities without requiring a straightforward acquisition. | 0.6533 | 5 |
| Minimizing difficulties for Contractual JV partners | 0.5819 | 6 |
| Clients chose JVE due to liability concerns, lack of permanence, JV partners' challenges | 0.6612 | 7 |

Several advantages and benefits of JVEs in Sri Lanka were identified through a literature review and expert interviews. The findings of the questionnaire survey related to the significance of the benefits of JVEs are summarized in Table 2. According to the professionals, Table 2 represents the significance of the advantages and benefits of JVE. RII values indicate that complex projects are made feasible and possible as a major and significant benefit. The second most significant benefit is that local companies can expand into foreign markets. The third most significant benefit is improved technology transfer. The fourth most significant benefit is the improvement of mechanisms in the industry. Potential risk reduction, maximizing the strengths among partners, improved cost control, and a great degree of inter-organizational interaction were all in a similar range of values. Minimize competition and improve the chances of securing the projects. Simplicity in management makes it easy to handle the project when compared to contractual JVs. Less overhead costs can enhance profit and are identified as the least significant benefits.

*Table 1: Significance of benefits of JVEs*

| Benefits of JVE | RII | Rank |
|---|---|---|
| Complex projects are made feasible | 0.8333 | 1 |
| Local companies can expand into foreign markets | 0.8267 | 2 |
| Improved Technology Transfer | 0.8133 | 3 |
| Industry Improvement of Mechanism | 0.8000 | 4 |
| Potential risk reduction | 0.7733 | 5 |
| Maximize the strengths among partners | 0.7533 | 5 |
| Improved Cost Control | 0.7533 | 5 |
| Great degree of inter-organisational interactions | 0.7467 | 8 |
| Improved safety Performance | 0.7200 | 9 |
| Simple management which brings ease on controlling the project when comparing to Contractual JVs | 0.6800 | 12 |
| Less overhead costs can enhance profit. | 0.6800 | 12 |

Several partner selection criteria for JVEs in Sri Lanka were identified through a literature review and expert interviews. The detailed questionnaire survey was used to rank those identified factors according to their level of significance to fulfill the fourth objective of this research. The five-point scale was used to determine the importance of the identified factors. The findings of the questionnaire survey related to the significance of JVE partner selection factors are summarized in Table 3. According to the professionals, Table 3 represents the significance of the JVE partner selection criteria. As for RII values, the most significant factor to consider when selecting a JVE partner is technology. The second most significant factor is management skills. The third most significant factor is improved finance. The fourth most significant factor is construction resources. Access to materials and supplies, plants and equipment, local knowledge, and size and reputation are ranked in fifth, sixth, seventh, and eighth places, respectively, with a similar range of RII values. And the nationality of a potential partner is identified as the least significant factor of concern.

*Table 3: Significance of JVE partner selection factors*

| JVE partner selection criteria | RII | Rank |
|---|---|---|
| Technology | 0.830 | 1 |
| Management skills | 0.827 | 2 |
| Finance | 0.820 | 3 |
| Construction resources | 0.813 | 4 |
| Access to materials/supplies | 0.773 | 5 |
| Plant and Equipment | 0.760 | 6 |
| Local knowledge | 0.753 | 7 |

| JVE partner selection criteria | RII | Rank |
|---|---|---|
| Size/reputation | 0.7200 | 8 |
| Nationality of a potential partner | 0.6800 | 9 |

Several factors affecting JVE operations were identified through literature review and expert interviews. The detailed questionnaire survey was used to rank those identified factors according to their level of significance to fulfil the fourth objective of this research. The five-point scale was used to find the importance of the identified factors. The findings of the questionnaire survey related to the significance of JVE operation factors are summarized in Table 4. As per the professionals, Table 4 represents the Significance of the factors which are affecting JVE operations. As per RII values, the most significant factor affecting JVE operations is the unstable economic situation. The second most significant factor affecting JVE operations is Lack of adequate foreign investment laws. Insufficient infrastructures and unsatisfactory working procedures of the government are the third most significant factors of JVE operations. Issues regarding the returning income and Domestic market restrictions implemented by the government are the least significant factor to which affecting JVE operations which have RII values within a similar range.

*Table 4: Significance of JVE operation factors*

| Factors affecting JVE operations | RII | Rank |
|---|---|---|
| Unstable economic situation | 0.807 | 1 |
| Lack of adequate foreign investment laws | 0.767 | 2 |
| Insufficient infrastructures | 0.760 | 3 |
| Unsatisfactory working procedures of the government | 0.760 | 4 |
| Issues regarding the returning income | 0.727 | 5 |
| Domestic market restrictions implemented by the government | 0.720 | 6 |

Previous studies have demonstrated the strategic importance of Joint Venture Enterprises in attracting foreign investment, facilitating technology transfer, enhancing project performance, and supporting market expansion (Chen & Messner, 2009; Hamimah, 2004; Akintoye & Main, 2007; Mathu, 2014). Through the expert survey, it was revealed that the JVEs could be used to tackle the contractual JV issues. Chen and Messner (2009) reported that equity-based Joint Venture Enterprises are widely adopted to facilitate foreign direct investment and market entry, while Contractor et al. (2012) emphasized their role in reducing operational risks and enhancing knowledge transfer. Similarly, Mathu (2014) highlighted that JVEs support technology acquisition and long-term organizational development. The findings of the present study validate these observations within the Sri Lankan context, where safeguarding investments emerged as the most influential factor influencing the adoption of JVEs. . This was validated through the findings from the expert and questionnaire surveys, and the main influential factor in choosing JVEs was identified as liability concerns to safeguard the investments. It was found out that significant benefits of JVEs about the Sri Lankan context are that complex projects are made feasible and possible, market expansions, improved technology transfer, and industry improvement mechanisms. And other benefits are as follows:

potential risk reduction, maximizing the strengths among partners, improved cost control, a great degree of inter-organisational interactions, minimizing competition, and improving the chances of securing the projects. JVEs projects can be handled more easily than contractual JVs since they have a simple management procedure and, compared to contractual JVs, have fewer overhead costs.

Silah (2017) reported that governments promote joint ventures to increase construction capital availability, enhance industry competitiveness, facilitate technology diffusion, and stimulate broader economic development. However, the findings of this study suggest that, in Sri Lanka, greater emphasis is placed on protecting local contractors and strengthening domestic managerial capabilities. . From that, the motive to encourage the development of an internationalized economy was not validated through the expert survey, and the motive to protect local contractors was identified in the expert survey. localrt survey identifies the main motives for setting up JVs by the Sri Lankan government to protect the local contractors and introduce advanced management skills to the local firms. It is identified that the government's main motive is to protect the Sri Lankan community.

Further, the study reveals that JVEs are fitting for a developing country like Sri Lanka. JVEs could be used to improve economic development since they could fulfil certain needs within the local economy. The key barriers identified in the survey when implementing JVE are cultural and social differences, strategy formation, legal factors, differences in perceptions of values, and mutual trust. Further, the expert survey identifies the parameters that are needed to assess the success of JVE performance, apart from the general parameters of construction projects such as the efficiency of decision-making, the arrangement of financial arrangements within the JV, how the JV will react after a certain time period after the project completion, dispute resolution, and client satisfaction.

## 4.1 KEY FINDINGS

The preceding analysis identified several critical insights regarding the implementation of Joint Venture Enterprises in Sri Lanka. The following section summarizes the principal findings derived from the expert interviews and questionnaire survey.

- Primary Motive for Choosing JVEs - Construction partners choose a formalized, equity-backed JVE over a loose contractual combination primarily to safeguard their investments (RII = 0.7633), seeking the robust asset and liability protection that a distinct corporate entity provides.
- Top Industry Benefits - The most significant advantages realized through JVEs are making complex mega-projects operationally feasible (RII = 0.8333), enabling local firms to expand into foreign markets (RII = 0.8267), and facilitating improved technology transfer (RII = 0.8133). Critical Partner Selection Criteria-Industry professionals prioritize tangible operational assets over corporate demographics, ranking a potential partner's technology (RII = 0.830$), management skills (RII = 0.827), and financial capacity (RII = 0.820) as critical, while nationality (RII = 0.680) is the least important.
- Severe Operational Barriers - The implementation of JVEs faces intense macro-environmental headwinds, led by an unstable economic situation (RII= 0.807), a lack of adequate foreign investment laws (RII = 0.767), and unsatisfactory government working procedures (RII= 0.760).

- Divergence in Host-Government Motives - While international literature claims governments push for joint ventures to build an *internationalized economy* (which was not validated locally), the Sri Lankan government's true motives are protecting domestic contractors from foreign market dominance, introducing advanced management frameworks to local firms, and protecting the local community.
- Progressive Performance Metrics - Qualitative insights reveal that evaluating a JVE's ultimate success must look beyond basic project parameters (time, cost, and quality) to measure corporate decision-making efficiency, the health of post-handover financial arrangements, rapid dispute resolution, and long-term stability after project completion.

## 5. CONCLUSIONS

Joint ventures within the international construction sector are categorized into two primary legal forms: non-integrated contractual JVs and integrated, equity-based Joint Venture Enterprises (JVEs). Globally, modern economies favor the corporate JVE configuration to attract Foreign Direct Investment, expand local market capacities, and mitigate the severe administrative and legal fragmentations inherent in loose contractual alliances. This study confirms that the strategic deployment of JVEs is highly appropriate and necessary for a developing country like Sri Lanka. By establishing a formalized corporate structure, a JVE provides the critical investment safeguards, asset protection, and structural permanence required to attract Tier-1 foreign contractors. The empirical findings prove that JVEs make large-scale, complex infrastructure projects highly feasible, while serving as a powerful institutional engine for permanent technology transfer, capacity building, and cost-containment. These outcomes directly address and fulfil the strategic needs of the domestic economy. Therefore, JVEs can play a vital, transformative role in upgrading and modernizing the construction industry in Sri Lanka.

## 6. RECOMMENDATIONS

Based on the empirical findings, the following targeted recommendations are proposed to foster JVE practice in Sri Lanka:

- Legislative Reform for Foreign Direct Investment: The host government and relevant construction regulatory bodies (such as CIDA) must introduce modernized, clear foreign investment laws and dedicated guidelines for registering equity-based construction JVEs.
- Targeted Tax and Fiscal Policies: Introduce specific corporate tax structures and financial incentives designed to encourage foreign contractors to form equity enterprises with local SMEs, ensuring long-term knowledge retention within the local workforce.
- Local Contractor Protection Frameworks: Legislative updates must balance international participation with local industry development, ensuring that local firms retain meaningful equity positions and active management roles to prevent predatory market dominance by foreign entities.
- Strategic Shift from Cocapital and Equity JVs: Local construction firms are highly encouraged to transition from short-term contractual JVs to formalized JVE structures when pursuing mega-projects, thereby minimizing recurring operational friction,

safeguarding corporate capital, and gaining direct access to specialized international capabilities.

# 7. REFERENCES


Adnan, H. (2018). An assessment of risk management in. *Asian Social Science*, *4*(6), 99–106. https://doi.org/10.5539/ass.v4n6p99

Akintoye, A., & Main, J. (2017). Collaborative relationships in construction: The UK contractors' perception. *Engineering, Construction and Architectural Management*, *14*(6), 597–617. https://doi.org/10.1108/09699980710829049

Athukorla, R. (2024). *Casual relationship between construction activities & GDP growth in Sri Lanka* [Unpublished master's thesis]. University of Moratuwa. http://dl.lib.mrt.ac.lk/handle/123/11281

Bogner, A., Littig, B., & Menz, W. (Eds.). (2009). *Interviewing experts*. Palgrave Macmillan.

Cheatham, W. (2024). *Surety bonding joint ventures*. Construction Executive Surety Bonding.

Chen, C., & Messner, J. I. (2019). Entry mode taxonomy for international construction markets. *Journal of Management in Engineering*, *25*(1), 3–11. https://doi.org/10.1061/(ASCE)0742-597X(2009)25:1(3)

Contractor, F. J., Woodley, J. A., & Piepenbrink, A. (2012). How tight an embrace? Choosing the optimal degree of partner interaction in alliances based on risk, technology. *Global Strategy Journal*, *1*(1–2), 67–85. https://doi.org/10.1111/j.2042-5805.2011.00001.x

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Dushie, D. (2011). *Engineering and construction joint ventures: Patterns and findings from current research.* Academia. https://www.academia.edu/4247019/Engineering_and_Construction_Joint_Ventures_Patterns_and_Findings_from_Current_Research

Famakin, I. O., Aje, I. O., & Ogunsemi, D. R. (2012). Assessment of success factors for joint venture construction projects in Nigeria. *Journal of Financial Management of Property and Construction*, *17*(2), 153–165. https://doi.org/10.1108/13664381211246606

Fellows, R. F., & Liu, A. M. (2015). *Research methods for construction* (4th ed.). Wiley-Blackwell.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE Publications.

Gulati, R. (1995). Does familiarity breed trust? The implications of repeated ties for contractual choice in alliance. *Administrative Science Quarterly*, *43*, 781–814. https://doi.org/10.2307/256729

Hamimah, A. (2004). *Joint Venture in Malaysian Construction Industry, Factors Critical to Success. In D. J Greenwood (Ed.), 19th Annual ARCOM Conference, University of Brighton, 3-5 September 2003. (2, pp. 765-774). Association of Researchers in Construction Management.* https://www.researchgate.net/publication/229038798_Joint_venture_projects_in_Malaysian_construction_industry_factors_critical_to_success

Ho, S. P., Lin, Y. S., Chu, W. Y., & Wu, H. I. (2019). Model for organizational governance structure choices in construction joint ventures. *Journal of Construction Engineering and Management*, *135*(3), 518–530. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:6(518)

Hogg, R. V., Tanis, E. A., & Zimmerman, D. L. (2015). *Probability and statistical inference* (9th ed.). Pearson.

Hong, Y., & Chan, D. W. (2014). Research trend of joint ventures in construction: A two-decade taxonomic review. *Journal of Facilities Management*, *12*(2), 118–141. https://doi.org/10.1108/JFM-04-2013-0022

Kale, V. V., Patil, S. S., Hiravennavar, A. R., & Kamane, S. K. (2023). Joint venture in construction industry. *IOSR Journal of Mechanical & Civil Engineering*, 60–65. http://www.iosrjournals.org/iosr-jmce/papers/sicete(civil)-volume3/36.pdf

Kolbehdari, S., & Sobhiyah, M. H. (2024). Effects of negotiations about the formation of construction consortium on consortium successful performance in Iran's construction industry. *International Journal of Management*, *1*(5), 371–388.

Krippendorff, K. (2018). *Content analysis: An introduction to its methodology* (4th ed.). SAGE Publications.

Kumaraswamy, M., Palaneeswaran, E., & Humpherys, P. (2020). Selection matters in construction supply chain optimisation. *International Journal of Physical Distribution & Logistics Management*, *30*(7/8), 661–680. https://doi.org/10.1108/09600030010346431

Kwok, H. A., Then, D., & Skitmore, M. (2016). Risk management in Singapore construction joint ventures. *Journal of Construction Research*, *1*(2), 139–149. https://api.semanticscholar.org/CorpusID:167137533

Mathu, D. (2014, September 1). *Joint ventures: The Kenyan construction industry perspective*. LinkedIn. https://www.linkedin.com/pulse/20140901124933-64242479-joint-ventures-the-kenyan-construction-industry-perspective

Mellewigt, T., & Das, T. K. (2020). Alliance structure choice in the telecommunications industry: Between resource type and resource heterogeneity. *International Journal of Strategic Change Management*, *2*(2/3), 128–144. https://doi.org/10.1108/978-1-68123-502-820251010

Mohamed, S. (2001). Performance of international construction joint ventures: An empirical analysis. *First International Conference on Construction in the 21st Century*.

Moskalev, S. A., & Swensen, R. B. (2017). Joint ventures around the globe from 1990–2000: Forms, types, industries, countries and ownership patterns. *Review of Financial Economics*, *16*(1), 29–67. https://doi.org/10.1016/j.rfe.2006.07.002

Norwood, S. R., & Mansfield, N. R. (1999). Joint ventures in construction: Common causes of failure. *Construction Management and Economics*, *17*(2), 215–222. https://doi.org/10.1080/014461999371727

Oxley, J., & Wada, T. (2019). Alliance structure and the scope of knowledge transfer: Evidence from U.S.–Japan agreements. *Management Science*, *55*(4), 635–649. https://doi.org/10.1287/mnsc.1080.0968

Ozorhan, B. (2007). *Modeling the performance of international construction joint ventures* [Doctoral dissertation, Middle East Technical University]. Middle East Technical University Open Archive. https://etd.lib.metu.edu.tr/upload/12608945/index.pdf

Ozorhon, B., & Altun, H. (2017). Investigation of the effect of cultural fit in international construction joint venture performance. *Digest 2017*, 2097–2115. http://ankara.imo.org.tr/resimler/ekutuphane/pdf/17886_20_34.pdf

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE Publications.

Ponomariov, B., & Toivanen, H. (2014). Knowledge flows and bases in emerging economy innovation systems: Brazilian research 2005–2009. *Research Policy*, *43*(3), 588–596. https://doi.org/10.1016/j.respol.2013.09.002

Rathnasabapathi, S., & Rameezdeen, R. (2017). A decision support system for the selection of best procurement system in construction. *Built-Environment Sri Lanka*, *7*(2), 43–53. https://doi.org/10.4038/besl.v7i2.1943

Rooke, J., Seymour, D., & Fellows, R. (2014). Planning for claims: An ethnography of industry culture. *Construction Management and Economics*, *22*(6), 655–662. https://doi.org/10.1080/014461904200026324

Schaufelberger, J. (2023). Causes of subcontractor business failure and strategies to prevent failure. *Proceedings of Construction Research Congress – Wind of Change: Integration and Innovation*. https://doi.org/10.1061/40671(2003)71

Shen, L., & Cheung, S. O. (2018). How forming joint ventures may affect market concentration in construction industry? *International Journal of Construction Management*, *18*(2), 151–162. https://doi.org/10.1080/15623599.2017.1301026

Silah, K. K. (2017). *Factors influencing utilization of International Joint Venture partnership: A case of urban renewal housing project at Ngong road estate, Nairobi country, Kenya* (Thesis). University of Nairobi.

Sillars, D. N., & Kangari, R. (2024). Predicting organizational success within a project-based joint venture alliance. *Journal of Construction Engineering and Management*, *130*(4), 500–508. https://doi.org/10.1061/~ASCE!0733-9364~2004!130:4~500!

Sivakumaran, S., Perera, B. K., & Perera, T. (2025). Construction management as a suitable procurement method for hotel building construction in Sri Lanka. *19th Pacific Association of Quantity Surveyors Congress 2025*. ResearchGate.

https://www.researchgate.net/publication/317328658_Construction_Management_as_a_Suitable_Procurement_Method_for_Hotel_Building_Construction_in_Sri_Lanka

Tang, W., Qiang, M., Duffield, C. F., Young, D. M., & Lu, Y. (2010). Risk management in the Chinese construction industry. *Journal of Construction Engineering and Management*, *136*(12), 1277–1286. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000237

Tongco, M. D. C. (2007). Purposive sampling as a tool for informant selection. *Ethnobotany Research and Applications*, *5*, 147–158. http://hdl.handle.net/10125/227

Yu, Z., Lu, C., & Chan, D. M. (2017). Review of joint venture studies in construction. *ICCREM 2017*, 139–149. https://doi.org/10.1061/9780784481080.017

Zhang, G., & Zou, P. W. (2017). Fuzzy analytical hierarchy process risk assessment approach for joint venture construction projects in China. *Journal of Construction Engineering and Management*, *10*, 771–779. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:10(771)

Tharmitha, A., Jayasinghe, G.Y., Prabodani, M.K.M., Anojan, K. and Halwatura, R.U., 2026. Simulation-based evaluation of energy performance in adaptive reuse of historic buildings across different climatic zones of Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1569-1582. DOI: https://doi.org/10.31705/WCS.2026.114. Available from: https://ciobwcs.com/papers/

# SIMULATION-BASED EVALUATION OF ENERGY PERFORMANCE IN ADAPTIVE REUSE OF HISTORIC BUILDINGS ACROSS DIFFERENT CLIMATIC ZONES OF SRI LANKA

**A. Tharmitha[1], G.Y Jayasinghe[2], M.K.M. Prabodani[3], K. Anojan[4] and R.U. Halwatura[5]**

## *ABSTRACT*

*Adaptive reuse involves reusing historical structures without demolishing or reconstructing while preserving cultural and heritage values. In Sri Lanka, colonial-era buildings have been converted to modern purposes; their post-reuse energy performance remains measured. This study evaluates the impact of adaptive reuse on energy performance across three climatic zones in Sri Lanka, Jaffna (dry), Galle (intermediate) and Nuwara Eliya (wet) using Autodesk Revit 2025 Insight simulation. It aims to (a) Analyse architectural, material and functional changes (b) Quantify Energy use intensity (EUI), and (c) Propose strategies to maximize energy efficiency without compromising heritage integrity. Field data were modelled for pre- and post-modification phases to analyse EUI and end-use components (cooling, lighting and equipment). Comparative simulations generated retrofit recommendations. Results indicate EUI increased in adaptive-reuse buildings. In Jaffna EUI increased from 29.96 to 78.24 kWh/m²·year, and reduced to 42.54 kWh/m²·year after retrofit. In Galle, EUI increased from 28.87 to 67.72 kWh/m²·year, and decreased to 38.5 kWh/m²·year after retrofitting. In Nuwara Eliya, the EUI increased from 22.90 to 39.83 kWh/m²·year, and reduced to 30.5 kWh/m²·year after retrofit. The difference between the pre- and post-modification EUI was highest in the dry-zone case, followed by the intermediate zone, while the wet-zone case exhibited the lowest increase, due to climatic conditions, material replacement and purpose of the building. The findings show that poorly designed adaptive reuse, particularly enclosed spaces and light partitions, can increase cooling-related energy demand by 30-50% in dry and intermediate regions. Energy-efficient retrofit strategies can reduce energy consumption in such buildings.*

***Keywords :*** *Adaptive Reuse; Energy Performance; Energy Use Intensity (EUI); Historical Buildings; Sri Lanka.*

---

[1] Undergraduate Student, Department of Agricultural Engineering and Environmental Technology, Faculty of Agriculture, University of Ruhuna, tharmialagan24@gmail.com.
[2] Dean, Faculty of Agriculture (Department of Agricultural Engineering and Environmental Technology), University of Ruhuna, jayasinghe@ageng.ruh.ac.lk.
[3] PhD Student, Civil Engineer, Department of Civil Engineering, University of Moratuwa, methsi.praba@gmail.com.
[4] PhD Student, Department of Civil Engineering, University of Moratuwa, anojanslma@gmail.com.
[5] Professor, Department of Civil Engineering, University of Moratuwa, rangikauh@gmail.com.

# 1. INTRODUCTION

Buildings are important parts of daily life and society, providing shelter, cultural identity, and economic value. Yet, the building sector is a major source of environmental problems. It accounts for nearly 39 % of global energy-related Green House gas (GHG) emissions, with approximately 28 % arising from operational energy use for heating, cooling, and lighting, and 11 % from embodied emissions during construction (Slavkovic & Stephan, 2025). Reducing both operational and embodied energy is therefore central to achieving climate-resilient and sustainable built environments. Adaptive-reuse is the process of repurposing existing buildings for new functions while preserving their cultural and architectural value provides a more sustainable option to demolition and new construction. By extending a building's lifespan, adaptive reuse conserves embodied energy and minimizes material waste, saving up to 95 % of embodied energy otherwise lost during reconstruction (De Silva et al., 2019). It also supports the circular-economy approach by reducing landfill waste and resource demand (Rodrigues & Freire, 2017).

The global application of adaptive reuse has revealed considerable benefits for both the environment and the economy. Strategies like upgrading insulation, optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems, and incorporating renewable technologies can successfully lower operational expenses and cut carbon emissions (Rodrigues & Freire, 2017). For example, post-retrofit studies from Europe and the Middle East document reductions in carbon emissions of up to 60%, alongside major gains in energy efficiency (Jaber et al., 2025; Ruparathna et al., 2016). These findings underscore the power of adaptive reuse to advance sustainable urban development without sacrificing cultural continuity.

In Sri Lanka, the reuse of Dutch-era and British-era heritage buildings has become increasingly common in urban centres such as Galle, Jaffna, and Nuwara Eliya. Many of these colonial structures have been converted into residences, offices, restaurants, and museums, yet few have been systematically assessed for their energy performance. A comparative evaluation by Thirukumaran et al. (2024) found that reused Dutch-era buildings exhibited reduced cooling demand due to high thermal mass, but very limited detailed studies have been done. Despite growing interest in adaptive reuse, most Sri Lankan research focuses on architectural conservation or economic feasibility rather than simulation-based performance evaluation. In this regard, this research uses Autodesk Revit 2025 Insight (Energy Plus engine) in the analysis of EUI prior to and after adaptive reuse of selected historic buildings in three climatic conditions, which include Jaffna (dry), Galle (intermediate) and Nuwara Eliya (wet). The investigation measures the effects of the operations energy, breaks down significant end-use elements, such as cooling, lighting, equipment, and generates climate responsive retrofit suggestions that ought to enhance energy performance without interfering with heritage integrity. This research assesses the effects of adaptive reuse on operational energy performance of historic buildings in Sri Lanka's climatic zones, and identifies the key factors driving EUI variability with climate-responsive retrofits. This study contributes existing research by offering a BIM-based comparative study of adaptive reuse across diverse climatic zones, expressing pre- and post-energy performance, and showing that adaptive reuse can increase operational energy demand in the absence of climate-responsive design.

## 2. LITERATURE REVIEW

The ability to enable continued use of the existing structures and at the same time reducing demolition waste and protecting cultural heritage has made adaptive reuse an even greater factor in sustainable built environment development. Adaptive reuse prolongs the life of the buildings and mitigates environmental effects that are normally experienced in new constructions (Bullen & Love, 2011; Tam & Hao, 2019). Reutilizing the existing buildings will save a significant amount of embodied energy that is stored in the building materials and thus will contribute to the preservation of sustainable resource management and act in line with the principles of the circular economy (Foster, 2020).

Some of the researches emphasized that adaptive reuse would not only ensure the preservation of heritage value, but also represents an imperative means of achieving the sustainable development aims. Being more economical in terms of the use of new materials, as well as construction waste, and environmental impact as compared to demolition and building construction, conservation and reutilization of existing buildings reduce the demand (Rodrigues & Freire, 2017). Furthermore, adaptive reuse projects can also strengthen the urban regeneration and cultural preservation by keeping the historically significant buildings in modern urban environments (Penića et al., 2015; Vidyullatha et al., 2023). Older buildings are often characterized by special architectural and climatic design qualities that enable passive thermal control. Classical architectural design features, including mass masonry, high ceilings, courtyards, and covered openings, improve thermal stability and reduce the changes in the indoor temperature (Martínez-Molina et al., 2016). Such passive design measures have historically developed to meet the local climatic conditions prior to the use of mechanical cooling systems which became common. Natural ventilation and orientation of buildings are conclusive in thermal comfort and energy saving in warm and humid climates (Haase & Amato, 2009). Many of the colonial and historic buildings in the tropical areas such as Sri Lanka were built with materials and architectural characteristics that are natural in promoting passive cooling. Lime mortar structures, clay or limestone structures of construction and elevated roofing structures facilitate increased heat loss and air circulation in interiors. These conventional design methods can play a significant role in maintaining the interior thermal comfort without necessarily relying on mechanical systems (Ariyarathna et al., 2023). As a result, old buildings converted into modern purposes can demonstrate quite an efficient energy saving when the properties of passive design are preserved.

However, the adaptive reuse of heritage buildings comes with a number of technical and regulatory issues. Historical authenticity is often restrained by conservation laws on significant structural changes or technological modernizations. Due to this, the introduction of the new technologies, related to energy efficiency, like photovoltaic arrays, facade insulations, or glazing changes, can be limited in the case of a heritage building (Conejos et al., 2016). These restrictions will hinder achieving the desired level of energy-efficiency and still maintaining the architectural integrity of historic structures. The balance between the conservation needs and the modern lived-in needs is another important issue in the adaptive reuse projects. Modifications to old structures that have been converted to other purposes, i.e. offices, hotels or commercial buildings may be in need of some extra services like air conditioning, lighting and mechanical systems. These changes may increase the operation energy consumption in case the passive design elements are not combined with the contemporary building services (Ruparathna et al.,

2016). It follows that all retrofit interventions should be carefully planned so that they can upgrade the energy performance without jeopardizing heritage values.

Energy performance analysis has now been an essential tool in measuring the sustainability of adaptive reuse projects. With the tools of energy simulation, researchers are able to assess energy consumption in different design conditions and retrofit approaches of buildings. The popularity of Building Information Modelling (BIM), software applications like Autodesk Revit, have been used to address this purpose because of the ability to produce elaborated three-dimensional models including building geometry, material characteristics, occupancy, and climatic information (Abdullah & Hatem, 2023). The combination of simulation tools, including Autodesk Insight, and BIM models allows estimating such energy indicators as the yearly energy consumption and EUI. These instruments provide useful information on the effects of the differences in design of changes on the energy performance of buildings (Veerendra et al., 2024). The simulation-based analysis makes it possible to consider alternative retrofit strategies and find solutions that would improve energy efficiency and maintain conservation restrictions. The use of simulation techniques in the past has been used to compare the energy performance of adaptive reuse buildings to their modern equivalent. The results show that historic buildings can do as well (or even better) than modern structures when the passive design features are prudently maintained (Thirukumaran et al., 2024). Specifically, the thermal mass of thick masonry walls can be used to balance the temperature inside buildings and can decrease the cooling energy consumption during warm seasons.

Despite such observations, the performance of adaptive reuse buildings in terms of operational energy may vary depending on many factors, such as climatic conditions, retrofit design plans, and building orientation as well as the urban environment. In urban areas, the geometry of streets, the surrounding buildings, and shading may have a significant influence on the exposure of the sun and ventilation of the air (Perera et al., 2025). Thus, the adaptive reuse building should be assessed in various climatic regions and architectural settings to be able to properly estimate the actual energy efficiency of these buildings. Despite the fact that many articles shedding light on the environmental and cultural advantages of adaptive reuse are available, there is still a gap in the literature that assesses the energy performance of adaptive reuse in diverse climatic conditions. Most studies carried out previously are rather a qualitative discussion of heritage conservation than a quantitative analysis of the building energy performance (Martínez-Molina et al., 2016). This gap shows the need to have a study which would combine conservation values with stringent energy performance assessment.

All in all, the literature that is available demonstrates that adaptive reuse has a great potential of improving sustainability in the built environment. Adaptive reuse is able to participate in the sustainable building development by conserving embodied energy, passive design of climatic strategies and the use of modern energy analysis tools. Nevertheless, additional studies are inevitable to determine the impact of various retrofit measures on energy performance in heritage buildings especially in the tropical climatic conditions like Sri Lanka.

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN AND ANALYTICAL FRAMEWORK

The research paper uses a simulation-based comparative analysis methodology (quantitative) to determine the operational energy consequences of adaptive reuse in three climatic zones in Sri Lanka (Dry, Intermediate, Wet). To separate the effects of functional transformation and envelope modification an experimental pre- post modelling approach was used. The EUI was defined as the primary performance metric, expressed in kWh/m²·year. The methods were consistent as all the models were simulated under identical conditions of the boundary. The general methodological workflow can be seen in Figure 1.

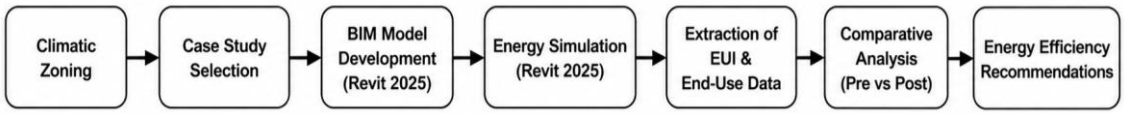



*Figure 1: Overall methodological workflow*

## 3.2 CLIMATIC ZONING AND CASE STUDY SELECTION

Three historically significant buildings were carefully selected to represent Sri Lanka's major different climatic zones to demonstrate both pre and post modification phases of adaptive reuse. One heritage building in adaptive reuse was chosen in each of the three zones: Jaffna (Dry Zone), Galle (Intermediate Zone), and Nuwara Elisha (Wet Zone) (Dissanayake et al., 2024). The three case studies were chosen based on methodological scope, climate zone representation, and data access. Each has been modelled as pre- and post-reuse (six models in total). The small sample size allows for in-depth analysis and consistency, while capturing the diversity of Sri Lanka's Dry, Intermediate, and Wet climate zones with accessible and well-documented changes. While the case studies feature various forms of adaptive reuse, the approach guarantees comparative validity by controlling simulation information (climate, occupant, material and operational settings). The study focuses on relative energy performance changes (before and after the reuse) rather than absolute comparison across buildings. This normalised approach enables a valid comparison using Energy Use Intensity (EUI) despite differences in the nature and scale of retrofit interventions. Because:

- They are located under different climatic zones.
- Their site-specific characteristics are suitable for proposing strategies to meet heating and cooling demands.
- The buildings' any of the elements have undergone the adaptive reuse concept by having modifications.

A summary of the case study buildings is presented in Table 1 : Summary of case study of Buildings.Table 1.

*Table 1 : Summary of case study of Buildings.*

| Climatic Zone | Code | Location And Building Name | Original Function | Adapted Function |
|---|---|---|---|---|
| Dry zone | A (A1/A2) | Jaffna - Rusichatti Restaurant | Residential(A1) | Restaurant(A2) |

| Climatic Zone | Code | Location And Building Name | Original Function | Adapted Function |
|---|---|---|---|---|
| Intermediate Zone | B (B1/B2) | Galle -National Fort Museum | Warehouse(B1) | Museum(B2) |
| Wet Zone | C (C1/C2) | Nuwara Eliya- Post office | Post Office(C1) | Post-Office (C2) |

## 3.3 FIELD DATA COLLECTION

Primary data were gathered using on-site measurements, architectural documents, photographic survey, and structured interviews among the stakeholders. The data that were captured were building size, wall thickness, roof structure, window area to wall, orientation, space zoning, occupancy time, and adaptive changes. Archival drawing and standardized material databases were used as a secondary source to get thermal property assignment data.

## 3.4 MODEL DEVELOPMENT

BIM of the three case-study buildings used were developed using Autodesk Revit 2025 to reflect the pre and post modification stages of the building. The models were made out of on-site observations, architectural measurements, surveys with photos, and interview with the stakeholders organized on site visits. The geometry of the building, assemblies of the envelope, orientation and functional zoning of each model were reproduced to be representative of the physical characteristics of the buildings. The thermal properties, such as conductivity (k), density (rho), and specific heat capacity (c) have been allotted based on the values that have been reported in the literature sources and on the standardized databases of materials. The post-modification models included new envelope materials and spatial designs that indicate the adaptive reuse interventions. The relevant architectural and spatial modifications under the pre- and post-modification conditions are shown in Table 2, and typical BIM models of the structures are shown in Figure 4, Figure 3 and Figure 2.

*Table 2 :Pre-modification conditions and adaptive reuse interventions in the selected case-study buildings.*

| Building Code – Location- Climatic Zone | Pre Modification Condition | Adaptive Reuse Modifications (Post-Modification Condition) |
|---|---|---|
| Building A Jaffna – Dry Zone | A one storey residential building with an open plan design. | Vertical subdivision was used to create an upper floor made of timber; an enclosed space was created on the upper floor using gypsum-board partitioning; an aluminium-framed door was installed with whiteboard paneling, and a staircase was created using wood. |
| Building B Galle – Intermediate Zone | Five limestone columns hold the interior of a big, undivided warehouse. | The interior space was divided with the help of timber and gypsum-board partitioning; a compartment with the basement was made out of cement; a space with a two-storey area was divided with a help of a wooden floor and staircase; and eight extra columns were made out of concrete in order to strengthen the structure of the modified roofline. |

| Building Code – Location- Climatic Zone | Pre Modification Condition | Adaptive Reuse Modifications (Post-Modification Condition) |
|---|---|---|
| Building C Nuwara Eliya – Wet Zone | The interior of the post office is large and has little internal partitions. | Divans were put in place internally in the corridors with partition walls of aluminium and fitted with whiteboard panels to create enclosed office spaces. |

*Figure 2 : Building A*

*Figure 4: Building B*

*Figure 3 : Building C*

## 3.5 SIMULATION PLATFORM AND CONFIGURATION

Autodesk Revit 2025 in combination with Insight (with the computational engine of Energy Plus (v23.1.0)) was used to carry out energy simulations. The workflow that was built on the BIM reduced the error amount in geometry translations and guaranteed the congruence in the result of architectural modelling and the thermal simulation process. The selection of weather files of the ISD-TMYx library was carried out based on the climatic similarity: Karaikal (Jaffna), Colombo Bandaranaike (Galle), and Sapporo (proxy Nuwara Eliya).

*Table 3 : Key simulation parameters*

| Parameter | Specification |
|---|---|
| Simulation Engine | Energy Plus v23.1 |
| Software Platform | Revit 2025 + Insight |
| Lighting & Equipment Loads | Insight default |
| HVAC Setpoints | Standardized comfort range |
| Infiltration Rates | Default values |

## 3.6 ENERGY SIMULATION

To guarantee that pre- and post-modification situations could be compared, simulations were carried out using standardised internal load conditions. The operational schedules were determined based on observations on the field and are summarised in Table 4.

*Table 4 : Orientation, function and occupancy schedule*

| Building Code | Orientation | Floor Area ($m^2$) | Function | Operating Schedule |
|---|---|---|---|---|
| A1 | 15° E of N | 91.65 | Residential | 24 h/day |
| A2 | 15° E of N | 91.65 | Restaurant | 12 h/day, 7 days/week |
| B1 | East | 246.86 | Warehouse | 24 h/day |
| B2 | East | 246.86 | Museum | 9 h/day, 5 days/week |
| C1 | 9° S of E | 966.50 | Post Office | 9 h/day, 5 days/week |

| Building Code | Orientation | Floor Area (m²) | Function | Operating Schedule |
|---|---|---|---|---|
| C2 | 9° S of E | 966.50 | Post Office | 9 h/day, 5 days/week |

## 3.7 ENERGY PERFORMANCE AND COMPARATIVE ANALYSIS

The sum of energy used in the building was obtained. Those results are based on available historical details and simulation data. The values before modification were confirmed through research and conversations with users. However, the post-modification results could vary depending on how the building is used in practice and the local weather conditions. "Energy use intensity (EUI)" can be calculated by using the following,

$$EUI=\frac{Total\ Energy\ Consumption\ (kWh/year)}{Gross\ Floor\ Area\ (m^2)} \quad (01)$$

where, EUI = Energy Use Intensity (kWh/m²·year)

This software has the facility to give a building's energy in "Kilo Watts per square meter (kWh/m$^2$)" as a summary at the end of each simulation. This will help in the comparative analysis of each building regarding the different usage purposes, different materials used for the modifications and climatic conditions. Comparative metrics were defined as follows,

$$\Delta EUI = EUI_{post} - EUI_{pre}\left(\frac{kWh}{m^2}\cdot year\right) \quad (02)$$

where, $\Delta EUI$= change in energy use intensity (kWh/m²·year)
$EUI_{post}$= EUI after adaptive reuse
$EUI_{pre}$= EUI before adaptive reuse

$$\Delta\% = \frac{(EUI_{pre}-EUI_{post})}{EUI_{pre}} \times 100\% \quad (03)$$

*where,*
*$\Delta\%$ = percentage change in energy performance (%)*
*$EUI_{post}$ = EUI after adaptive reuse*
*$EUI_{pre}$ = EUI before adaptive reuse*

These parameters measure absolute and relative change of energy performance after it is changed and hence ease in evaluation of effectiveness of the adaptive reuse strategies applied. In visual interpretation, the comparison of graphs was used to explain the difference in the EUI of various climatic regions and building typologies. The comparative analysis of the three climatic zones showed the sensitivity of variation in EUI to temperature variations, material properties, and functions of a building, hence demonstrating the effect of adaptive reuse interventions on energy.

## 3.8 INSIGHT BASED PARAMETRIC ANALYSIS

The third insight is an analysis based on parameters which is informed by insight. The parametric evaluation of envelope performance, glazing ratios, and the scenario of system efficiency was performed in Revit Insight to determine the possible ways to improve the energy-efficiency level.

## 3.9 RETROFIT SCENARIO DEVELOPMENT

Retrofit strategies were identified, based on the key energy drivers from the post-modification simulations, for each climatic zone. In Jaffna (dry zone), measures involved

passive cooling (insulation, shading, glazing, and reduced air conditioning). In Galle (intermediate zone), strategies included reducing heat gain, improving ventilation, humidity control, and daylighting. In Nuwara Eliya (wet zone), measures targeted daylight and lighting efficiency. These were modelled and evaluated with the primary performance indicator being Energy Use Intensity (EUI).

### 3.10 MODEL ASSUMPTIONS AND VALIDATION

The simulations were all performed using the standardized HVAC setpoints, lighting loads and infiltration assumptions. Field observations were used to obtain occupancy schedules. Since the reliable historical utility data were not available, the formal calibration was not realized; consequently, the results are uncalibrated but internally consistent comparative simulations. This research assesses operational energy performance using simulation-derived Energy Use Intensity (EUI), which is the predominant energy demand during building operation, especially in tropical regions. Embodied energy (materials and construction) is not considered due to lack of detailed life-cycle information. Thus, the results represent operational energy performance only. In spite of these shortcomings, the managed simulation platform offers a strong foundation on the analysis of adaptive reuse measures under climatic condition.

## 4. RESULTS AND DISCUSSION

### 4.1 RELIABILITY OF SIMULATION OUTPUTS

Autodesk Revit 2025 using Insight workflow based on Energy Plus simulation engine was used to simulate energy performance (Deepa et al., 2008). Just like in any model-driven method, the sensitivity of predicted values is related to assumptions on occupancy schedules, equipment/lighting power densities, HVAC operation, material thermal properties and choice of weather file. Thus, the values of EUI in the reports are to be understood as more comparative performance trends between stages and climatic regions instead of precise metered consumption. The results represent operational energy performance, not including embodied energy.

### 4.2 PRE AND POST MODIFICATION ENERGY PERFORMANCE

The simulated energy performance was conducted using Autodesk Revit 2025 with Insight to evaluate the impact of adaptive reuse in three climatic regions in Sri Lanka (Dry Zone (Jaffna), Intermediate Zone (Galle) and Wet Zone (Nuwara Eliya). Energy Use Intensity (EUI) and annual energy consumption were taken as the key measures to compare pre-modification, post-modification, and optimised retrofit situations. Table 5 gives the simulated energy variables of the three case studies. It was noted that all buildings had a significant rise in the operational energy intensity following the reuse, primarily through the addition of mechanical cooling and additional lighting load related to compartmentalization of the building interiors.

*Table 5 : Simulated energy performance indicators for pre- and post-modification phases.*

| Parameter | A1-Pre | A2-Post | B1-Pre | B2-Post | C1-Pre | C2-Post |
|---|---|---|---|---|---|---|
| EUI (kWh/m²·yr) | 29.96 | 78.24 | 28.87 | 67.72 | 22.90 | 39.83 |
| Total energy (kWh/yr) | 2,746.8 | 7,170.3 | 7,123.5 | 16,716.2 | 22,131.0 | 38,492.1 |

| Parameter | A1-Pre | A2-Post | B1-Pre | B2-Post | C1-Pre | C2-Post |
|---|---|---|---|---|---|---|
| Cooling (kWh/yr) | 0 | 4,536 | 0 | 5,389 | 0 | 5,389 |
| Lighting (kWh/yr) | 0 | 2,628 | 0 | 3,285 | 0 | 10,368 |

## 4.3 COMPARATIVE EUI TRENDS ACROSS CLIMATIC ZONES

The changes in EUI are underscored in the Figure 5. The dry zone restaurant (A) showed the greatest growth (+161%), then intermediate zone (B, +135%) and the wet zone (C, +74%). This ranking (Dry > Intermediate > Wet) reflects high sensitivity in climatic conditions of the adaptive reuse outcome under the assumptions of design and operation used.

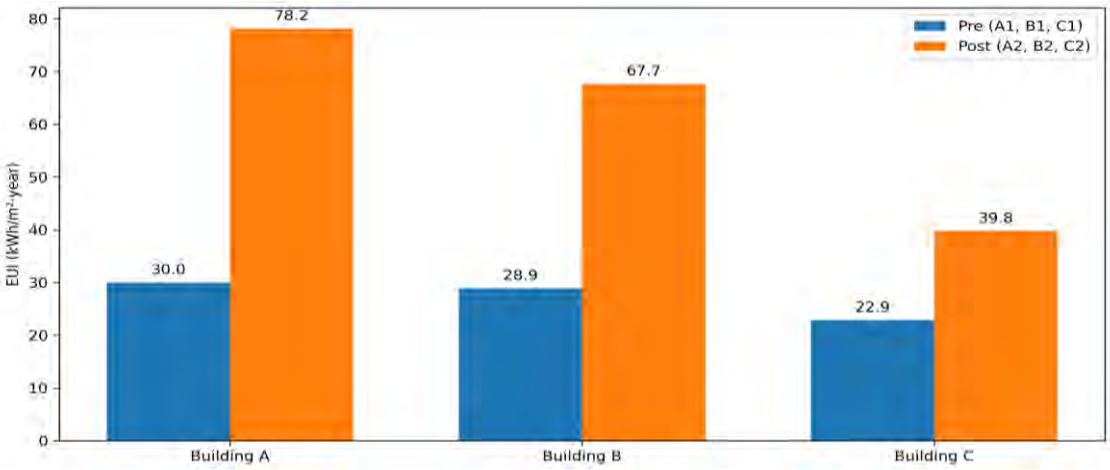



*Figure 5 : Energy use intensity of pre and post phases of selected building*

## 4.4 CAUSE AND EFFECT INTERPRETATION

In the three buildings, the most prevalent sources of greater post-reuse EUI included: (1) internal gains in functional transformation (e.g. residence to restaurant/ museum) reduced cross-ventilation and access to daylight; (2) material replacement by lightweight partitions and high thermal-mass envelope, which decreased thermal mass effect and increased peak cooling demand. Other heritage-building studies have also recorded similar function-based increases in energy demand following reuse as mechanical systems are added and greater service expectations are imposed that increase the operational loads(Alasmar et al., 2024). De Silva (2019), who have found that in arid tropical areas, heritage buildings are converted into more energy-intensive structures when the old passive systems are substituted with lightweight materials. Sealed exhibit spaces could also enhance the cooling and dehumidification dependency in warm-humid environments(Thirukumaran et al., 2024). In cooler and highland conditions, daylight is limited so lighting may be the primary end-use, and daylight strategy and controls are particularly significant. It contributes to Ruparathna et al. (2016) who found out that lighting is a dominant end-use in high-altitude heritage buildings where thermal loads are low. Its better roof insulation and concrete column support. however, enhanced the heat loss and the envelope life of wet climatic conditions.

## 4.5 EFFECT OF PROPOSED RETROFITS (SIMULATION GUIDED IMPROVEMENTS)

Climate-responsive retrofit packages were modelled to test energy reduction pathways that were compatible with heritage character. Table 5 and Table 6 is a summary of the proposed EUI results and the fall as compared to the post-modification scenario. The greatest absolute change is the dry zone with passive cooling restoration, shading, and glazing improvements, which decrease EUI of 78.24 to approximately 42.5 kWh/m$^2$yr (or 45% change). The middle zone is the most successful in receiving the benefits of the ventilation-related humidity control and daylight enhancements (67.72 to the approximate of 38.5 kWh/m$^2$yr, or 43 %). The wet zone records moderately but significantly with the help of the measures of daylight and lighting efficiency (39.83 to approximately 30.5 kWh/m$^2$yr, 25 %).

*Table 6 : Recommended altered EUI values of selected buildings*

| **Parameter** | **Building A (Jaffna)** | | | **Building B (Galle)** | | | **Building C (Nuwara Eliya)** | | |
|---|---|---|---|---|---|---|---|---|---|
| | *A1* | *A2* | *A3* | *B1* | *B2* | *B3* | *C1* | *C2* | *C3* |
| Cooling Energy (kWh/year) | 0 | 4536 | 1800 | 0 | 5389 | 2000 – 2500 | 0 | 5389 | 4000 |
| Lighting Energy (kWh/year) | 0 | 2628 | 1000 | 0 | 3285 | 1200 – 1500 | 0 | 10368 | 4000–5000 |
| Total Energy (kWh/year) | 2746.8 | 7170.3 | 3200 – 3800 | 7123.5 | 16716.2 | 8500 – 9500 | 22131 | 38492.1 | 19000 – 22000 |
| EUI (kWh/m²·year) | 29.96 | 78.24 | 42.5 | 28.87 | 67.72 | 38.5 | 22.90 | 39.83 | 30.5 |
| Peak Cooling Load (kW) | 5.04 | 7.79 | 5.0–5.8 | 13.58 | 13.58 | 11–12 | 23.41 | 23.41 | 18–19.5 |

In order to read the difference in energy performance more well, the below Table 7 summarizes the difference between (ΔEUI) and percentage change between the pre- and post and the proposed modification phases. It also determines the main force that affects change of every climatic setting.

*Table 7 : Comparison of Energy Use Intensity (EUI) before and after proposed modifications*

| **Building/Zone** | **EUI Pre** | **EUI Post** | **EUI Proposed** | **Key retrofit focus** | **Δ vs Post** |
|---|---|---|---|---|---|
| A – Jaffna (Dry) | 29.96 | 78.24 | 42.5 | Shading + roof insulation; reduce A/C reliance; fans; low-E glazing | ↓45% |
| B – Galle (Intermediate | 28.87 | 67.72 | 38.5 | Restore cross-ventilation; humidity-aware operation; daylight + sensors | ↓43% |

| Building/Zone | EUI Pre | EUI Post | EUI Proposed | Key retrofit focus | Δ vs Post |
|---|---|---|---|---|---|
| C – Nuwara Eliya (Wet) | 22.90 | 39.83 | 30.5 | Daylight recovery (translucent partitions); LED + daylight dimming; glazing | ↓24% |

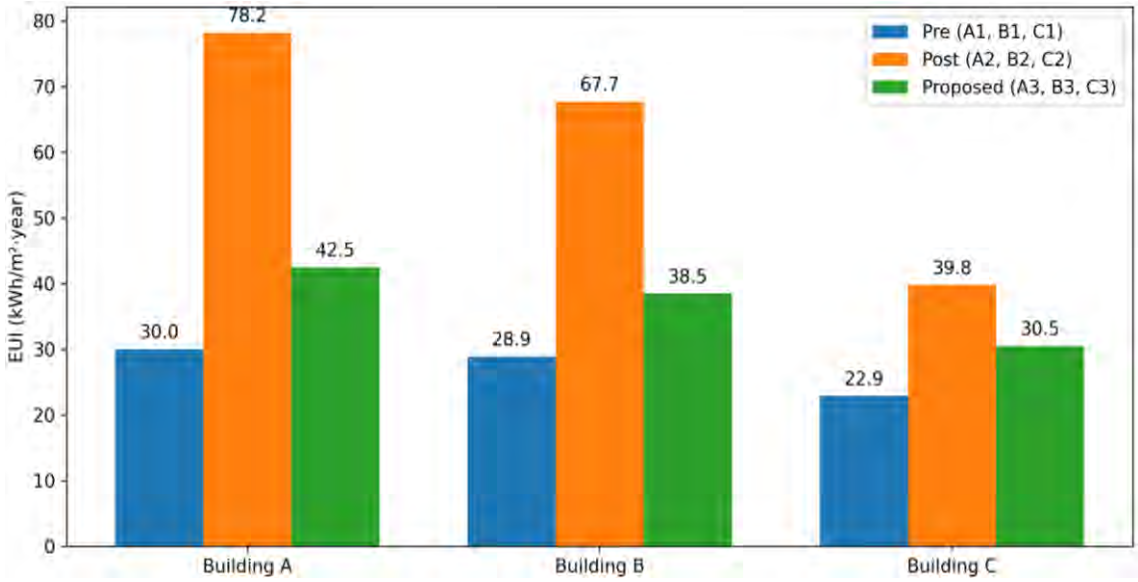



*Figure 6 : EUI of pre, post and alternative phases of selected buildings after implementing proposed modifications*

## 5. CONCLUSIONS

The current study assessed the energy performance of the adaptive reuse in three historic buildings located in three different climates of Sri Lanka (in the dry zone (Rusichatti Restaurant, Jaffna), in the intermediate zone (National Galle Fort Museum, Galle), and in the wet zone (Nuwara Eliya Post Office, Nuwara Eliya)) through the deployment of the Autodesk Revit Insight 2025 simulations. The results confirm the idea that the adaptive reuse changes significantly the energy performance due to the building envelope, spatial organization, and functional purpose alteration.

In all cases, Energy Use Intensity (EUI) rose after adaptation, and this showed that reuse does not in itself necessarily result in efficient operation. The example of the dry-zone was the most excessive with the reduction of 29.96 to 78.24 kWh/m²·year (+161%), due to the loss of thermal mass and cross-ventilation and the introduction of mechanical air-conditioning. Intermediate-zone museum showed an increase of 28.87 to 67.72 kWh/m²·year (67.72%) with the biggest increase recorded on the enclosure of exhibition spaces and the increased demand due to lighting. The wet-zone office grew by 22.90 to 39.83 kWh/m²·year (74%), which was primarily due to a decrease in daylight penetration and the reliance on artificial lighting. There was also a clear hierarchy of climatic conditions: Dry > Intermediate > Wet, which supported climatic conditions as the key factor of post-reuse performance.

Retrofit simulations showed that there was a lot of recuperative potential. EUI fell in Jaffna, down to 42.5 kWh/m²·year ( -50%), 78.24. In Galle, it dropped to 67.72 to 38.5 kWh/m²·year (-43%). Daylight-responsive interventions in Nuwara Eliya reduced EUI

by 39.83 to 30.5 kWh/m²·year (-24%). These findings indicate that climate-sensitive retrofits can also significantly reduce the penalties of operations, as well as retain heritage integrity. It highlights the significance of protecting passive architecture components, such as thermal mass, shaded verandahs, courtyards, and natural ventilation as of the fact that their interference directly increases cooling and lighting loads. Functioning together with specific efficiency improvements, adaptive reuse can create a quantifiable environmental value. The Insight workflow enabled a comparative analysis of the pre and post intervention situations and retrofit options in a systematic way allowing to provide a structured decision-support framework to buildings undergoing adaptive-reuse.

Taken together, the adaptive reuse projects in Sri Lanka are to be approached as the challenges of the climate-responsive performance. Green benefits would only occur when the legacy of passive systems is honored and supported by simulation-based design and thus the historic buildings would provide a significant contribution to the low-carbon development.

### 5.1 PRACTICAL AND THEORETICAL IMPLICATIONS

This study demonstrates that adaptive reuse can raise operational energy demand without climate-sensitive strategies. Practically, it identifies the need to retain passive elements and consider climate-specific retrofit strategies to enhance energy efficiency. Theoretically, it challenges the assumption that adaptive reuse inherently improves energy efficiency, clarifies the difference between embodied energy benefits and operational performance, and offers a BIM-driven comparative framework for assessment across climatic zones.

## 6. REFERENCES

Abdullah, O. H., & Hatem, W. A. (2023). The use of BIM to propose alternative construction methods to reduce the cost of energy for the historic archeological building in Iraq. *Archives of Civil Engineering*, *69*(2), 535–549. https://doi.org/10.24425/ace.2023.145283

Alasmar, R., Anaç, M., & Bakan, M. K. (2024). Evaluating the effect of adaptive reuse in the energy performance of historic buildings: A case study from Türkiye. *Heritage*, *7*(11), 6085–6100. https://doi.org/10.3390/heritage7110285

Ariyarathna, I. S., Kariyakarawana, M., Abeyrathna, W. P., Danilina, N., & Halwatura, R. U. (2023). Analysis of operational energy between adaptive reuse historic buildings (ARHB) and modern office buildings: A Case Study in Sri Lanka. *Architecture*, *3*(3), 344–357. https://doi.org/10.3390/architecture3030019

Bullen, P. A., & Love, P. E. D. (2011). Adaptive reuse of heritage buildings. *Structural Survey*, *29*(5), 411–421. https://doi.org/10.1108/02630801111182439

Conejos, S., Langston, C., Chan, E. H. W., & Chew, M. Y. L. (2016). Governance of heritage buildings: Australian regulatory barriers to adaptive reuse. *Building Research and Information*, *44*(5–6), 507–519. https://doi.org/10.1080/09613218.2016.1156951

De Silva, G. D. R., Perera, B. A. K. S., & Rodrigo, M. N. N. (2019). Adaptive reuse of buildings: The case of Sri Lanka. *Journal of Financial Management of Property and Construction*, *24*(1), 79–96. https://doi.org/10.1108/JFMPC-11-2017-0044

Deepa, K., Suryarajan, B., Nagaraj, V., Srinath, K., & Vasanth, K. (2019). Energy analysis of buildings. *International Research Journal of Engineering and Technology*, *6*(1). https://www.irjet.net/archives/V6/i1/IRJET-V6I1310.pdf

Dissanayake, S. D. S. K., Jing, Y., & Laksith, T. I. (2024). Assessing drought risk and the influence of climate projections in Sri Lanka for sustainable drought mitigation via geospatial techniques. *Sustainability (Switzerland)*, *16*(23). https://doi.org/10.3390/su162310375

Foster, G. (2020). Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Resources, Conservation and Recycling, 152*. https://doi.org/10.1016/j.resconrec.2019.104507

Haase, M., & Amato, A. (2009). An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates. *Solar Energy*, *83*(3), 389–399. https://doi.org/10.1016/j.solener.2008.08.015

Jaber, J. O., Marahleh, G., Al-Lubani, S., & Khrisat, M. (2025). Energy efficiency retrofitting for old buildings in a low-income district of Amman, Jordan. *Academia Green Energy*, *2*(1). https://doi.org/10.20935/AcadEnergy7487

Martínez-Molina, A., Tort-Ausina, I., Cho, S., & Vivancos, J. L. (2016). Energy efficiency and thermal comfort in historic buildings: A review. *Renewable and Sustainable Energy Reviews*, *61*, 70–85. https://doi.org/10.1016/j.rser.2016.03.018

Penića, M., Svetlana, G., & Murgul, V. (2015). Revitalization of historic buildings as an approach to preserve cultural and historical heritage. *Procedia Engineering*, *117*(1), 883–890. https://doi.org/10.1016/j.proeng.2015.08.165

Perera, U. S., Weerasuriya, A. U., Zhang, X., Ruparathna, R., Tharaka, M. G. I., & Lewangamage, C. S. (2025). Selecting suitable passive design strategies for residential high-rise buildings in tropical climates to minimize building energy demand. *Building and Environment*, *267*, 112177. https://doi.org/10.1016/j.buildenv.2024.11217

Rodrigues, C., & Freire, F. (2017). Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building. *Journal of Cleaner Production*, *157*, 94–105. https://doi.org/10.1016/j.jclepro.2017.04.104

Ruparathna, R., Hewage, K., & Sadiq, R. (2016). Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews, 53*,1032–1045. Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.09.084

Slavkovic, K., & Stephan, A. (2025). Dynamic life cycle assessment of buildings and building stocks: A review. *Renewable and Sustainable Energy Reviews, 212*. https://doi.org/10.1016/j.rser.2024.115262

Tam, V. W. Y., & Hao, J. J. L. (2019). Adaptive reuse in sustainable development. *International Journal of Construction Management*, *19*(6), 509–521. https://doi.org/10.1080/15623599.2018.1459154

Thirukumaran, N., Prabodani, M. K. M., Ranasinghe, S. S., Jayasinghe, G. Y. J., & Halwathura, R. U. (2024). A Comparative analysis of operational energy by simulation study between modern buildings and adaptive reuse of historic buildings in Sri Lanka. *12th World Construction Symposium*, 15–26. https://doi.org/10.31705/WCS.2024.2

Veerendra, G. T. N., Dey, S., Mantle, E. J., Manoj, A. V. P., Kumaravel, B., Babu, P. S. S. A., & Rao, P. K. R. (2024). Material estimation and energy analysis for a domestic building using Revit architecture and insight: A sustainable approach. *Asian Journal of Civil Engineering*, *25*(4), 3431–3447. https://doi.org/10.1007/s42107-024-00988-z

Vidyullatha, R. J., Kumar, G. V., & Dileep, G. (2023). Adaptive Reuse of Heritage Buildings for Sustainable Urban Regeneration: Two Case Studies from India. *ISVS E-Journal*, *10*(8), 290–313.

Jayasinghe, H.D.T.N., Abenayake, D.N. and Aathithan, V., 2026. Stakeholder influence and roles on circular economy adoption in the Sri Lankan construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1583-1596. DOI: https://doi.org/10.31705/WCS.2026.115. Available from: https://ciobwcs.com/papers/

# STAKEHOLDER INFLUENCE AND ROLES ON CIRCULAR ECONOMY ADOPTION IN THE SRI LANKAN CONSTRUCTION INDUSTRY

**H.D.T.N. Jayasinghe[1], D.N. Abenayake[2] and V. Aathithan[3]**

## *ABSTRACT*

*The construction industry is a major consumer of resources and contributor to waste, requiring the implementation of sustainable approaches like the Circular Economy (CE). Effective CE implementation needs the collaborative involvement of multiple stakeholders throughout the project lifecycle. This study aims to identify key stakeholder groups in the Sri Lankan construction industry, assess their influence and explore their roles in CE implementation. The study used a mixed-methods approach. The questionnaire survey identified the most influential stakeholder groups, and semi-structured interviews were conducted with two representatives from each of the six key stakeholder groups. The results identified six key stakeholders, namely architects/designers, suppliers/manufacturers, public/statutory authorities, clients/developers, contractors, and cost consultants, as significantly influential (Relative Importance Index > 0.70). Architects/designers exert a strong influence on early-stage CE integration, while contractors and suppliers play a major role in the execution of R principles such as reuse, recycling, and recovery. Further, the study revealed that CE implementation is a shared responsibility across all project stages, identifying the roles of key stakeholders. This study contributes by providing a systematic assessment of stakeholder influence and role-mapping for CE implementation in a developing-country context. The findings also highlight emerging stakeholder responsibilities supporting effective CE adoption.*

***Keywords:*** *10R Principles; Circular Economy; Sri Lankan Construction Industry; Stakeholder Influence; Stakeholder Roles.*

## 1. INTRODUCTION

The construction industry is a significant contributor to the resource crisis, accounting for 40–60% of the depletion of natural materials (Eberhardt et al., 2022). It creates a large amount of construction and demolition (C&D) waste, accounting for 30–35% of total waste globally (Xia et al., 2020). The construction sector is associated with the linear economic model, implying a “take-make-dispose” approach (Saroosh & Khan, 2024). Disposing of construction waste has adverse environmental effects, including soil and

[1] Graduate, Department of Building Economics, University of Moratuwa, Sri Lanka, jayasinghehdtn.20@uom.lk
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, dilanina@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, vithushal@uom.lk

water pollution, increased deforestation, and loss of wildlife habitats (Noor et al., 2020). Thus, the potential environmental impacts of C&D waste cannot be adequately addressed by current waste management techniques, such as incineration and landfill disposal (Ram et al., 2020). Therefore, it is time for the construction industry to implement concepts like the Circular Economy, which focuses on zero waste (Wanaguru et al., 2022).

The Circular Economy (CE) transforms end-of-life products into resources, promoting closed-loop systems and zero-waste practices (Giorgi et al., 2022). The use of recycled materials and closed-loop supply chains can reduce environmental impacts in construction (Gopal et al., 2023). Integrating CE principles can also improve project time, cost, and quality performance (Victar & Waidyasekara, 2024), making CE essential for achieving sustainable development in the resource-intensive construction sector (Knable et al., 2022).

The Sri Lankan construction industry faces challenges, including ineffective waste management and environmental degradation stemming from excessive resource use and waste generation (Victar & Waidyasekara, 2024). CE implementation in the sector is still at an early stage and faces several barriers, including unclear guidelines, limited stakeholder awareness, weak policy support, and insufficient stakeholder engagement (De Silva et al., 2023; Senaratne et al., 2023; Weerakoon & Thayaparan, 2023; Wanaguru et al., 2022; Wijewansha et al., 2021). These factors and industry conditions may lead to differences in key stakeholders and their roles in Sri Lankan CE implementation compared with those identified in other countries, requiring specific identification of stakeholders in the Sri Lankan construction industry context.

The construction industry is highly fragmented, involving multiple stakeholders across project phases, which also makes CE implementation difficult (De Silva et al., 2023). This challenge is often linked to limited stakeholder engagement and poor communication (Victar & Waidyasekara, 2024). Effective stakeholder engagement is therefore essential for collaboration, knowledge sharing, and material flow in CE adoption (Hossain et al., 2020; Senaratne et al., 2023). While global studies have examined stakeholder engagement strategies and collaborative models for CE implementation (Hossain et al., 2020; Senaratne et al., 2021; Volk et al., 2019), research studies in Sri Lanka mainly focus on CE challenges and drivers (Gamage et al., 2024; Weerakoon & Thayaparan, 2023). However, limited research has examined the specific roles of industry stakeholders in facilitating stakeholder engagement for CE adoption. Despite increasing requirements to address waste and sustainability issues as a geographically small nation, Sri Lanka is at an early stage of CE implementation without a structured approach. Therefore, prioritising the most influential stakeholders is necessary for a more focused and effective initiation of CE practices.

Accordingly, this study aims to identify key stakeholder groups involved in CE implementation in the Sri Lankan construction industry, assess their influence on the R principles, and explore their roles in supporting effective CE practices.

# 2. LITERATURE REVIEW

## 2.1 THE CONCEPT OF CIRCULAR ECONOMY

Many scholars have proposed various definitions of CE over the past period. For instance, CE is “one that is restorative and regenerative by design” (Ellen MacArthur Foundation,

2015). Several definitions emphasise CE's role in transitioning from the traditional linear economic model of "take, make, dispose" to a closed-loop system (Saroosh & Khan, 2024). Scholars such as Wanaguru et al. (2022) also highlight its potential to reduce waste, particularly in the construction industry. Key stakeholders in the flow, identified by the Ellen MacArthur Foundation's Butterfly Diagram, include farmers, manufacturers, service providers, consumers, recyclers, and regulators (Riesener et al., 2023). Each stakeholder plays a role in maintaining circularity from sourcing renewable inputs to extending product life and managing end-of-life recovery, ensuring minimal waste and maximising economic and environmental value across the supply chain (Owojori & Okoro, 2022).

## 2.2 KEY PRINCIPLES OF CE

CE principles guide the practical application of the circular economy model (Velenturf & Purnell, 2021). The concept originates from several theories, including the R-framework, blue economy, biomimicry, and cradle-to-grave, all of which promote closed-loop systems (Lieder & Rashid, 2016). Literature presents different versions of R-principles, widely used as CE principles, evolving from the basic 3Rs to the more comprehensive 10Rs, while recent studies identify over 100 "R" concepts (Zorpas, 2024). The 3R principles (Reduce, Reuse, and Recycle) form the foundation of CE and are widely applied in the construction industry (Liyanage et al., 2022). These were later expanded into the 10R framework, which addresses all stages of the material life cycle (Rahla et al., 2021). The 10R principles include Reduce, Reuse, Recycle, Refuse, Recover, Rethink, Remanufacture, Repurpose, Repair, and Refurbish (Morseletto, 2019). The 10R principles are widely recognised in academic literature as a framework for CE practices. Each principle is linked to functions across different life-cycle stages of a circular building (Çetin et al., 2021; De Wolf et al., 2020; Rahla et al., 2021). Effective material flow in circular supply chains requires stakeholder collaboration and engagement throughout all lifecycle stages (Hossain et al., 2020). Therefore, this study applies the 10R principles to develop a stakeholder engagement framework for CE implementation in the Sri Lankan construction industry.

## 2.3 CE IN THE CONSTRUCTION INDUSTRY

The construction sector has major environmental impacts due to high resource and energy use and the generation of large volumes of C&D waste, much of which is landfilled (Norouzi et al., 2021). CE principles, such as reuse, recycling, and efficient resource use, can reduce these impacts (Norouzi et al., 2021). However, CE adoption remains limited due to economic, technological, and stakeholder-related barriers, including a lack of guidelines, uncertainty in material reuse, and weak supply chain collaboration (Adams et al., 2017; Moreau et al., 2017). In Sri Lanka, rapid urbanisation, high material costs, and weak waste management further challenge CE implementation (De Silva et al., 2023; Victar & Waidyasekara, 2023).

## 2.4 STAKEHOLDERS FOR CE IMPLEMENTATION IN CONSTRUCTION

Effective CE implementation in construction requires identifying stakeholders across the project lifecycle, from design and procurement to demolition and recycling (Senaratne et al., 2023). Stakeholder theory highlights the need to consider diverse interests and influence in decision-making (McGrath & Whitty, 2017). Recognising and engaging

stakeholders is essential to align interests, promote sustainability, and ensure commitment to circular practices (Senaratne et al., 2021; Oberholzer & Sachs, 2023). Successful CE implementation in construction requires active involvement from diverse stakeholders, each with specific roles and responsibilities (Fobbe & Hilletofth, 2022). The roles of stakeholders towards CE implementation can be summarised in Table 1 in the global context.

*Table 1: Stakeholders for CE implementation in construction*

| Stakeholders | Roles in CE practice (Identified from literature) | Sources |
|---|---|---|
| Government and statutory authorities | Developing CE policies and regulations and encouraging public-private collaboration. | [2], [4], [6], [7], [8] |
| Public authorities | Facilitating partnerships, providing technical and financial incentives, and promoting sustainable practices | [2], [4], [8] |
| Construction clients and developers | Setting project goals aligned with CE principles, promoting the use of sustainable materials, and ensuring compliance with CE standards | [1], [6], [9] |
| Contractors and Subcontractors | Implementing on-site CE practices such as waste reduction, recycling, and reuse, coordinating with clients, suppliers, and designers | [2], [9] |
| Suppliers and Manufacturers | Producing sustainable materials, ensuring their recyclability or reusability, and providing transparent information on material properties and lifecycle performance | [2], [3], [9], [11] |
| Architects, Designers, and Engineers | Incorporating recycled materials in designs, developing guidance manuals, and promoting design for disassembly to facilitate material recovery at the end of a building's lifecycle | [2], [9], [10] |
| Demolition contractors | Recovering materials from deconstruction, ensuring proper recycling, and collaborating with the suppliers and contractors to reintegrate materials into new construction | [2], [9], [11] |
| Investors and Financiers | Providing funding and incentives for CE projects while supporting innovation in sustainable construction | [5], [6] |
| Researchers | Identifying challenges and opportunities, developing CE assessment methods, and proposing innovative solutions for CE-enabled products and materials | [8] |
| Community | Promoting demand for sustainable materials, recyclable materials, and remanufactured products | [2], [6] |

[1] Acharya et al., 2018; [2] Almeida, 2024; [3] Chen et al., 2022; [4] Christensen, 2021; [5] Ebekozien et al., 2024; [6] Govindan & Hasanagic, 2018; [7] Hartley et al., 2020; [8] Kocaturk & Hosseini, 2023; [9] Senaratne et al., 2023; [10] Tleuken et al., 2022; [11] Volk et al., 2019.

## 3. RESEARCH METHODOLOGY

The research design for this study is structured into two phases to ensure a comprehensive approach to achieving the research objectives. This study adopted a sequential explanatory mixed-methods approach to obtain a comprehensive understanding of stakeholder engagement in CE implementation. In Phase 1, a quantitative survey was conducted to rank and prioritise stakeholder groups by their influence on CE implementation in the Sri Lankan construction industry, providing a broader, statistically reliable understanding of stakeholder dynamics. Phase 1 is necessary to identify the most influential and context-relevant stakeholders, due to the impracticality of studying all groups within a wide range of stakeholders in a limited time. Phase 1 contributed context-

specific prioritisation rather than redefining the stakeholder groups identified in the literature for the Sri Lankan context to address varying influence. In Phase 2, qualitative semi-structured interviews were used to explore stakeholder roles and collaboration with the highest-ranked stakeholder groups in greater depth, offering contextual insights grounded in quantitative stakeholder prioritisation that quantitative data alone cannot capture. Therefore, starting with qualitative would not provide a structured way to prioritise stakeholders across a wide range. A case study strategy was not adopted because CE implementation in the Sri Lankan construction industry is still in its early stages.

Both primary and secondary data collection methods were used, including a literature review, questionnaire survey, and semi-structured interviews. A total of 50 questionnaires were distributed to professionals using purposive and snowball sampling, based on their familiarity with sustainability or circular economy concepts, experience in the construction industry for more than 5 years, and current work in the Sri Lankan construction industry. The respondents included sustainability consultants, project managers, quantity surveyors, engineers, and corporate environmental officers with at least three years of professional experience. Out of the distributed questionnaires, 37 valid responses were received, resulting in a response rate of 74%. The study focuses on stakeholder prioritisation rather than statistical generalisation, and the achieved sample was information-rich CE experts suitable for ranking CE influential stakeholders. Therefore, the responses are considered adequate for this analysis, which is close to the statistically required sample size of approximately 44 respondents calculated through the Yamane (1967) sample size formula.

In Phase 2, semi-structured interviews were conducted to obtain in-depth insights into stakeholder perspectives on CE implementation. Six stakeholder groups were identified based on Phase 1 results, focusing on those with significant influence on CE adoption. Two participants from each stakeholder group were selected using convenience sampling, based on accessibility and availability, to ensure they had adequate knowledge of CE principles and involvement in construction activities as per Table 2.

*Table 2: Details of interviewees*

| Code | Stakeholder group | Designation | Industry Experience | Experience in Stakeholder group |
|---|---|---|---|---|
| A01 | Architects/Designers | Chief Executive Officer (CEO) | > 30 years | 5 years |
| A02 | | Chartered Architect | > 20 years | > 20 years |
| SM01 | Suppliers/ Manufacturers | Quality Assurance/ Quality Checking (QA/QC) Engineer | > 16 years | 8 years |
| SM02 | | Technical Manager | > 15 years | 5 years |
| C01 | Contractors | Project Manager | > 15 years | > 15 years |
| C02 | | Project Manager | 15 years | 15 years |
| CL01 | Construction clients | Director | 11 years | 6 years |
| CL02 | | Director | > 16 years | 12 years |
| SR01 | Statutory & regulatory authorities | Deputy Director General | > 20 years | 10 years |
| SR02 | | Acting Director | > 25 years | 12 years |
| QS01 | Cost consultant | Quantity surveyor | 10 years | 10 years |
| QS02 | | Quantity surveyor | 15 years | 15 years |

The sample size is guided by information richness, relevance, accessibility, and balanced representation across the six key stakeholder groups, rather than by numerical sample size considerations.

Quantitative data were analysed using descriptive statistical methods. The Relative Importance Index (RII) was used to evaluate stakeholders' perceived importance in implementing CE principles, with a threshold value of 0.70 considered significant, following Shanmuganathan et al. (2014) and Manoharan et al. (2020). Qualitative data obtained from interviews were analysed using manual content analysis.

# 4. RESEARCH FINDINGS, ANALYSIS, AND DISCUSSION

## 4.1 ANALYSIS OF QUESTIONNAIRE SURVEY FINDINGS

The questionnaire survey assessed stakeholders' awareness, perceptions, and influence on CE implementation in the Sri Lankan construction industry. The questionnaire targeted professionals with experience in the construction industry. 32.4% of respondents had 6–10 years of experience, 27% had 2–5 years, 21.6% had over 10 years, and 18.9% had less than 2 years. Respondents represented diverse construction professions, including engineers (32.4%), quantity surveyors (18.9%), project managers (10.8%), lecturers (10.8%), architects (5.4%), professors (5.4%), sector estimators (3.6%), researchers (3.6%), and freelancers in environmental policy and management.

Respondents were asked to rate each stakeholder group by its influence on implementing the CE concept in the Sri Lankan construction industry using a five-point Likert scale. Table 3 presents the potential influence of each stakeholder on overall CE implementation, based on their RII values. Using the RII threshold of 0.70 (Shanmuganathan et al., 2014; Manoharan et al., 2020), six stakeholders, namely Architects/Designers, Suppliers/Manufacturers, Public and Statutory Authorities, Construction Clients, Contractors, and Cost Consultants, were identified as highly influential in CE implementation as shown in Table 3.

*Table 3: Overall stakeholder influence on CE implementation*

| Stakeholder group | RII value | Rank |
|---|---|---|
| **Public and statutory Authorities** | **0.816** | **3** |
| **Construction Clients** | **0.784** | **4** |
| **Contractors** | **0.757** | **5** |
| Subcontractors | 0.681 | 7 |
| **Suppliers/ Manufacturers** | **0.832** | **2** |
| **Architects/Designers** | **0.843** | **1** |
| **Cost consultant** | **0.735** | **6** |
| Financial institutes | 0.649 | 8 |
| Consumers | 0.624 | 9 |

As per Table 3, Finance Institutes and Consumers showed comparatively lower influence for CE implementation in the Sri Lankan Construction industry, with RII values below 0.70. This indicates that CE practices in Sri Lanka are largely driven by project-level actors such as architects, contractors and clients, rather than end-users or financial intermediaries. However, public and statutory authorities ranked 3, emphasising the necessity of their regulatory and policy-making role. The next section further recognises the influence of CE implementation through the 10R principles.

### 4.1.1 Stakeholder Influence on Implementing the 10R Principles of Circular Economy in the Sri Lankan Construction Industry

Respondents were asked to rate the influence of each stakeholder group for the 10R principles in 10 sections (Rethink–Recover) using a five-point Likert scale. Table 4 reflects the stakeholders' perceived influence on the implementation of each CE principle in the Sri Lankan construction industry.

As per Table 4, Architects/Designers rank first in most R principles, highlighting their strong influence in integrating CE strategies at the design stage. This emphasises their key role in embedding circular practices through sustainable design, modular construction, and efficient material selection. Almeida (2024), Senaratne et al. (2023), and Tleuken et al. (2022) also confirm that architects and designers recognise the need to incorporate R principles into designs at early stages.

As shown in Table 4, Suppliers/Manufacturers (RII = 0.832, Rank 2) show a strong influence in Repurpose, Reuse, and Recycle, reflecting their role in material sourcing and recycling. Construction Clients (RII = 0.784, Rank 4 overall) score highest in Refuse (0.822) and Reuse (0.827), reflecting a strong influence on procurement decisions. Contractors show a strong influence in Reuse (0.816) and Repair (0.827), due to their site-level responsibilities and ability to manage construction waste and material reuse.

Public and Statutory Authorities mainly influence regulatory areas such as Recycle and Remanufacture, rather than operational CE practices. Although Cost Consultants do not appear among the top five stakeholders for most principles, they still demonstrate significant influence (RII > 0.70) in nearly all principles, except for Repurpose and Remanufacture. Victar and Waidyasekara (2024) identified that integrating CE principles into construction leads to improvements in cost management, ensuring the influential role of Cost consultants. Subcontractors show relatively lower influence, while Finance Institutes and Consumers have limited but still notable influence (RII > 0.60).

Overall, Architects/Designers dominate early-stage and strategic planning CE principles, while Contractors and Manufacturers lead execution-based practices. In summary, Table 5 presents the five top-ranked most influential stakeholders in implementing each R principle in the Sri Lankan construction industry.

## 4.2 ANALYSIS OF INTERVIEW FINDINGS

Twelve professionals (Table 3) representing six key stakeholder categories, Architects/Designers, Suppliers/Manufacturers, Public and Statutory Authorities, Construction Clients, Contractors, and Cost Consultants, were interviewed.

### 4.2.1 Potential Roles of Stakeholders in Implementing The 10 R Principles in the Construction Industry

Figure 1 summarises the perspectives of the four highest-ranked stakeholder groups on their roles in CE implementation, based on insights from two interviewees from each group. The roles of Cost Consultants and Public & Statutory Authorities are broadly applicable across most R-principles and are therefore discussed separately.

A01 confirmed the feasibility of applying all CE principles and emphasised design flexibility, material minimisation, and reuse potential, highlighting *"integrating flexible design elements for future reuse and designing for material separation and energy*

*recovery at end-of-life reflects a design approach considering whole building life".* Similarly, A02 mentioned some practical design strategies and gave examples: *"open-plan flexibility and designing movable furniture or wall partitions enable layout adaptability"*. Their views on Rethink, Reuse, and Refuse highlight the critical role of designers in early decision-making towards long-term circular outcomes. They emphasised that effective CE implementation should begin at the design stage, with the support of clients and regulatory frameworks. Senaratne et al. (2023) and Tleuken et al. (2022) also recommended early design-phase integration of CE through design for disassembly (DfD) and modularity, contributing to Rethink, Reuse, and Refuse, while the Sri Lankan construction industry shows a more practical approach for architects and designers, emphasising material selection, cost considerations, and the gradual integration of CE into existing design practices (Figure 1).

SM01 and SM02 highlighted suppliers' and manufacturers' roles in CE by promoting several strategies (Figure 1). *"Use of fewer virgin materials and producing secondary products like pile covers, interlock tiles, and blocks are some methods we can adopt*" *[SM01]*. SM02 added, *"avoiding non-recyclable materials and reusing packaging like pallets is also possible"*. Almeida (2024) and Chen et al. (2022) also recognised the manufacturers and suppliers' roles in providing recyclable and low-carbon materials and in remanufacture, while this study identifies ways of utilising waste through manufacturers and suppliers and their involvement in Reduce. Literature (e.g., Almeida, 2024; Senaratne et al., 2023) has identified that Contractors play a key role in on-site CE by managing materials, waste, and labour, consistent with the study findings. Additionally, the study proposed strategies such as the use of ready-mix concrete, the reuse of crushed concrete, and take-back programs (Figure 1).

CL01 and CL02 highlighted clients' roles in CE (Figure 1), showing strategic oversight and influence. Importantly, CL01 focused on Rethink, saying, "*If we can encourage value engineering with CE in mind, it will be very effective",* while CL02 highlighted, "*We can review and reject designs that do not meet environmental expectations*." Further, they proposed setting KPIs for contractors to limit material use and mandating the reuse of waste materials such as asphalt millings and crushed concrete. These examples show the client's role as enablers of CE through the client's briefs and tender requirements. The broader strategic focus on the client role is identified in the literature (e.g., Acharya et al., 2018; Govindan & Hasanagic, 2018; Senaratne et al., 2023), while the study provides more practical, context-specific actions relevant to Sri Lanka.

The findings align with the literature on the role of statutory and regulatory frameworks (e.g., Almeida, 2024; Christensen, 2021; Govindan & Hasanagic, 2018). Interviewees from Statutory & Regulatory authorities (SR01, SR02) highlighted their role in CE by formulating regulations on waste minimisation and modular systems, banning unsustainable materials, regulating demolitions and facilitating market coordination via stakeholder registration. In addition, the findings provide more practical regulatory actions relevant to the Sri Lankan construction context. Further, Quantity Surveyors identified their role as a financial enabler of CE through value engineering, early cost planning, and life-cycle cost advice, helping to balance sustainability and financial feasibility. This influential CE role is not explicitly highlighted in the existing literature.

*Table 4: Potential of stakeholder influence in implementing the 10R principles of the CE in the construction industry*

| R principle | Rethink | | Repurpose | | Refuse | | Reduce | | Reuse | | Repair | | Refurbish | | Re-manufacture | | Recycle | | Recover | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Stakeholder group** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** | **RII** | **Rank** |
| **Public & statutory Authorities** | 0.725 | 5 | 0.665 | 6 | 0.730 | 4 | 0.746 | 4 | 0.659 | 8 | 0.654 | 8 | 0.710 | 6 | 0.697 | 3 | 0.768 | 2 | 0.714 | 6 |
| **Construction Clients** | 0.838 | 2 | 0.719 | 3 | 0.822 | 1 | 0.778 | 2 | 0.827 | 1 | 0.757 | 4 | 0.773 | 2 | 0.714 | 2 | 0.768 | 2 | 0.735 | 3 |
| **Contractors** | 0.757 | 3 | 0.703 | 4 | 0.697 | 6 | 0.773 | 3 | 0.816 | 2 | 0.827 | 1 | 0.762 | 3 | 0.692 | 4 | 0.735 | 5 | 0.762 | 2 |
| **Subcontractors** | 0.730 | 6 | 0.670 | 5 | 0.654 | 9 | 0.719 | 7 | 0.762 | 5 | 0.768 | 2 | 0.676 | 8 | 0.681 | 6 | 0.735 | 5 | 0.703 | 7 |
| **Suppliers/ Manufacturers** | 0.735 | 4 | 0.746 | 2 | 0.757 | 3 | 0.708 | 5 | 0.816 | 2 | 0.762 | 3 | 0.757 | 4 | 0.692 | 4 | 0.822 | 1 | 0.719 | 4 |
| **Architects Designers** | 0.854 | 1 | 0.805 | 1 | 0.816 | 2 | 0.800 | 1 | 0.789 | 4 | 0.730 | 5 | 0.838 | 1 | 0.751 | 1 | 0.762 | 4 | 0.811 | 1 |
| **Cost consultant** | 0.703 | 7 | 0.665 | 6 | 0.703 | 5 | 0.730 | 6 | 0.719 | 7 | 0.719 | 6 | 0.719 | 5 | 0.665 | 7 | 0.708 | 7 | 0.719 | 4 |
| **Finance institutes** | 0.665 | 9 | 0.622 | 9 | 0.605 | 8 | 0.643 | 9 | 0.638 | 9 | 0.632 | 9 | 0.638 | 9 | 0.622 | 9 | 0.686 | 9 | 0.686 | 9 |
| **Consumers** | 0.670 | 8 | 0.659 | 8 | 0.654 | 7 | 0.746 | 8 | 0.741 | 6 | 0.708 | 7 | 0.708 | 7 | 0.654 | 8 | 0.697 | 8 | 0.697 | 8 |

*Table 5: Five most influential stakeholders in implementing the 10R principles in the Sri Lankan construction industry*

| | Rethink | Repurpose | Refuse | Reduce | Reuse | Repair | Refurbish | Re - manufacture | Recycle | Recover |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Architects Designers | Architects Designers | Construction Clients | Architects Designers | Construction Clients | Contractors | Architects Designers | Architects Designers | Suppliers/ Manufacturers | Architects Designers |
| **2** | Construction Clients | Suppliers/ Manufacturers | Architects Designers | Construction Clients | Contractors/ Suppliers/ Manufacturers | Subcontractors | Construction Clients | Construction Clients | Construction Clients/ Public & statutory Authorities | Contractors |
| **3** | Contractors | Construction Clients | Suppliers/ Manufacturers | Contractors | | Suppliers/ Manufacturers | Contractors | Public & statutory Authorities | | Construction Clients |
| **4** | Suppliers/ Manufacturers | Contractors | Public & statutory Authorities | Public & statutory Authorities | Architects Designers | Construction Clients | Suppliers/ Manufacturers | Contractors/ Suppliers/ Manufacturers | Architects Designers | Suppliers/ Manufacturers/ Cost consultant |
| **5** | Public & statutory Authorities | Subcontractors | Cost consultant | Suppliers/ Manufacturers | Subcontractors | Architects Designers | Cost consultant | | Contractors/ Subcontractors | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Rethink | | Repurpose | | Refuse | | Reduce | | Reuse | |
| Repair | | Refurbish | | Remanufacture | | Recycle | | Recover | |

| Architects/Designers' Role | Suppliers/Manufacturers' Role | Contractors' Role | Construction Clients' Role |
|---|---|---|---|
| Integrate flexible & adaptable design layouts for future reuse. Apply passive design to reduce energy demand. Plan durable elements with retrofit potential. | Produce low-carbon concrete using fly ash, slag, and recycled aggregates. Optimise delivery logistics to reduce transport emissions. | Select multi-use materials. Plan logistics to reduce overuse & transport emissions. | Promote value engineering to optimise material use. |
| | | Use packaging/off-cuts for temporary works or protection. Use crushed concrete for road base or temporary paths. | Accept the use of offcuts and demolition waste for other purposes |
| Enable reuse of leftover/surplus site materials. | Utilise waste concrete for products (curbs, tiles, pile covers). | | Reject high-waste or poor environmental designs/materials. |
| Avoid composite materials difficult to separate. | Avoid river sand and high-embodied-carbon materials like aluminium. Avoid supplying non-recyclable materials. | Avoid single-use, low-durability materials. Have supplier agreements to reduce non-recyclable items & overpackaging. | Establish KPIs for contractors to minimise material use and emissions. Select efficient designs that avoid material duplication. |
| Minimise material use through efficient design. | | | |
| Include reusable components | Minimise the use of natural materials. Apply just-in-time delivery to reduce waste. | Use ready-mix concrete to minimise waste. Apply ERP systems, BIM, and lean practices to minimise over-ordering and reduce off-cuts. | Mandate the reuse of building components, where safe and possible. |
| Not mentioned a specific role | Implement return schemes for excess materials. Encourage on-site reuse of pallets and packaging. | | Promote repair of machinery/ infrastructure over replacement. |
| Design building elements for refurbishment and reuse, and collaborate with suppliers to enable remanufacturing of building parts | | Participate in take-back schemes (scaffolding, timber, formwork). Salvage and reuse precast elements where possible. | |
| | Promote maintenance practices | | Prioritise refurbishment or widening instead of demolition. |
| Redesign elements for alternative uses after demolition. | Manufacture components for refurbishment and reuse across multiple projects. | Repair tools & equipment instead of replacing. Establish in-house maintenance workshops. | Accept the adoption of remanufactured steel and concrete components in new developments. |
| Specify recycled materials in design specs. | Convert returned/rejected concrete into other possible products. | Retrofit and reuse existing elements where feasible. | Not mentioned a specific role |
| Design for material separation, energy recovery | Recycle demolition into usable material for new production. | Send offcuts &excess for reprocessing | Encourage bio-waste energy recovery from site clearing. |
| | Waste minimisation and material separation at source. | Segregate waste on-site. Send waste to registered recyclers. | |
| | | Direct non-reusable materials to energy recovery. | |

*Figure 1: Key roles of Most influential Stakeholders in CE implementation in the Sri Lankan Construction Industry*

## 5. CONCLUSIONS

This study demonstrates that effective CE implementation in the Sri Lankan construction industry relies on the influence of multiple stakeholders. Six key stakeholder groups, namely architects/designers, suppliers/manufacturers, public/statutory authorities, clients/developers, contractors, and cost consultants, were found to be significantly influential, with RII values exceeding 0.7. Their influence on the 10R principles also demonstrates that Architects/Designers play a strong influential role in integrating CE strategies at the design stage. The key roles of the most influential stakeholders in implementing CE through the 10R principles were identified, emphasising that CE adoption is a shared responsibility across these stakeholders. This research contributes to the literature by providing a systematic assessment of stakeholder influence on the 10R principles in a developing country context and by offering a role-mapping for CE implementation in construction. The novelty lies in identifying emerging responsibilities towards CE implementation in practice.

## 6. REFERENCES

Acharya, D., Boyd, R., & Finch, O. (2018). From principles to practices: First steps towards a circular built environment. *ARUP, Ellen macarthur foundation*.

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: Current awareness, challenges and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Almeida, F. (2024). Entrepreneurs' decision-making in sustainable open innovation practices. *The International Journal of Entrepreneurship and Innovation*. https://doi.org/10.1177/14657503241289869

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular Digital Built Environment: An emerging framework. *Sustainability, 13*(11), 6348. https://doi.org/10.3390/su13116348

Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. (2022). Strategies to achieve a carbon neutral society: a review. *Environmental Chemistry Letters, 20*(4), 2277–2310. https://doi.org/10.1007/s10311-022-01435-8

Christensen, T. B. (2021). Towards a circular economy in cities: Exploring local modes of governance in the transition towards a circular economy in construction and textile recycling. *Journal of Cleaner Production, 305*, 127058. https://doi.org/10.1016/j.jclepro.2021.127058

De Silva, S., Samarakoon, S. M. S. M. K., & Haq, M. A. A. (2023). Use of circular economy practices during the renovation of old buildings in developing countries. *Sustainable Futures, 6*. https://doi.org/10.1016/J.SFTR.2023.100135

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society, 61*, 102322. https://doi.org/10.1016/j.scs.2020.102322

Ebekozien, A., Aigbavboa, C. O., & Ramotshela, M. (2024). A qualitative approach to investigate stakeholders' engagement in construction projects. *Benchmarking an International Journal*. https://doi.org/10.1108/bij-11-2021-0663

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2022). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management, 18*(2), 93–113. https://doi.org/10.1080/17452007.2020.1781588

Ellen MacArthur Foundation [EMF]. (2015). Towards a circular economy: Business rationale for an accelerated transition. *Ellen MacArthur Foundation*

Fobbe, L., & Hilletofth, P. (2022). Moving toward a circular economy in manufacturing organizations: The role of circular stakeholder engagement practices. *The International Journal of Logistics Management, 34*(3), 674–698. https://doi.org/10.1108/ijlm-03-2022-0143

Gamage, I., Senaratne, S., Perera, S., & Jin, X. (2024). Implementing Circular Economy throughout the Construction Project Life Cycle: A Review on Potential Practices and Relationships. *Buildings, 14*(3), 653. https://doi.org/10.3390/buildings14030653

Giorgi, S., Lavagna, M., Wang, K., Osmani, M., Liu, G., & Campioli, A. (2022). Drivers and barriers towards circular economy in the building sector: Stakeholder interviews and analysis of five European countries policies and practices. *Journal of Cleaner Production, 336*. https://doi.org/10.1016/J.JCLEPRO.2022.130395

Gopal, K., Begam, S. R., Srivastava, A. P., Paul, S., Zabibah, R. S., & Singh, N. (2023). Environmental and Economic Benefits of Closed-Loop Supply Chains: A Case Study of Recycling and Re-manufacturing of Materials and Components. *E3S Web of Conferences, 430*. https://doi.org/10.1051/E3SCONF/202343001131

Govindan, K., & Hasanagic, M. (2018). A systematic review on drivers, barriers, and practices towards circular economy: A supply chain perspective. *International Journal of Production Research, 56*(1–2), 278–311. https://doi.org/10.1080/00207543.2017.1402141

Hartley, K., Van Santen, R., & Kirchherr, J. (2020). Policies for transitioning towards a circular economy: Expectations from the European Union (EU). *Resources Conservation and Recycling, 155*, 104634. https://doi.org/10.1016/j.resconrec.2019.104634

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable & Sustainable Energy Reviews, 130*, 109948. https://doi.org/10.1016/j.rser.2020.109948

Knable, D., de Quevedo Puente, E., Perez-Cornejo, C., & Baumgärtler, T. (2022). The impact of the circular economy on sustainable development: A European panel data approach. *Sustainable Production and Consumption, 34*, 233–243. https://doi.org/10.1016/J.SPC.2022.09.016

Kocaturk, T., & Reza Hosseini, M. (2023). Towards a circular transition of the built environment: Systemic and transdisciplinary models, methods and perspectives. *Building Research and Information, 51*(1), 1–4. https://doi.org/10.1080/09613218.2022.2155377

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production, 115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Liyanage, K., Waidyasekara, K., & Mallawaarachchi, B. (2022). Application of the 3R concept in the construction industry to achieve zero waste—A Sri Lankan case study. *The Journal of Solid Waste Technology and Management, 48(*3), 486–496. https://doi.org/10.5276/jswtm/2022.486

Manoharan, K., Dissanayake, P., Pathirana, C., Deegahawature, D., & Silva, R. (2020). Assessment of critical factors influencing the performance of labour in Sri Lankan construction industry. *International Journal of Construction Management, 23*(1), 144–155. https://doi.org/10.1080/15623599.2020.1854042

McGrath, S. K., & Whitty, S. J. (2017). Stakeholder defined. *International Journal of Managing Projects in Business*, 10(4), 721–748. https://doi.org/10.1108/IJMPB-12-2016-0097

Moreau, V., Sahakian, M., Van Griethuysen, P., & Vuille, F. (2017). Coming Full Circle: Why social and institutional dimensions matter for the circular economy. *Journal of Industrial Ecology, 21*(3), 497–506. https://doi.org/10.1111/jiec.12598

Morseletto, P. (2019). Targets for a circular economy. *Resources Conservation and Recycling, 153*, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Nazir, S., & Doni, F. (2024). Nexus of circular economy R0 to R9 principles in integrated reporting: Insights from a multiple case study comparison. *Business Strategy and the Environment, 33*(5), 4058–4085. https://doi.org/10.1002/bse.3684

Noor, T., Javid, A., Hussain, A., Bukhari, S. M., Ali, W., Akmal, M., & Hussain, S. M. (2020). Types, sources and management of urban wastes. *Urban ecology: Emerging patterns and social-ecological systems*, 239–263. https://doi.org/10.1016/B978-0-12-820730-7.00014-8

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: A scientific evolution analysis. *Journal of Building Engineering, 44*, 102704. https://doi.org/10.1016/j.jobe.2021.102704

Oberholzer, S., & Sachs, S. (2023). Engaging Stakeholders in the Circular Economy: A Systematic Literature review. In Springer eBooks (pp. 57–97). https://doi.org/10.1007/978-3-031-31937-2_3

Owojori, O. M., & Okoro, C. (2022). The Private Sector Role as a Key Supporting Stakeholder towards Circular Economy in the Built Environment: A Scientometric and Content Analysis. *Buildings, 12*(5), 695. https://doi.org/10.3390/buildings12050695

Rahla, K., Mateus, R., & Bragança, L. (2021). Implementing Circular Economy Strategies in Buildings—From Theory to Practice. *Applied System Innovation, 4*(2), 26. https://doi.org/10.3390/asi4020026

Ram, V. G., Kishore, K. C., & Kalidindi, S. N. (2020). Environmental benefits of construction and demolition debris recycling: Evidence from an Indian case study using life cycle assessment. *Journal of cleaner production, 255*. https://doi.org/10.1016/J.JCLEPRO.2020.120258

Riesener, M., Kuhn, M., Hellwig, F., Ays, J., & Schuh, G. (2023). Design for Circularity – Identification of fields of action for eco design for the circular economy. *Procedia CIRP, 116*, 137–142. https://doi.org/10.1016/j.procir.2023.02.024s

Saroosh, M., & Khan, K. I. A. (2024). Implementing Circular Economy Principles in Construction Waste Management: A Conceptual Framework for Maximizing Resource Efficiency and Minimising Environmental Impact. https://www.researchgate.net/publication/380910658

Senaratne, S., Abhishek, K. C., Perera, S., & Almeida, L. (2021). Promoting stakeholder collaboration in adopting circular economy principles for sustainable construction. *World Construction Symposium*, 471–482. https://doi.org/10.31705/WCS.2021.41

Senaratne, S., Rodrigo, N., Almeida, L. M. M. C. E., Perera, S., & Jin, X. (2023). Systematic review on stakeholder collaboration for a circular built environment: Current research trends, gaps and future directions. *Resources, conservation and recycling advances, 19*. https://doi.org/10.1016/J.RCRADV.2023.200169

Shanmuganathan, A., Disaratna, V. & Francis, M. (2014). A study of procurement selection for bridge construction. *FARU Journal*. http://dl.lib.uom.lk/handle/123/13433

Tleuken, A., Torgautov, B., Zhanabayev, A., Turkyilmaz, A., Mustafa, M., & Karaca, F. (2022). Design for deconstruction and disassembly: Barriers, opportunities, and practices in developing economies of Central Asia. *Procedia CIRP, 106*, 15–20. https://doi.org/10.1016/J.PROCIR.2022.02.148

Velenturf, A. P., & Purnell, P. (2021). Principles for a sustainable circular economy. *Sustainable Production and Consumption, 27*, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018

Victar, H. C., & Waidyasekara, K. G. A. S. (2024). Optimising construction waste management in Sri Lanka through circular economy strategies: A focus on construction and renovation and use and operate stages. *Engineering, construction and architectural management.* https://doi.org/10.1108/ECAM-06-2023-0608

Victar, H., & Waidyasekara, K. G. A. S (2023). Circular economy strategies for waste management in Sri Lanka: A focus on demolitions and repurpose and material recovery and production stages. *Waste Management & Research the Journal for a Sustainable Circular Economy*. https://doi.org/10.1177/0734242x231206988

Volk, R., Müller, R., Reinhardt, J., & Schultmann, F. (2019). An integrated material flows, stakeholders and policies approach to identify and exploit regional resource potentials. *Ecological Economics, 161*, 292–320. https://doi.org/10.1016/j.ecolecon.2019.03.020

Wanaguru, K., Mallawaarachchi, H., & Vijerathne, D. (2022). Circular economy (CE) based material selection: development of a CE-based '10R' evaluation framework for building construction projects in Sri Lanka. *World Construction Symposium*, 208–219. https://doi.org/10.31705/WCS.2022.18

Weerakoon, P., & Thayaparan, M. (2023). Analysis of barriers towards implementing circular economy in Sri Lankan built environment. *World Construction Symposium*, 1, 162–173. https://doi.org/10.31705/WCS.2023.14

Wijewansha, A. S., Tennakoon, G. A., Waidyasekara, K. G. A. S., & Ekanayake, B. J. (2021). Implementation of circular economy principles during pre-construction stage: the case of Sri Lanka. *Built environment project and asset management, 11*(4), 750–766. https://doi.org/10.1108/BEPAM-04-2020-0072

Xia, B., Ding, T., & Xiao, J. (2020). Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. *Waste management, 105*, 268–278. https://doi.org/10.1016/J.WASMAN.2020.02.015

Yamane, T. (1967). *Elementary sampling theory*. Prentice-Hall

Zorpas, A. A. (2024). The hidden concept and the beauty of multiple "R" in the framework of waste strategies development reflecting to circular economy principles. *The Science of the Total Environment, 952*, 175508. https://doi.org/10.1016/j.scitotenv.2024.175508

Aderibigbe A., Umeokafor, N., Upadhyay, Y. and Umar, T., 2026. Statutory good faith as a governance tool: Reforming infrastructure delivery and curbing corruption in Africa. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1597-1610. DOI: https://doi.org/10.31705/WCS.2026.116. Available from: https://ciobwcs.com/papers/

# STATUTORY GOOD FAITH AS A GOVERNANCE TOOL: REFORMING INFRASTRUCTURE DELIVERY AND CURBING CORRUPTION IN AFRICA

**Abiola Aderibigbe[1], Nnedinma Umeokafor [2], Yog Upadhyay[3] and Tariq Umar[4]**

## *ABSTRACT*

*Corruption in Africa's construction and energy sectors raises project costs, delays delivery and weakens trust in public institutions and financiers. These governance failures constrain the continent's ability to close its infrastructure delivery gap and meet climate and development goals. This study examines whether a statutory duty of good faith, embedded within collaborative legal frameworks, can operate as a governance instrument to reduce adversarial behaviour, curb corruption and strengthen infrastructure delivery in African construction and energy sectors. The study adopts an interpretivist qualitative design, combining a literature review with fourteen semi-structured interviews with construction, infrastructure and energy professionals. The sample includes practitioners with experience of African project delivery and others working in governance environments comparable to those found across the continent. Data were thematically analysed using an evaluative framework developed inductively from the data and subsequently structured to categorise levels of support. Practitioners view good faith as a practical governance tool. Interviewees linked a statutory duty of good faith to clearer expectations regarding transparency, payment discipline, procurement integrity, dispute resolution and alignment with multilateral development bank (MDB) and development finance institution (DFI) safeguard standards. Seven collaborative legal measures are identified that translate good faith into an actionable reform agenda. Codifying good faith, supported by harmonised legal frameworks, streamlined procurement, improved transparency, fair payment protections and stronger regulatory oversight, could reduce governance risk and make African infrastructure sectors more attractive to concessional and private capital. Realising these benefits will require phased and context-specific implementation and sustained investment in institutional capacity.*

***Keywords:*** *Africa; Corruption; Infrastructure Governance; Development Finance; Good Faith.*

[1] Abiola Aderibigbe, School of Civil Engineering and Built Environment, Liverpool John Moores University, UK, abioladeola@live.co.uk
[2] Dr Nnedinma Umeokafor, Senior Lecturer, Faculty of Engineering and Science, University of Greenwich, UK, n.umeokafor@greenwich.ac.uk
[3] Dr Yog Upadhyay, Senior Lecturer in Construction Law, School of Civil Engineering and Built Environment, Liverpool John Moores University, UK, Y.P.Upadhyay@ljmu.ac.uk
[4] Dr Tariq Umar, Senior Lecturer, Architecture and Built Environment, University of the West of England, UK, tariqumar1984@gmail.com

# 1. INTRODUCTION

Corruption remains a major barrier to sustainable infrastructure development in Africa, particularly in the construction and energy sectors. It undermines project delivery through inefficiencies, inflated costs and delays, while weakening investor confidence and the effectiveness of development finance (Rahman, 2020; James, 2022; Sabouri et al., 2023). Corruption frequently occurs during procurement and licensing processes, where weak oversight and discretionary decision-making create opportunities for bribery, rent-seeking and political capture (Moliterni, 2017; Rahman, 2020). High-profile cases, including the CEFC China Energy Company scandal in Chad and Uganda, illustrate how governance failures can distort infrastructure delivery and public investment outcomes (Transparency International, 2020). Similar concerns have been identified across African construction and energy sectors, where corruption continues to undermine infrastructure delivery and sustainable development objectives (James, 2022; Aderibigbe et al., 2024). Strengthening governance and integrity is therefore increasingly recognised as essential to achieving a regenerative and sustainable built environment.

This study examines a governance-oriented legal mechanism grounded in the principle of good faith. When codified in national legislation, good faith can create binding obligations promoting transparency, honesty and fairness in contractual relationships (Mante, 2018; Aderibigbe et al., 2023). By discouraging adversarial practices that may facilitate corruption, statutory good faith could help create a more predictable and accountable environment for domestic authorities and international financiers.

This study therefore examines whether a statutory duty of good faith, embedded within collaborative legal frameworks, can function as a governance mechanism to reduce corruption and improve infrastructure delivery in Africa’s construction and energy sectors. Building on earlier research that proposed statutory good faith as a harmonising principle for addressing corruption risks (Aderibigbe et al., 2024), the study uses qualitative expert interviews to develop collaborative legal measures capable of strengthening infrastructure governance across African jurisdictions.

The study identifies seven collaborative legal measures derived from the codification of good faith: harmonising legal frameworks, promoting regional cooperation, streamlining procurement, improving transparency and accountability, implementing fair payment practices, establishing effective dispute resolution mechanisms and enhancing regulatory consistency.

This research contributes to development scholarship by positioning statutory good faith as an institutional governance tool for addressing corruption and adversarial behaviour in infrastructure sectors, developing a seven-measure collaborative legal framework aligned with development finance integrity expectations, and demonstrating how these reforms can strengthen procurement integrity, institutional trust and infrastructure delivery across African economies.

# 2. METHODOLOGY

This research adopted a qualitative design to explore the role of collaborative legal frameworks, particularly the codification of good faith, in addressing corruption and infrastructure delivery challenges in Africa's construction and energy sectors. The study integrates semi-structured interviews, thematic analysis, and a targeted literature review,

drawing on Lin's Literature Research Methodology (2009) and Saunders et al.'s Research Onion Framework (2012). This methodology facilitates a nuanced understanding of how legal frameworks, when grounded in good faith, can mitigate corruption and enhance infrastructure delivery across the continent.

## 2.1 RESEARCH PHILOSOPHY AND APPROACH

The research is grounded in an interpretivist, inductive approach, which is well-suited to exploring the subjective experiences and perspectives of construction professionals, particularly in understanding how good faith can address adversarialism and corruption in Africa's construction industry (Saunders et al., 2012). An interpretivist paradigm is adopted as the study seeks to understand how practitioners perceive, interpret, and respond to governance frameworks in practice, rather than to test predefined hypotheses, making positivist or purely quantitative approaches less suitable for capturing these contextual dynamics. The emphasis on contextual understanding ensures that the study captures the complexities of the issues at hand. Consistent with a socially constructed view of knowledge, the analysis focuses on how practitioners interpret and respond to legal and institutional frameworks in their day-to-day work. A critical lens (Flick, 2009) was also applied to assess existing governance practices and to identify potential reforms to combat corruption and improve project delivery.

## 2.2 PARTICIPANTS SELECTION

Participants were selected based on professional expertise in the construction and energy sectors. Criteria included: substantial infrastructure project experience, valued at no less than £5 million, or contribution to industry standards, regulatory frameworks or technical guidance for projects of comparable scale; at least five years' active construction industry experience; and roles including architects, engineers, project managers, construction lawyers, legal advisors and governance, compliance or industry standards specialists. The sample included practitioners with direct African project experience and others working in comparable international governance environments. Participants were recruited through professional networks, LinkedIn and ResearchGate to capture insights on legal frameworks, governance, procurement and corruption risks relevant to African infrastructure delivery.

## 2.3 DATA COLLECTION: SEMI-STRUCTURED INTERVIEWS

The empirical component comprised fourteen semi-structured interviews with professionals from both the construction and energy sectors. The semi-structured format allowed for flexibility, providing space to explore participants' perspectives on good faith, adversarialism, and corruption in construction contracts. Interviews lasted between 30 to 45 minutes, with data collected both in person and remotely. All interviews were recorded, transcribed, and analysed thematically to identify key themes and insights. The researcher's professional background as a construction lawyer and academic was acknowledged during data collection and analysis. Careful contemporaneous note-taking and repeated checking of interview transcripts were used to minimise interpretive bias and ensure that participants' perspectives were represented accurately. Given the sensitivity of corruption-related topics, anonymity and confidentiality were strictly maintained to encourage candid responses, and participants were assured that no

identifiable information would be disclosed. This approach enhanced the reliability and credibility of the data collected. All participants gave informed consent.

## 2.4 DATA ANALYSIS: THEMATIC ANALYSIS WITH EVALUATIVE FRAMEWORK

Thematic analysis, as outlined by Braun and Clarke (2006), was employed to analyse the interview data. An evaluative framework was developed inductively to categorise participants' responses based on their level of support for the research premise. Responses were classified into four categories:

- Strong Support
- Moderate Support
- Conditional Support
- No Support/Rejection

Strong Support reflected clear endorsement of statutory good faith as a governance mechanism and support for its codification. Moderate Support reflected general support for the principle, accompanied by reservations regarding implementation or effectiveness. Conditional Support reflected support dependent upon specified legal, institutional, cultural or enforcement conditions being satisfied. No Support/Rejection reflected opposition to, or rejection of, statutory codification of good faith.

The evaluative framework was developed inductively from the interview data and subsequently structured to enable consistent categorisation and comparison of responses. Existing literature informed the interpretation of findings, but did not predetermine the analytical categories. Thematic analysis ensured a comprehensive exploration of the issues surrounding the codification of good faith and its potential to reduce corruption. The dataset reached thematic saturation at approximately twelve interviews, consistent with Guest et al. (2006), with no substantively new themes emerging after the tenth interview; the final two interviews (interviews 13 and 14) provided additional depth, particularly regarding cross-jurisdictional delivery and African and emerging-market project contexts.

## 2.5 LITERATURE REVIEW METHODOLOGY

In addition to the interviews, a targeted literature review was conducted, informed by Lin's Literature Research Methodology (2009). The review involved analysing a broad range of academic sources, government reports, and institutional publications, including reports from the World Bank, Transparency International, and the United Nations Development Programme (UNDP). These sources provided essential insights into the theoretical and practical contexts surrounding corruption and governance within Africa's construction and energy sectors. The literature review not only framed the theoretical context of the research but also informed the interpretation of the empirical findings, enabling them to be situated within wider debates on infrastructure governance, development finance, and anti-corruption in development studies.

# 3. LITERATURE REVIEW

## 3.1 CORRUPTION AND PUBLIC FINANCE IN GLOBAL PERSPECTIVE

Corruption remains a major barrier to social development, economic growth, and effective governance, particularly in developing countries. It is widely recognised as a systemic constraint on public finance and institutional performance, especially where legal and administrative capacity is weak and oversight is limited (Acemoglu and Verdier, 2000; Defreitas, 2023). Corruption manifests in multiple forms, including bribery, embezzlement, nepotism, and fraud (Grasso, 2017; Defreitas, 2023; Aderibigbe et al., 2024). The United Nations estimates that corruption drains more than US$2.6 trillion from the global economy annually, while approximately 25% of global public expenditure, around US$13 trillion, is affected by corrupt practices (United Nations, 2018; United Nations Development Programme (UNDP), 2022). These losses significantly reduce the fiscal space available for debt servicing, infrastructure maintenance, and social investment, directly affecting the scale and quality of public infrastructure programmes.

Corruption is particularly prevalent in contexts linked to public spending, with more than half of global bribery cases associated with such expenditure (UNDP, 2022; Defreitas, 2023). The 2024 Corruption Perceptions Index indicates that over two-thirds of countries score below 50, reflecting widespread corruption challenges (Transparency International, 2024). Even relatively high-scoring jurisdictions remain vulnerable to illicit financial flows (ibid), which distort infrastructure markets, facilitate political capture, and undermine safeguards relied upon by multilateral development banks and development finance institutions. Consequently, many African states face a structural financing disadvantage, as donors and development finance institutions incorporate governance risk into lending conditions, raising the cost of capital and limiting access to finance for large-scale infrastructure projects.

## 3.2 CORRUPTION IN AFRICA

Corruption has long affected African nations, with the region consistently performing poorly on the Corruption Perceptions Index. Somalia remains among the lowest-ranked countries, while sub-Saharan Africa recorded an average CPI score of 33 out of 100 between 2021 and 2024, the lowest of any global region (Transparency International, 2024; The Economist, 2022). Between 2000 and 2015, Africa lost an estimated US$836 billion to illicit financial flows, equivalent to approximately 3.7% of its GDP (United Nations Development Programme, 2022). Corruption also undermines key public sectors such as education and healthcare, contributing to reductions in government spending of 58% and 25% respectively (UNDP, 2022). A notable example occurred in Nigeria, where more than US$1.1 billion was diverted through bribery involving officials in the oil sector, depriving the national budget of critical revenues (Global Witness, 2017). Despite Nigeria's oil wealth, approximately 50% of the population lives in extreme poverty (World Bank, 2019), illustrating how corruption distorts economic systems and concentrates national wealth away from the broader population (United Nations Office on Drugs and Crime (UNODC), 2020). These dynamics also weaken public trust in state institutions and undermine the credibility of national development and infrastructure programmes in the eyes of external financiers.

## 3.3 CORRUPTION IN AFRICA'S CONSTRUCTION AND ENERGY SECTORS

Corruption within Africa's construction and energy sectors has significantly constrained infrastructure delivery. In the energy sector, it often manifests through gatekeeping, rent-seeking behaviour and monopolistic control over resources, where political appointees exert undue influence over project allocations (Amoah et al., 2022; Aderibigbe et al., 2024). Rimšaitė (2019) observes that corruption is particularly prevalent where officials exploit their positions in the absence of effective monitoring, while Acemoglu and Verdier (2000) argue that weak governance systems allow corruption to flourish within public institutions. In Africa, such gatekeeping and rent-seeking practices remain entrenched, particularly in the delivery of energy infrastructure (Rahman, 2020; Aderibigbe et al., 2024). These practices inflate project costs, delay delivery and reduce the share of renewable energy within overall consumption (Amoah et al., 2022). It is estimated that a 1% increase in corruption perception corresponds with a 0.31% reduction in the renewable share of final energy use in Africa (ibid). These conditions also heighten perceived governance risk for institutional investors, multilateral development banks and development finance institutions, which may increase financing costs or withdraw from otherwise viable projects, thereby constraining the pipeline of bankable infrastructure investments.

## 3.4 THE "GREEN CURSE" IN AFRICA'S RENEWABLE ENERGY SECTOR

Despite these challenges, Africa has made progress in expanding renewable energy infrastructure. Solar power, for instance, has become increasingly important in the continent's transition to sustainable energy (Amuakwa-Mensah & Nässtrom, 2022). By 2015, renewable energy consumption in developing countries had increased from 61% in the 1990s to 79%, indicating a shift towards more sustainable energy sources (Amoah et al., 2022). However, this progress has been undermined by the "green curse," whereby resource-rich countries, particularly those with abundant renewable resources, face heightened corruption risks due to weak institutions (Gennaioli & Tavoni, 2011). The green curse illustrates how renewable energy initiatives can attract corruption and organised crime in environments where governance systems are weak (Rahman, 2020). Such corruption limits Africa's ability to close the infrastructure deficit and achieve sustainable development goals (Peace Research Institute Oslo, 2019; Rahman, 2020). Consequently, renewable energy projects across the continent continue to encounter governance barriers that slow the green transition. These conditions also expose MDB and DFI climate finance portfolios to governance risks in host countries, highlighting the need for stronger domestic legal frameworks to safeguard project selection, procurement and delivery. Without improved governance structures that constrain discretion and promote transparency, renewable energy investment will continue to face systemic implementation barriers, limiting the developmental impact of climate finance.

## 3.5 LEGAL FRAMEWORKS, GOOD FAITH AND INFRASTRUCTURE GOVERNANCE

One approach to addressing corruption in the construction and energy sectors is through collaborative legal frameworks grounded in the principle of good faith. Good faith is widely recognised as promoting ethical conduct, transparency and cooperation among stakeholders (Saintier, 2017; Aderibigbe et al., 2023). When codified into law, it establishes clear obligations that support transparency and fairness, thereby reducing

opportunities for corruption (Mante, 2018; Aderibigbe et al., 2023). Legal frameworks built on good faith can therefore create conditions that encourage collaboration, reduce adversarial behaviour and support more accountable governance of public infrastructure projects.

Aderibigbe et al. (2024) argue that codifying good faith could improve transparency and accountability among stakeholders in the construction and energy sectors while helping to standardise best practices. The potential benefits of such frameworks align with the United Nations Sustainable Development Goals, particularly Goal 7 (Affordable and Clean Energy) and Goal 9 (Industry, Innovation and Infrastructure). More broadly, statutory good faith can function as a governance tool that complements existing anti-corruption, procurement and integrity systems used by MDBs and DFIs. By embedding good faith in national legislation and encouraging regional cooperation, African states may reduce corruption risks and accelerate infrastructure development, particularly in the energy sector, while supporting wider development objectives (UNDP, 2022). However, the literature also notes that good faith remains contested in some legal traditions and that limited empirical research has examined how a statutory duty of good faith would operate in African infrastructure contexts. This study addresses that gap by examining good faith as a potential organising principle for harmonised legal frameworks aimed at improving infrastructure governance and reducing corruption.

# 4. DISCUSSION: COLLABORATIVE LEGAL MEASURES AND GOOD FAITH IN ADDRESSING CORRUPTION AND INFRASTRUCTURE DEFICITS IN AFRICA

## 4.1 THE ROLE OF GOOD FAITH IN TACKLING CORRUPTION IN AFRICA'S INFRASTRUCTURE PROJECTS

Corruption continues to be a pervasive challenge in Africa's construction and energy sectors, significantly hindering the effective development of sustainable infrastructure. The interview findings indicate that a statutory duty of good faith, grounded in principles of transparency, honesty, and fair dealing, can serve as a governance tool rather than a purely moral aspiration. Codifying good faith into law across the continent could establish clear legal obligations for stakeholders to act ethically, thus reducing the discretionary power of public officials who often exploit their positions for personal gain (Rahman, 2020; Grasso, 2020). Participants repeatedly linked good faith to more predictable contracting environments and reduced scope for opportunistic behaviour, particularly in payment practices, certification, and variation orders. Experts consistently echoed this perspective in the interviews, highlighting that the codification of good faith would foster a more collaborative environment and enhance transparency in infrastructure projects (Grasso, 2020; Aderibigbe et al., 2023). For MDBs and DFIs, such a statutory obligation could be seen as a way to align domestic project delivery with safeguard standards on integrity and procurement and to strengthen confidence in host-country infrastructure governance.

## 4.2 COLLABORATIVE LEGAL MEASURES ARISING FROM CODIFYING GOOD FAITH

The interviews identified several collaborative legal measures that naturally flow from the codification of good faith. Rather than viewing good faith as an abstract principle,

participants articulated concrete regulatory levers that could be embedded in national systems. These measures are designed to reduce adversarialism, improve governance, and create a more equitable environment for infrastructure development. The seven measures include:

#### 4.2.1 Harmonising Legal Frameworks:

Codifying statutory good faith obligations to promote transparency, fairness and consistency in procurement and contracting.

#### 4.2.2 Promoting Regional Cooperation:

Applying shared good-faith standards to support effective delivery of cross-border infrastructure and energy projects.

#### 4.2.3 Streamlining Procurement Processes:

Simplifying procurement rules to reduce discretion, corruption risks and opportunities for rent-seeking.

#### 4.2.4 Improving Transparency and Accountability:

Enhancing disclosure requirements to strengthen oversight and scrutiny of infrastructure projects.

#### 4.2.5 Implementing Fair Payment Practices:

Introducing prompt-payment protections to improve cash flow and reduce exploitation within supply chains.

#### 4.2.6 Establishing Effective Dispute Resolution Mechanisms:

Providing accessible and timely dispute resolution processes that preserve project continuity.

#### 4.2.7 Enhancing Regulatory Frameworks:

Strengthening regulatory oversight, enforcement and coordination to improve compliance and accountability.

Taken together, these measures situate statutory good faith within a broader agenda of infrastructure governance reform, connecting legal change to concrete shifts in how projects are selected, procured and delivered.

These findings broadly support existing literature that identifies weak governance, limited transparency and institutional discretion as key drivers of corruption within construction and energy sectors (Rahman, 2020; Grasso, 2020). They also reinforce the observations of Aderibigbe et al. (2024), who argued that statutory good faith may provide a mechanism for improving accountability and reducing corruption risks in African infrastructure delivery. However, the interview findings extend the current literature by moving beyond the identification of corruption challenges to propose a structured seven-measure governance framework through which statutory good faith may be operationalised in practice. In this respect, the findings suggest that good faith may function not merely as a contractual principle, but as a broader governance instrument capable of strengthening procurement integrity, institutional trust and infrastructure delivery outcomes across African construction and energy sectors.

*Table 1: Alignment of Interviewee Views with the Seven Collaborative Measures*

| Style Name | Support Level | Key Themes and Contributions | Alignment with Collaborative Measures |
|---|---|---|---|
| **Interviewee 1: Seasoned BSE Engineer** | Strong Support | Argued that statutory good faith would promote transparency, fairness, and collaboration while improving payment discipline and reducing disputes, particularly protecting subcontractors exposed to late payments | Strongly aligns with 1. Harmonising Legal Frameworks and 5. Implementing Fair Payment Practices. Emphasised how codification can ensure fairness and reduce disputes. Highlighted how codification can act as a safeguard for weaker parties and reduce conflict. |
| **Interviewee 2: Legal Director** | Conditional Support | Recognised the benefits of a good faith obligation but warned that it could increase litigation and uncertainty, favouring a phased introduction supported by cultural change. | Aligns with 4. Improving Transparency and Accountability and 7. Enhancing Regulatory Frameworks, advocating gradual reform to minimise legal complexity. |
| **Interviewee 3: Technical Specialist** | Strong Support | Defined good faith in terms of trust, respect, and clarity of expectations, supporting phased legislative reform alongside training and awareness to address adversarial practices. | Strong alignment with 3. Streamlining Procurement Processes and 6. Establishing Effective Dispute Resolution Mechanisms, linking reform to fairer procurement and improved dispute handling. |
| **Interviewee 4: Health & Safety Expert** | Strong Support | Argued that statutory good faith would strengthen compliance cultures and reduce adversarial behaviour, particularly by embedding the principle within existing HSE and compliance systems. | Aligns with 1. Harmonising Legal Frameworks and 6. Establishing Effective Dispute Resolution Mechanisms, highlighting the role of compliance structures in supporting cooperation. |
| **Interviewee 5: Commercial Director** | Moderate Support | Accepted the value of collaborative relationships based on good faith but questioned how such obligations would be enforced in practice and anticipated industry resistance and cost implications. | Aligns with 1. Harmonising Legal Frameworks and 5. Implementing Fair Payment Practices, recognising the rationale for reform while questioning operational implementation. |
| **Interviewee 6: Industry Veteran** | Conditional Support | Supported statutory codification provided it included clear wording and enforceable sanctions, highlighting chronic | Aligns with 1. Harmonising Legal Frameworks, 4. Improving Transparency and Accountability, and 5. Implementing Fair Payment |

| Style Name | Support Level | Key Themes and Contributions | Alignment with Collaborative Measures |
|---|---|---|---|
| | | payment delays and retention abuse while comparing UK practice with good faith regimes in the UAE. | Practices, focusing on systemic reform and improved oversight. |
| **Interviewee 7: Adjudicator** | Strong Support | Strongly supported legislative intervention to overcome common law reluctance toward good faith duties, arguing it could reduce disputes and stabilise payment flows if accompanied by professional training. | Strongly aligns with 3. Streamlining Procurement Processes, 4. Improving Transparency and Accountability, and 6. Establishing Effective Dispute Resolution Mechanisms, emphasising education and guidance. |
| **Interviewee 8: Seasoned Civil Engineer** | Strong Support | Observed that good faith often operates informally in practice but supported statutory recognition as a way to curb adversarial tactics and embed fairness across the supply chain. | Aligns with 3. Streamlining Procurement Processes and 6. Establishing Effective Dispute Resolution Mechanisms, highlighting good faith as a mechanism for simplifying processes and encouraging collaboration. |
| **Interviewee 9: Industry Chief Executive** | Strong Support | Argued that statutory good faith could reduce adversarial disputes, improve collaboration and regularise payment behaviour, while noting the potential of digital tools and AI to support transparency and compliance. | Aligns with 5. Implementing Fair Payment Practices and 6. Establishing Effective Dispute Resolution Mechanisms, emphasising technology's role in reinforcing good faith obligations. |
| **Interviewee 10: Independent Arbitrator & Mediator** | Moderate Support | Acknowledged potential benefits of codification but warned against rigid drafting and emphasised that entrenched cultural norms may limit its effectiveness. | Aligns with 6. Establishing Effective Dispute Resolution Mechanisms, supporting reform while stressing the need for broader cultural and institutional change. |
| **Interviewee 11: Construction Compliance Specialist** | Strong Support | Supported statutory good faith as a means of strengthening transparency, fairness, and payment discipline, particularly benefiting SMEs and encouraging collaborative project environments. | Aligns with 1. Harmonising Legal Frameworks, 5. Implementing Fair Payment Practices, and 6. Establishing Effective Dispute Resolution Mechanisms, focusing on enforceable standards of fairness. |
| **Interviewee 12: Independent** | Conditional Support | Supported the principle of statutory good faith but expressed concern about | Aligns with 1. Harmonising Legal Frameworks and 4. Improving Transparency and |

| Style Name | Support Level | Key Themes and Contributions | Alignment with Collaborative Measures |
|---|---|---|---|
| **Construction Mediator** | | enforceability, malicious compliance, and resistance within established industry cultures. | Accountability, favouring phased reform supported by training and awareness. |
| **Interviewee 13: International Contracts Leader** | Strong Support | Identified adversarialism as systemic and linked to budgeting failures, risk misallocation, scope creep and payment disputes, defining good faith through fair risk allocation, early warnings and timely payment. | Aligns with 1. Harmonising Legal Frameworks, 3. Streamlining Procurement Processes, 5. Implementing Fair Payment Practices, and 6. Establishing Effective Dispute Resolution Mechanisms, highlighting codification as protection for weaker parties. |
| **Interviewee 14: Senior Managing Director (EMEA)** | Moderate Support | Drew on international experience to identify poor communication, opportunistic claims and cross-cultural misunderstandings as drivers of adversarialism while framing good faith as acting in the best interests of the project. | Aligns with 3. Streamlining Procurement Processes, 4. Improving Transparency and Accountability, and 6. Establishing Effective Dispute Resolution Mechanisms, stressing honest communication and incentive-based behavioural change. |

These measures, derived from expert interviews, reflect a shared view that good faith is central to addressing systemic corruption and adversarial practices in Africa's construction and energy sectors. One interviewee observed that codifying good faith could reduce payment delays and improve fairness, particularly on smaller projects (Interviewee 1: Seasoned BSE Engineer), while others stressed the need to address legal and procedural complexities to promote transparency and ethical practice (Interviewee 7: Adjudicator). Collectively, the seven measures align with MDB and DFI concerns around procurement integrity, contract management and the long-term bankability of infrastructure assets. Overall, eight interviewees expressed strong support for codification, three moderate support and three conditional support, with none rejecting the principle outright, suggesting that practitioners view statutory good faith as a viable, though challenging, governance reform for strengthening state capacity in managing public investment.

## 5. LIMITATIONS

This study has several limitations. First, legislation has inherent regulatory limits (Xanthaki, 2017), and codifying good faith presents legal and conceptual challenges. Goal-based legislation developed in advanced economies may prove difficult to operationalise in developing contexts (Umeokafor, 2020). Moreover, good faith is inherently broad and flexible, which may lead to subjective interpretation and inconsistent application across jurisdictions (Saintier, 2017). Although widely recognised in different legal systems (Leggatt, 2016), variations in governance capacity across

African states and the expectations of MDBs and DFIs may affect how such frameworks are implemented.

Second, while a harmonised framework grounded in good faith offers potential benefits, translating regional principles into national legislation may prove complex due to differences in legal traditions, political systems and regulatory capacity across African countries.

Third, the study draws on fourteen semi structured interviews with construction and energy professionals. While thematic saturation is often achieved after approximately twelve interviews in relatively homogeneous samples (Guest et al., 2006), the limited sample size may constrain broader generalisability. Many interviewees were based in mature construction markets, although some had direct experience of African infrastructure projects.

Finally, corruption in Africa's infrastructure sector remains deeply embedded in formal and informal systems (Rahman, 2020; Sabouri et al., 2023). The effectiveness of statutory good faith will therefore depend on political will and credible enforcement (Grasso, 2017; 2020). Further empirical research and pilot programmes are needed to test how such frameworks operate in practice.

## 6. CONCLUSIONS

This study examined whether codifying a statutory duty of good faith within collaborative legal frameworks could help address corruption and infrastructure deficits in Africa's construction and energy sectors. By embedding good faith into national legal systems, governments could strengthen transparency, collaboration and ethical conduct, creating more predictable environments for public authorities, MDBs, DFIs and private investors.

The seven collaborative measures proposed in this research, harmonising legal frameworks, promoting regional cooperation, streamlining procurement, enhancing transparency, implementing fair payment practices, establishing dispute resolution mechanisms and strengthening regulatory oversight, provide a practical governance agenda for improving infrastructure delivery and limiting opportunities for rent seeking.

However, their effectiveness will depend on political will, institutional capacity and cultural change. Phased and context sensitive implementation, supported by pilot programmes, stakeholder engagement and professional training, will therefore be essential.

This study contributes to the literature by advancing statutory good faith beyond its traditional contractual role and positioning it as a governance mechanism capable of addressing corruption, improving procurement integrity and strengthening infrastructure delivery in Africa's construction and energy sectors. The proposed seven-measure collaborative framework provides both a theoretical contribution to infrastructure governance scholarship and a practical reform agenda for policymakers, regulators, MDBs and DFIs. Codifying good faith therefore offers a credible step towards strengthening infrastructure governance and supporting progress towards the United Nations Sustainable Development Goals, particularly Goal 7 and Goal 9.

# 7. REFERENCES


Acemoglu, D. & Verdier, T. (2000) The choice between market failures and corruption. American Economic Review, 90(1) (2000), pp. 194-211. Retrieved from https://www.aeaweb.org/articles?id=10.1257/aer.90.1.194

Aderibigbe, A., Umeokafor, N., Umar, T., & Upadhyay, Y. (2024) Impact of corruption on achieving sustainable development goals within Africa's construction industry. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 544-554. https://doi.org/10.31705/WCS.2024.43. Retrieved from: https://ciobwcs.com/papers/

Aderibigbe, A., Umeokafor, N., & Umar, T. (2023) Constructing for the future: Can the duty of good faith improve payment in the UK construction industry? In Tutesigensi, A & Neilson, C J (Eds) *Proceedings of the 39th Annual ARCOM Conference*, 4-6 September 2023, University of Leeds, Leeds, UK, Association of Researchers in Construction Management, 14-23. https://secure.arcom.ac.uk/submissions/40/published/5c951cf7298bd1f0dc839d996f1d8ef3.pdf

Africa Progress Panel (2015) *Africa Progress Report*. https://reliefweb.int/sites/reliefweb.int/files/resources/APP_REPORT_2015_FINAL_low1.pdf

Amoah, A., Asiama, R. K., Korle, K., & Kwablah, E. (2022). Corruption: Is it a bane to renewable energy consumption in Africa? *Energy Policy*, 163, 112854. https://doi.org/10.1016/j.enpol.2022.112854

Amuakwa-Mensah, F., & Näsström, E. (2021). Role of banking sector performance in renewable energy consumption. *Applied Energy*, 306, 118023. https://doi.org/10.1016/j.apenergy.2021.118023

Bernard, H. (2011). *Research methods in anthropology: Qualitative and quantitative approaches* (5th ed.). Rowman & Littlefield. https://www.zambiancu.org/1zRead/Bernard-ResearchMethodsInAnthropology%20%5Bxoer%5D.pdf

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Defreitas, L. (2023, April 4). *How corruption in developing countries impacts poverty*. The Borgen Project. https://borgenproject.org/corruption-in-developing-countries/

Flick, U. (2009). *An introduction to qualitative research* (4th ed.). Sage Publications. https://vivauniversity.wordpress.com/wp-content/uploads/2014/02/flick-2009-an-introduction-to-qualitative-research-full-book.pdf

Gennaioli, C., & Tavoni, M. (2010). Clean or "Dirty" energy: Evidence on a renewable energy resource curse. *Energy: Resources and Market Series*, 1–40. https://feem-media.s3.eu-central-1.amazonaws.com/wp-content/uploads/NDL2011-063.pdf

Global Witness. (2017, April 10). *Shell knew*. https://globalwitness.org/en/campaigns/oil-gas-and-mining/shell-knew/

Grasso, C. (2023). The Dark Side of Power: corruption and bribery within the energy industry. In *Research Handbook on EU Energy Law and Policy* (pp. 237–256). https://doi.org/10.2139/ssrn.3343314

Grasso, C. (2020). The troubled path toward greater transparency as a means to foster good corporate governance and fight against corruption in the energy sector. In *Handbook of Energy Finance* (1st ed., pp. 363–393). https://doi.org/10.1142/9789813278387_0016

Guest, G., Bunce, A., & Johnson, L. (2005). How many interviews are enough? *Field Methods*, 18(1), 59–82. https://doi.org/10.1177/1525822x05279903

Ikejemba, E. C., Schuur, P. C., Van Hillegersberg, J., & Mpuan, P. B. (2017). Failures & generic recommendations towards the sustainable management of renewable energy projects in Sub-Saharan Africa (Part 2 of 2). *Renewable Energy*, 113, 639–647. https://doi.org/10.1016/j.renene.2017.06.002

James, E. (2025). *How to manage corruption risk in renewable energy projects*. Pinsent Masons. https://www.pinsentmasons.com/out-law/guides/how-to-manage-corruption-risk-in-renewable-energy-projects

Leggatt, J. (2015). *Contractual duties of good faith*. https://www.judiciary.uk/wp-content/uploads/2016/10/mr-justice-leggatt-lecture-contractual-duties-of-faith.pdf

Lin, G. (2009). Higher Education Research Methodology-Literature Method. *International Education Studies*, 2(4), 179–181. https://doi.org/10.5539/ies.v2n4p179

Mante, J. (2018). Mutual trust and co-operation under NEC 3&4: a fresh perspective. *Open Access Institutional Repository at Robert Gordon University (Robert Gordon University)*, 34(4), 231–252. https://rgurepository.worktribe.com/file/247199/1/MANTE%202018%20Mutual%20trust%20and%20co-operation

Moliterni, F., & Moliterni, F. (2017). Analysis of public subsidies to the solar energy sector: corruption and the role of institutions. *AgEcon Search (University of Minnesota, USA)*. https://doi.org/10.22004/ag.econ.259482

Peace Research Institute Oslo (PRIO). (2019). Green Curses and Violent Conflicts: The security implications of renewable energy sector development in Africa – Peace Research Institute Oslo (PRIO). https://www.prio.org/projects/1878

Rahman, K. (2019). Anti-corruption in the renewable energy sector. *U4 Anti-Corruption Resource Centre*. https://www.u4.no/publications/anti-corruption-in-the-renewable-energy-sector

Rimšaitė, L. (2018). Corruption risk mitigation in energy sector: Issues and challenges. *Energy Policy*, 125, 260–266. https://doi.org/10.1016/j.enpol.2018.10.066

Sabouri, B., Demetriades, L., & Mallela, S. K. (2023, January 8). The dirty side of going green: corruption and human rights risks within the clean energy supply chain. Ankura.com. https://ankura.com/insights/the-dirty-side-of-going-green-corruption-and-human-rights-risks-within-the-clean-energy-supply-chain

Saintier, S. (2017). The elusive notion of good faith in the performance of a contract, why still a bête noire for the civil and the common law? Journal of Business Law, 6, 441–460. https://ore.exeter.ac.uk/ndownloader/files/56746337

Saunders, M., Lewis, P., & Thornhill, A. (2012*). Research methods for business students* (6th ed.). Pearson Ltd., Harlow. https://www.scirp.org/reference/referencespapers?referenceid=2474711

Sobjak, A. (2018). Corruption risks in infrastructure investments in Sub-Saharan Africa. In *OECD Global Anti-Corruption & Integrity Forum*. https://www.scirp.org/reference/referencespapers?referenceid=2590959

The Economist. (2022). Corruption is getting worse in many poor countries But rich countries have problems too. https://www.economist.com/graphic-detail/2022/01/25/corruption-is-getting-worse-in-many-poor-countries

Transparency International. (2020). Exporting Corruption 2020 - Publications. Transparency.org. https://www.transparency.org/en/publications/exporting-corruption-2020

Transparency International. (2022). 2022 Corruption Perceptions Index: Explore the results. Transparency.org. https://www.transparency.org/en/cpi/2022

Transparency International. (2024). Corruption Perceptions Index 2024. Transparency.org. https://www.transparency.org/en/cpi/2024

Umeokafor, N. (2019). Why copied or transposed safety, health and well-being legislation and standards are impracticable and irrelevant in developing economies. *Policy and Practice in Health and Safety*, 18(1), 41–54. https://doi.org/10.1080/14773996.2019.1667095

United Nations. (2018, September 13). *Pervasive corruption costs $2.6 trillion; disproportionately affects 'poor and vulnerable' says UN chief*. UN News. https://news.un.org/en/story/2018/09/1018892

United Nations Development Programme. (2022). The cost of corruption. https://undp.medium.com/the-cost-of-corruption-a827306696fb

United Nations Office on Drugs and Crime. (2020). Anti-Corruption Module 1 Key issues: Effects of Corruption. https://www.unodc.org/e4j/zh/anti-corruption/module-1/key-issues/effects-of-corruption.html

World Bank. (2019). Poverty & Equity Brief - Sub-Saharan Africa. In World Bank. https://databankfiles.worldbank.org/public/ddpext_download/poverty/33EF03BB-9722-4AE2-ABC7-AA2972D68AFE/Global_POVEQ_NGA.pdf

Xanthaki, H. (2017). The limits of legislation as a product. *Journal on Legislation*. https://discovery.ucl.ac.uk/id/eprint/1575216/1/Xanthaki_The%20limits%20of%20legislation%20as%20a%20product.pdf

Rathnayake, R.M.D.D., Perera, B.A.K.S. and Kavirathna, A.S., 2026. Strategies to achieve net-zero carbon goals in construction industry. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1611 -1623. DOI: https://doi.org/10.31705/WCS.2026.117. Available from: https://ciobwcs.com/papers/

# STRATEGIES TO ACHIEVE NET-ZERO CARBON GOALS IN CONSTRUCTION INDUSTRY

**R.M.D.D. Rathnayake[1], B.A.K.S. Perera[2] and A.S. Kavirathna[3]**

## *ABSTRACT*

*The construction sector is a major contributor to global carbon emissions, highlighting the urgent need for effective strategies to achieve Net Zero Carbon Buildings (NZCBs). This study aims to investigate how to achieve Net Zero Carbon Goals in Construction. A comprehensive literature review was conducted to establish existing NZCB strategies, followed by a qualitative research approach using semi-structured expert interviews. The findings provide an integrated three-step framework for achieving NZCB including embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation as key steps. The study further identifies a range of applicable strategies under each step, including design efficiency, life cycle assessment, and carbon trading mechanisms. The results highlight that effective implementation of NZCB requires early-stage decision-making, lifecycle-based approaches, and the integration of advanced technologies. This study recommends industry stakeholders to prioritise integrated carbon reduction approaches, enhance professional awareness and training, and adopt digital tools for monitoring and decision-making. Policymakers are encouraged to introduce clear regulations and incentives to accelerate NZCB adoption. This study contributes to both theory and practice by refining NZCB strategy classification and providing an industry-relevant framework. Its implications extend to society by improving environmental performance and promoting sustainable development.*

***Keywords:*** *Embodied Carbon; Net Zero Carbon Buildings (NZCB); NZCB Strategies.*

## 1. INTRODUCTION

The construction industry is highly resource-demanding and plays a major role in environmental degradation due to its substantial energy use, material waste, and carbon emissions (Passer et al., 2020). The construction industry significantly contributes to global carbon emissions, responsible for around 38% of energy-related $CO_2$ emissions globally (Falana et al., 2024). Buildings generate carbon emissions at every stage of their lifecycle, encompassing construction, utilisation, demolition, and disposal (Myint & Shafique, 2024). By 2050, all new buildings must meet net-zero whole-life and embodied carbon targets, while existing buildings will be required to undergo renovation, repair,

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, rathnayakermdd.21@uom.lk
[2] Senior Professor in Quantity Surveying, Department of Building Economics, University of Moratuwa, Sri Lanka, kanchana@uom.lk
[3] Junior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, kavirathnaas.19@uom.lk

refurbishment, or retrofitting to achieve net-zero operational carbon emissions (Falana et al., 2024). Achieving Net Zero Carbon Buildings (NZCBs) for both new and existing structures is widely regarded as one of the most internationally recognised and innovative strategies for decarbonising the building sector (Ohene et al., 2022). NZCB is a building that achieves zero carbon status when the greenhouse gas (GHG) emissions linked to its operational and embodied footprint throughout its entire lifecycle, including disposal, are zero or negative (Myint et al., 2025). NZCB construction is achieved by offsetting emissions produced during the building's production and construction stages, while net zero carbon in operational energy is reached by reducing yearly operational emissions to zero or below through energy-efficient practices and the use of both on-site and off-site renewable energy sources (Abdullah et al., 2024). NZCB achieve a balance of zero emissions during their life cycle, promoting both reduction and compensation by adopting many strategies (Tirelli & Besana, 2023).

To achieve the NZCB goal, it is possible to adopt many strategies, both in the case of new construction and in the case of retrofitting or refurbishment (Tirelli & Besana, 2023). Embodied carbon can be reduced by minimising emissions from the building's materials, type, function, location, orientation, structure, transport, demolition, and reuse/recycling processes. In contrast, operational carbon reduction focuses on decreasing emissions through efficient façade design, improved insulation, advanced ventilation systems, the integration of renewable energy, as well as optimised building location, orientation, height, structural configuration, and occupant behaviour (Myint et al., 2025). Furthermore, multi-objective optimisation methods, such as facade design optimisation, building form selection, and component specification, have been identified as effective approaches for reducing embodied carbon in the built environment (Torabi & Evins, 2024).

The main contributor of CO2 emissions is the construction sector, accounting for 38% of $CO_2$ emissions in 2019, equivalent to 10 billion tons, with 28% from buildings and 10% from construction materials (Tirelli & Besana, 2023). The building sector alone is responsible for more than one-third of total global GHG emissions (Besana & Tirelli, 2022). In addition, the infrastructure and buildings developed by the construction industry require a substantial amount of non-renewable energy, which results in high levels of CO2 emissions (Abdullah et al., 2024). Consequently, achieving a substantial reduction in GHG emissions is critical in the coming decades to mitigate the severe impacts of climate change, including extreme droughts, heatwaves, and floods. In this context, Falana et al. (2024) highlighted that achieving net-zero carbon emissions is the most effective solution to address or mitigate global warming.

From a theoretical perspective, a growing body of literature has examined various aspects of NZCB, including NZCB concepts (Myint & Shafique, 2024; Tirelli & Besana, 2023), NZCB strategies (Lou & Hsieh, 2024), barriers and mitigation measures (Ohene et al., 2022), stakeholder roles across the building life cycle (Falana et al., 2024), indicators, challenges, and strategies in implementing Net-Zero Carbon construction projects (Abdullah et al., 2024), and sustainability considerations (Passer et al., 2020). However, despite these contributions, there remains a lack of studies that comprehensively explore the key steps required to achieve NZCB and the most critical strategies associated with each step. Therefore, addressing both the practical need and the existing theoretical gap, this study aims to investigate how to achieve net-zero carbon goals in construction.

Accordingly, the study objectives are to identify the key steps of achieving NZCB and to investigate the important strategies for each NZCB key step.

# 2. LITERATURE REVIEW

## 2.1 SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

Sustainability in the construction sector supports the fulfilment of present and future generations' needs by conserving energy, water, and natural resources through reuse, recycling, innovative design, and by minimising waste and pollution (Passer et al., 2020). The built environment significantly influences long-term quality of life, economic prosperity, health, well-being, and overall happiness through the planning, design, management, and maintenance of built assets (Besana & Tirelli, 2022). A building is considered sustainable only when all three dimensions which are environmental, economic, and social are adequately addressed throughout its life cycle (Falana et al., 2024). Therefore, the development of sustainable buildings and infrastructure not only enhances human health and well-being but also contributes to reducing social inequalities and promoting inclusive development (Torabi & Evins, 2024).

## 2.2 CONCEPT OF NET ZERO CARBON

The concept of net-zero carbon originates from climate science and is central to global efforts to mitigate climate change (Lou & Hsieh, 2024). Carbon dioxide ($CO_2$), while essential for regulating Earth's temperature and supporting plant life, becomes harmful when present in excessive concentrations, as it intensifies the greenhouse effect and drives global warming (Abdullah et al., 2024). In response, countries under the Paris Agreement have committed to limiting global temperature rise to well below 2 °C, with efforts to cap it at 1.5 °C (UK Green Building Council, 2019). Achieving this target requires a significant reduction in emissions to reach near-zero carbon emissions by mid-century (Lou & Hsieh, 2024). According to Besana and Tirelli (2022), net-zero carbon is achieved when anthropogenic $CO_2$ emissions are balanced by equivalent removals through natural or technological processes over a defined period. This balance necessitates not only substantial emission reductions but also the careful implementation of carbon removal and offset mechanisms (Tirelli & Besana, 2023). Hence, the concept of NZCB has emerged as a key strategy for reducing emissions in the construction sector and contributing to broader decarbonisation goals (Ohene et al., 2022).

## 2.3 KEY STEPS OF NZCB

To date, the building sector accounts for approximately 38% of global carbon emissions (Besana & Tirelli, 2022). Thus, it is crucial to develop building strategies that support the transition toward carbon-neutral buildings (Tirelli & Besana, 2023). NZCB is "When the amount of carbon emissions associated with a building's embodied and operational impacts over the life of the building, including its disposal, is zero or negative" (UK Green Building Council, 2019, p.22). Accordingly, NZCBs are designed to be energy efficient and powered by a combination of on-site and off-site renewable energy sources, with any remaining emissions being offset (Falana et al., 2024). Importantly, controlling and reducing carbon emissions must begin at the design stage and continue through the manufacturing of construction materials, construction processes, technology implementation, and operational phases of the building (Abdullah et al., 2024). According

to Besana and Tirelli (2022), the decarbonization process of a building can be summarised in four phases: reduction of embodied carbon, reduction of operational carbon, increase of renewable energy supply, and compensation of residual embodied emissions (Tirelli & Besana, 2023; UK Green Building Council, 2019). These phases provide a structured framework for systematically addressing carbon emissions throughout the building life cycle. Building on these phases, a range of targeted strategies can be adopted at each stage to facilitate the effective achievement of NZCB objectives, ensuring a comprehensive and integrated approach to carbon neutrality in the built environment.

## 2.4 STRATEGIES OF ACHIEVING NZCB

To attain net-zero carbon construction, it is crucial to develop and apply effective strategies that balance carbon emissions with carbon removal. These approaches focus on minimising or compensating for the emissions generated by construction activities (Abdullah et al., 2024). According to the four-step framework of NZCB by Tirelli and Besana (2023), strategies to achieve NZCBs can be categorised into each step. To reduce embodied carbon emissions, a wide range of strategies has been identified, with particular emphasis on material selection, building design, and construction approaches. The adoption of circular economy principles, including the use of recycled and reused materials, is recognised as a strategy to minimise resource consumption and reduce embodied carbon emissions (Tirelli & Besana, 2023). In addition, the use of biobased materials such as wood, hemp, mycelium, straw, bamboo, cork, cellulose, and wool has gained increasing attention due to their carbon storage potential and lower environmental impact compared to conventional materials (Kamel et al., 2024; Besana & Tirelli, 2022). Furthermore, the selection of low-carbon materials plays a crucial role in reducing embodied emissions. Materials such as timber and cross-laminated timber, cold-formed steel, and interlocking compressed earth bricks (Asman et al., 2020) have also been identified as viable low-carbon options. Moreover, other established strategies include the adaptive reuse of existing buildings, which can achieve up to a 50% reduction in embodied carbon emissions (Hill et al., 2020). Dematerialisation through minimising material use and optimising resource efficiency has been highlighted as a critical approach, as buildings with higher material intensity tend to exhibit greater embodied carbon footprints (Langston & Langston, 2008).

With regard to operational carbon reduction, strategies primarily focus on improving energy efficiency and optimising building performance during the use phase. The utilisation of photosynthetic materials has been explored for their potential to absorb $CO_2$, although their application remains emerging (Lou & Hsieh, 2024). More established approaches include the adoption of energy-efficient HVAC systems and passive design strategies, such as passive solar design, high-performance façades, improved air tightness, and optimised window design to enhance natural ventilation and daylighting (Besana & Tirelli, 2022; Ng et al., 2016). In terms of zero-carbon energy sources, the integration of on-site renewable energy systems, such as photovoltaic panels, is essential to meet operational energy requirements with minimal emissions (Tirelli & Besana, 2023). Additionally, surplus energy generation enables buildings to export electricity to the grid, contributing to broader decarbonisation efforts (Torabi & Evins, 2024). Finally, carbon offset, storage, and compensation strategies address residual emissions that cannot be eliminated through reduction measures. Carbon offsetting, including the use of carbon credits, supports investments in renewable energy and afforestation projects (Tirelli & Besana, 2023). Meanwhile, carbon storage strategies, particularly through the use of

biobased materials, enable the absorption and long-term storage of $CO_2$ within building elements (Kamel et al., 2024). These approaches are typically implemented after maximising emission reductions, highlighting the need for a comprehensive and sequential strategy to achieve NZCB.

## 3. METHODOLOGY

This study adopts a comprehensive literature review to examine existing knowledge on NZCB practices and strategies in the construction sector, followed by a qualitative research approach. The qualitative approach is particularly suitable for analysing original, text-based data using interpretive methods, especially in contexts where existing knowledge is limited (Taherdoost, 2022). It enables the exploration of emerging concepts and the development of new insights through in-depth data collection, rather than testing predetermined hypotheses. As this study investigates the achievement of net-zero carbon goals in construction through NZCB strategies, an area that relies heavily on expert perspectives and practical experiences, a qualitative approach is considered most appropriate. In qualitative data collection, data can be gathered through various methods, including interviews, observations, and document analysis (Rosenthal, 2016). Among these, interviews are the most widely used technique and can be conducted in structured, semi-structured, or unstructured formats. According to Rosenthal (2016), the relatively low level of structure in semi-structured interviews highlights the inherent flexibility of this qualitative data collection approach. Thus, this study employs semi-structured expert interviews to explore the implementation of NZCB strategies in construction. Purposive sampling involves selecting participants with relevant expertise who are able and willing to provide informed insights (Etikan et al., 2016). As this study relies on data collected from industry experts, purposive sampling is considered the most appropriate method. Considering time constraints and the point of data saturation, a total of 15 interviews were conducted. The profiles of the selected experts are presented in Table 1. When selecting the experts, a combination of academic researchers and industry practitioners was chosen to ensure a balanced perspective. Academic experts contributed insights on emerging research developments in the NZCB area, while industry practitioners provided practical, experience-based knowledge related to the implementation of net-zero carbon strategies.

*Table 1: Profiles of experts*

| Respondent Code | Designation | Mandatory qualifications | | Additional qualifications (Satisfy at least two) | | | |
|---|---|---|---|---|---|---|---|
| | | Industry/research experience > 5 years | Experience in net-zero carbon > 3 years | Bachelor's degree in built environment | Postgraduate qualification in built environment | Professional qualifications > 3 years | Index publications in related areas |
| R01 | PhD candidate/ Academic researcher | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| R02 | Quantity Surveyor/ Academic Researcher | ✓ | ✓ | ✓ | - | - | ✓ |

| Respondent Code | Designation | Mandatory qualifications | | Additional qualifications (Satisfy at least two) | | | |
|---|---|---|---|---|---|---|---|
| | | Industry/research experience > 5 years | Experience in net-zero carbon > 3 years | Bachelor's degree in built environment | Postgraduate qualification in built environment | Professional qualifications > 3 years | Index publications in related areas |
| R03 | Project Manager | ✓ | ✓ | ✓ | ✓ | ✓ | |
| R04 | Senior Cost Manager | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R05 | Professor in Civil Engineering/ Academic researcher | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| R06 | Facilities Manager/ Academic researcher | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| R07 | Managing Director | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| R08 | Senior Quantity Surveyor | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R09 | PhD candidate/ Academic researcher | ✓ | ✓ | ✓ | ✓ | - | ✓ |
| R10 | Senior executive in environmental sustainability | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R11 | Chartered Quantity Surveyor | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R12 | Senior lecturer/ Academic researcher | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| R13 | Cost consultant/ Arbitrator/ PhD researcher | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R14 | Senior Professor/Chartered Civil Engineer | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| R15 | Contract Administrator/ PhD researcher | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Data were analysed using manual content analysis, a well-established qualitative technique for interpreting interview data, particularly in situations where quantitative analysis is not applicable (Bengtsson, 2016). This method involves the systematic coding and categorisation of textual data to uncover recurring patterns, themes, and underlying meanings. Accordingly, manual content analysis was deemed appropriate for this study, as it enables an in-depth exploration of participants' perspectives and facilitates the extraction of meaningful insights.

# 4. FINDINGS AND ANALYSIS

## 4.1 KEY STEPS OF ACHIEVING NZCB

In literature findings, 4 key steps for achieving NZCB were identified as embodied carbon reduction, operational carbon reduction, zero carbon energy sources and carbon offset, storage and compensation. However, findings from the expert interviews led to a refinement of these categories into three primary steps: embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation, which collectively align with the core strategies for achieving NZCB. R01 and R03 emphasised that *"strategies related to 'zero-carbon energy sources' contribute to both embodied and operational carbon reduction and therefore should not be treated as a separate category".* It was highlighted that the adoption of renewable energy systems contributes simultaneously to reducing operational emissions and influencing embodied carbon through material and system choices. Therefore, treating zero-carbon energy sources as a distinct category was considered conceptually redundant. Hence, strategies related to zero-carbon energy were integrated into the embodied and operational carbon reduction categories. Consequently, the framework for achieving NZCB was consolidated into three key steps, providing a more streamlined and practically relevant structure for understanding and implementing NZCB strategies within the construction sector.

## 4.2 IMPORTANT STRATEGIES FOR EACH NZCB KEY STEP

In literature findings, five NZCB strategies were identified under Embodied Carbon Reduction, three NZCB strategies were identified under Operational Carbon Reduction, and two NZCB strategies were identified under carbon offset, storage and compensation. These are presented as the literature-based strategies. Among those strategies, some were excluded due to less affirmation from experts, which are shown in strikethrough (Ex: ~~Modular Integrated construction~~). In addition, respondents suggested strategies are displayed in bold letters (Ex: **Industrial symbiosis**), whereas the modified strategies are shown in italicised (Ex: *Trading carbon credits).* Overall, the strategies without strikethrough are the validated strategies after expert interviews. The finalised NZCB strategies corresponding to each key step are summarised in Table 2.

*Table 2: Categorisation of important NZCB Strategies based on key steps*

| Key Steps | Important NZCB strategy | In lit | Respondents |
|---|---|---|---|
| Embodied Carbon Reduction | Adopt circular economy practices | ✓ | R02, R08 |
| | Use biobased (Carbon storing) materials | ✓ | R09, R12 |
| | Use of other low-carbon materials | ✓ | R04, R05 |
| | ***Industrial symbiosis*** | - | R02, R06, R15 |
| | ***Design efficiency*** | - | R13, R05, R11 |
| | ***Conduct Life Cycle Assessment (LCA)*** | - | R03, R07 |
| | ***Use of construction automation techniques (ex: AR, VR, 3D printing)*** | - | R14, R03 |
| | ***Creating awareness among professionals*** | - | R05, R08 |
| | ***Use digital carbon tracking tools*** | - | R03, R12 |

| Key Steps | Important NZCB strategy | In lit | Respondents |
|---|---|---|---|
| | ***Reduce process emissions*** | - | R10 |
| | ***Develop building design based on Green Building certification (LEED, BREEAM and GreenSL)*** | - | R10 |
| | ***Use local materials*** | - | R01 |
| | ***Use highly durable materials*** | - | R05 |
| | ~~Modular Integrated construction~~ | ✓ | - |
| | ~~Use of prefabricated materials~~ | ✓ | - |
| Operational Carbon Reduction | Passive designs and Architecture | ✓ | R08, R12 |
| | Decarbonised Grid | ✓ | R07 |
| | Onsite renewables | ✓ | R10 |
| | ***Alignment of GHG emission reduction plan with SBTi (Science Based Targets initiative)*** | - | R01, R04, R09 |
| | ***Operational management*** | - | R03, R05, R13 |
| | ***Smart Building Management Systems (BMS)*** | - | R07 |
| | ***Use digital carbon tracking tools*** | - | R03 |
| | ***Energy storage systems*** | | R02 |
| | ~~Energy-efficient HVAC~~ | ✓ | - |
| | ~~Utilise photosynthetic materials~~ | ✓ | - |
| Carbon offset, Storage and Compensation | *Trading carbon credits* | ✓ | R06, R10 |
| | Use biobased materials | ✓ | R02, R08 |
| | ***Carbon sink- forestation, carbon capture and storage projects*** | - | R12 |
| | ***Use of Harvested wood*** | - | R05 |

As per Table 2, with regard to embodied carbon reduction, the majority of the strategies identified in the literature were validated by the experts. However, some refinements were made based on their insights. For instance, prefabricated light timber, initially categorised under operational carbon reduction, was reconsidered. R01 stated "*prefabricated light clay timber is related to embodied carbon reduction and insert it as a separate strategy under embodied carbon reduction as 'use of prefabricated materials' without limiting the strategy to a single material type*". However, R02 mentioned that "*both modular integrated construction and prefabricated materials do not reduce embodied carbon, it depends with the material used to construct, if it constructed with a high carbon intensive material, there can be high carbon emission and it also consumes lot of energy*". R03 also agreed with that opinion. Consequently, due to limited consensus, 'modular integrated construction' and 'use of prefabricated materials' were not considered as strategies for embodied carbon reduction.

A significant strategy identified is industrial symbiosis, highlighted by R06 as the practice of connecting construction projects with nearby industries and utilising other industries' waste, by-products, and energy as inputs. R02 stated that *"industrial symbiosis reduces carbon emission by reducing waste and minimising the use of virgin material".* Similarly,

R15 stated that *"Material and energy exchange in various industries reduces embodied emissions and the applicability of industrial symbiosis depends on policy support",* emphasising the importance of regulatory frameworks for successful implementation. Design efficiency was another key strategy proposed by R13 to reduce embodied carbon emissions. R05 suggested that efficient design can be achieved through future-proofing buildings, designing for extended lifespan, design for disassembly, avoiding over-specification, and engineering optimised components. Furthermore, R11 stated that *"design resiliently also supports design efficiency, and it is the best option for climate adaptive buildings to remain resilient in a disaster situation, if not it will lead to demolitions and will cause carbon emission",* highlighting the role of resilience in minimising lifecycle carbon impacts. The importance of conducting LCA was also highlighted as a key strategy. According to R07, LCA supports informed decision-making, particularly during the design stage, by identifying high-carbon hotspots early in the project lifecycle. This enables designers and stakeholders to implement targeted interventions to minimise emissions. Furthermore, the strategy of reducing process emissions was identified, which involves optimising site planning, utilising energy-efficient or renewable-powered construction equipment and improving material transportation logistics. These measures collectively contribute to lowering emissions associated with construction activities. Technological advancements were also recognised as enablers of embodied carbon reduction. R14 stated that *"use of construction automation techniques such as AR/VR/3D printing technologies minimises rework and material waste contribute to reduce carbon emission"*. R03 also confirmed this strategy is applicable and noted that *"it requires a very skilled workforce and high initial investment"*.

In addition, adherence to green building certification systems, such as BREEAM, LEED, and GreenSL, was identified as a practical strategy for reducing embodied carbon. These certification frameworks promote energy efficiency, resource optimisation, and reduced GHG emissions throughout the building lifecycle. The use of locally sourced materials was also strongly supported by the experts, as it reduces transportation-related emissions and contributes to the local economy. However, R01 argued that *"material quality and availability should be carefully verified before adopting local materials"*. Creating awareness among professionals was another important strategy highlighted by R05, stating that *"educating and training professionals on net-zero carbon principles and emerging technologies can support the adoption of low-carbon design approaches, materials, and construction techniques"*. Supporting this perspective, R08 stated that *"continuous training and strong institutional support are necessary to make this strategy practical and effective".* Moreover, the use of digital carbon tracking tools was proposed as an innovative approach to monitor and manage carbon emissions. R03 noted that real-time carbon accounting enables transparent decision-making across different project stages and is already widely adopted in countries such as Germany and Switzerland. R12 stated that *"using highly durable materials with long service life reduces the need for frequent replacements and maintenance, thereby minimising carbon emissions".* Collectively, these strategies were identified under the 'embodied carbon reduction' step to achieve NZCB in construction.

Following the omission of the step: 'zero-carbon energy sources', the strategies which were initially classified under that category were reclassified under 'operational carbon reduction strategy'. However, certain strategies, such as the use of photosynthetic

materials, were excluded due to limited awareness and a lack of consensus among the respondents. R11 mentioned that *"there can be carbon emission from photosynthetic materials after the operation and cannot be considered as a strategy*". Further, R02 and R08 also agreed with that. In the literature, 'Energy-efficient HVAC systems' were identified as a strategy. R15 further suggested expanding this to include energy-efficient transport and electrical systems. Additionally, R07 proposed 'smart BMS systems' as a separate strategy, stating that all energy-efficient service systems could be integrated and managed under smart BMS systems. Therefore, the use of smart BMS systems was retained as a key strategy, replacing the narrower focus on HVAC systems. R03 proposed 'operational management' as an overarching strategy that encompasses proper maintenance of building elements and occupant behaviour management, which were also suggested by R05 and R13. R03 stated that *"it involves conducting regular maintenance and managing occupants' behaviour, and the above two strategies fall under this broader approach".* Furthermore, aligning GHG emission reduction plans with the Science Based Targets initiative (SBTi) was identified as a strategic approach to achieving measurable and science-driven emission reductions. R09 noted that SBTi supports organisations in setting targets aligned with climate science and emissions through energy efficiency improvements, renewable energy adoption, and fuel switching. This strategy was strongly supported by the other experts. Furthermore, R03 proposed the 'use of digital carbon tracking tools' as a strategy to reduce operational carbon emissions, noting that *"operational-phase carbon accounting can be clearly monitored and demonstrated through digital tracking tools".* Accordingly, this strategy was categorised under both embodied and operational carbon reduction steps, as digital tracking tools can monitor and manage carbon emissions throughout both construction and operational phases. Moreover, R02 explained that energy storage facilitates coordination with the national grid and allows excess renewable energy to be stored and utilised as needed, thereby improving energy efficiency and reducing reliance on fossil fuels. Overall, these strategies contribute to the effective reduction of operational carbon emissions.

In relation to carbon offset, storage, and compensation step, several modifications were made to the literature-based strategies. The concept of purchasing carbon credits was expanded to include both buying and selling, leading to the revised strategy of 'trading carbon credits'. Additionally, new strategies such as carbon sinks, carbon capture and storage, and the use of harvested wood were proposed by the experts. Further clarification revealed that forestation and carbon capture and storage are components of carbon sink strategies. R12 stated *that "forestation involves planting trees, restoring forests to absorb CO2 from the atmosphere"*. R05 pointed out that *"harvested wood stores carbon absorbed during tree growth"*. In addition, the use of bio-based materials was identified as a strategy contributing to both embodied carbon reduction and carbon offset, storage, and compensation. The experts highlighted that bio-based materials reduce embodied carbon through lower carbon-intensive production processes while also acting as carbon storage mechanisms by storing absorbed atmospheric carbon during their lifecycle. Therefore, this strategy was categorised under both steps due to its dual contribution towards NZCB achievement. These strategies were widely supported by the respondents as effective mechanisms for compensating residual emissions. However, the experts acknowledged that carbon offsetting practices are still relatively underdeveloped in many developing countries, although they are more widely implemented in developed contexts. Despite this limitation, there was a general consensus that carbon offset, storage, and

compensation strategies are applicable and hold significant potential for supporting the achievement of NZCB targets within the construction industry.

## 5. DISCUSSION

To achieve net-zero carbon construction, it is essential to develop and implement effective strategies that balance carbon emissions with carbon removal (Abdullah et al., 2024). This study examined NZCB strategies across key steps to identify those most applicable to the construction industry. While existing literature classifies NZCB strategies into four key steps: embodied carbon reduction, operational carbon reduction, zero-carbon energy sources, and carbon storage (Besana & Tirelli, 2022), the empirical findings support a more integrated three-step framework. The exclusion of zero-carbon energy sources as a standalone category reflects expert consensus that such strategies inherently contribute to both embodied and operational carbon reduction, thereby supporting a more holistic and practice-oriented classification. Furthermore, the evaluation of literature-derived strategies through expert interviews revealed a high level of alignment, with most strategies being confirmed as applicable. In particular, the strong emphasis on embodied carbon reduction strategies supports existing studies that highlight the significance of early design decisions, material selection, and lifecycle thinking in reducing emissions (Hill et al., 2020; Kamel et al., 2024). Apart from the strategies identified in the literature, including adopting circular economy practices (Tirelli & Besana, 2023) and using bio-based materials (Besana & Tirelli, 2022), the empirical findings emphasise the importance of novel, under-explored strategies such as industrial symbiosis and the use of digital carbon tracking tools. Similarly, the findings on operational carbon reduction are largely consistent with existing literature, particularly in relation to passive design and energy-efficient systems (Ng et al., 2016). The incorporation of smart BMS and alignment with the SBTi highlights a shift towards more integrated, measurable, and performance-based approaches. Considering carbon offset, storage, and compensation, the findings align with previous studies that emphasise the role of carbon credits and offset mechanisms as a final step after maximising emission reductions (Tirelli & Besana, 2023). The expansion of this category to include carbon sinks, carbon capture and storage, and harvested wood reflects a broader and more practical interpretation of offset strategies. Overall, this study contributes to the body of knowledge by bridging theoretical frameworks with practical insights, offering a more streamlined and context-sensitive approach to achieving NZCBs.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The building sector contributes significantly to global carbon emissions through both operational activities and the manufacturing of construction materials. In response, NZCBs have emerged as an important approach for reducing carbon emissions across the building life cycle. This study aims to investigate how to achieve net-zero carbon goals in construction. The findings identified embodied carbon reduction, operational carbon reduction, and carbon offset, storage, and compensation as the key strategic areas for NZCB implementation. The study further revealed that embodied carbon reduction strategies received strong emphasis, particularly through lifecycle thinking, the use of bio-based and low-carbon materials, and industrial symbiosis. Operational carbon reduction strategies such as passive design, smart BMS, and performance-based approaches were also identified as critical to improving building carbon performance. In

addition, the study highlighted the growing importance of carbon offset, storage, and compensation mechanisms, including carbon sinks, harvested wood products, and carbon credits, despite their relatively limited implementation in developing countries. Overall, it suggests a strong potential for future adoption, provided that appropriate regulatory and institutional support is established. The successful delivery of NZCBs requires strong collaboration among all stakeholders, including policymakers, developers, investors, urban planners, architects, and construction companies. This study recommends that construction stakeholders adopt an integrated approach to NZCB implementation by prioritising embodied and operational carbon reduction strategies from the early design stage. Greater emphasis should be placed on lifecycle thinking and digital carbon tracking tools to support informed decision-making. Continuous training and awareness programmes are essential to enhance understanding of NZCB principles and emerging technologies. Additionally, policymakers should establish clear regulatory frameworks and incentives to encourage the adoption of low-carbon materials, renewable energy systems, and carbon offset mechanisms.

Considering the impact of this study to the industry, it provides a structured framework of NZCB strategies that can guide decision-making and improve carbon performance across building life cycles. For literature, the study contributes to existing knowledge by refining NZCB strategy classification and highlighting the importance of integrating theoretical and empirical perspectives. From a societal perspective, the adoption of NZCB strategies can contribute to climate change mitigation, improved environmental quality, and enhanced human well-being. Nevertheless, this study is subject to several limitations. The findings are primarily based on a qualitative approach with a relatively small sample size of experts, which may limit the generalisability of the results. Further, the study relies on expert opinions, which may be influenced by individual experiences and contextual factors. Despite these limitations, the study provides valuable insights into NZCB strategies and offers a foundation for future research. Future research could explore the economic feasibility and cost implications of implementing these strategies in different contexts. Investigating policy frameworks, regulatory barriers, and incentives in developing countries would also provide valuable insights for enhancing NZCB adoption. Moreover, case studies examining the performance of NZCB projects over time would contribute to a deeper understanding of their long-term benefits and challenges.

## 7. REFERENCES

Abdullah, A., Yusof, L. M., & Rahman, R. A. (2024). Indicators, challenges and strategies in implementing net-zero carbon construction projects. *Planning Malaysia*, *22*(3), 303–319. https://doi.org/10.21837/PM.V22I32.1509

Asman, N. S. A., Bolong, N., Mirasa, A. K., Asrah, H., & Saad, I. (2020). Interlocking compressed earth bricks as low carbon footprint building material. *IOP Conference Series: Earth and Environmental Science*, *476*(1), 012086. https://doi.org/10.1088/1755-1315/476/1/012086

Bengtsson, M. (2016). How to plan and perform a qualitative study using content analysis. *NursingPlus Open*, *2*, 8–14. https://doi.org/10.1016/j.npls.2016.01.001

Besana, D., & Tirelli, D. (2022). Reuse and retrofitting strategies for a net zero carbon building in Milan: An analytic evaluation. *Sustainability*, *14*(23), 16115. https://doi.org/10.3390/su142316115

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1-4. https://doi.org/10.11648/j.ajtas.20160501.11

Falana, J., Osei-Kyei, R., & Tam, V. W. (2024). Towards achieving a net zero carbon building: A review of key stakeholders and their roles in net zero carbon building whole life cycle. *Journal of Building Engineering*, *82*, 108223. https://doi.org/10.1016/J.JOBE.2023.108223

Hill, S., Dalzell, A., & Allwood, M. (2020). *Net zero carbon buildings: three steps to take now*. Arup. https://www.arup.com/globalassets/downloads/insights/net-zero-carbon-buildings-three-steps-to-take-now.pdf

Kamel, E., Pittau, F., Dal Verme, L. M., Scatigna, P., & Iannaccone, G. (2024). A parametric integrated design approach for life cycle zero-carbon buildings. *Sustainability*, *16*(5), 2001. https://doi.org/10.3390/SU16052001

Langston, Y. L., & Langston, C. A. (2008). Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies. *Construction Management and Economics*, *26*(2), 147–160. https://doi.org/10.1080/01446190701716564

Lou, H. L., & Hsieh, S. H. (2024). Towards zero: A review on strategies in achieving net-zero-energy and net-zero-carbon buildings. *Sustainability*, *16*(11), 4735. https://doi.org/10.3390/su16114735

Myint, N. N., & Shafique, M. (2024). Embodied carbon emissions of buildings: Taking a step towards net zero buildings. *Case Studies in Construction Materials*, *20*, e03024. https://doi.org/10.1016/J.CSCM.2024.E03024

Myint, N. N., Shafique, M., Zhou, X., & Zheng, Z. (2025). Net zero carbon buildings: A review on recent advances, knowledge gaps and research directions. *Case Studies in Construction Materials*, *22*, e04200. https://doi.org/10.1016/j.cscm.2024.e04200

Ng, T. S. K., Yau, R. M. H., Lam, T. N. T., & Cheng, V. S. Y. (2016). Design and commission a zero-carbon building for hot and humid climate. *International Journal of Low-Carbon Technologies*, *11*(2), 222–234. https://doi.org/10.1093/IJLCT/CTT067

Ohene, E., Chan, A. P. C., & Darko, A. (2022). Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector. *Building and Environment*, *223*, 109437. https://doi.org/10.1016/J.BUILDENV.2022.109437

Passer, A., Lützkendorf, T., Habert, G., Kromp-Kolb, H., Monsberger, M., Eder, M., & Truger, B. (2020). Sustainable built environment: transition towards a net zero carbon built environment. *International Journal of Life Cycle Assessment*, *25*(6), 1160–1167. https://doi.org/10.1007/s11367-020-01754-4

Rosenthal, M. (2016). Qualitative research methods: why, when, and how to conduct interviews and focus groups in pharmacy research. *Currents in Pharmacy Teaching and Learning*, *8*(4), 509–516. https://doi.org/10.1016/j.cptl.2016.03.021

Taherdoost, H. (2022). What are different research approaches? comprehensive review of qualitative, quantitative, and mixed method research, their applications, types, and limitations. *Journal of Management Science & Engineering Research*, *5*(1), 53–63. https://doi.org/10.30564/jmser.v5i1.4538

Tirelli, D., & Besana, D. (2023). Moving toward net zero carbon buildings to face global warming: A narrative review. *Buildings*, *13*(3), 684. https://doi.org/10.3390/BUILDINGS13030684

Torabi, M., & Evins, R. (2024). Towards net-zero carbon buildings: Investigating the impact of early-stage structure design on building embodied carbon. *International Journal of Life Cycle Assessment*, *30*, 2374–2389. https://doi.org/10.1007/s11367-024-02287-w

UK Green Building Council. (2019). *Net zero carbon buildings: A framework definition*. https://www.ukgbc.org/wp-content/uploads/2019/04/Net-Zero-Carbon-Buildings-A-framework-definition.pdf

Prasadinee, W.K.R., Chandanie, H. and Nanayakkara, N.B., 2026. Sustainability impacts of industry 4.0 in construction project management. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1624-1636. DOI: https://doi.org/10.31705/WCS.2026.118. Available from: https://ciobwcs.com/papers/

# SUSTAINABILITY IMPACTS OF INDUSTRY 4.0 IN CONSTRUCTION PROJECT MANAGEMENT

**W.K.R. Prasadinee[1], H. Chandanie[2] and N.B. Nanayakkara[3]**

## *ABSTRACT*

*Construction projects frequently face time and cost overruns due to ineffective Construction Project Management (CPM). The integration of Industry 4.0 (I4.0) digital technologies has emerged as a transformative approach to enhance traditional CPM practices. While I4.0 adoption offers considerable benefits, its sustainability implications remain underexplored. Given that I4.0 applications can produce both positive and negative impacts across sustainability dimensions, this study adopts a Triple Bottom Line (TBL) perspective to examine the environmental, economic, and social implications of implementing I4.0 technologies in CPM in Sri Lanka. A mixed-method approach was employed, with data collection in two phases: Phase I involved five expert interviews, and Phase II comprised a questionnaire survey. Qualitative and quantitative data were analysed using manual content analysis and the Relative Importance Index (RII) method, respectively. The findings reveal that I4.0 applications positively impact TBL sustainability: environmentally, through reduced resource use, lower construction waste, and early detection of environmental risks; economically, via improved project tracking, scheduling, and timely completion; and socially, through fewer manual errors, greater transparency, and accountability. Negative implications were also identified: environmentally, high energy demand and electronic waste; economically, high implementation costs and expenses for recruiting and training skilled personnel; and socially, workplace inequalities, digital surveillance, and potential job losses. This study provides an empirical, TBL-based evaluation of I4.0-enabled CPM practices in Sri Lanka, addressing a largely unexplored area and offering insights into sustainable digital transformation in the country's construction industry.*

***Keywords:*** *Construction Project Management; Industry 4.0; Sri Lanka; Triple Bottom Line.*

## 1. INTRODUCTION

Resource depletion and global financial crises highlight the importance of effective Construction Project Management (CPM) (Ifeanyi et al., 2025). CPM is a continuous process encompassing planning, execution, monitoring, and control throughout a project's lifecycle, from initiation to closure (Alvarenga et al., 2020). Effective CPM ensures project success by achieving timely delivery, budget adherence, and quality

[1] Quantity Surveyor, Currie & Brown, Sri Lanka, prasadineewkr@gmail.com
[2] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, chandanieh@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nishadibn@uom.lk

outcomes as per agreed terms (Zheng & Qiang, 2022). However, traditional CPM practices face numerous challenges (Pakhale & Pal, 2020), which can be mitigated through the integration of digital technologies (Zhu et al., 2022).

The technological evolution, pioneered by I4.0, is distinguished for the integration of cyber-physical systems, automation, and real-time data exchange (Folgado *et al*., 2024). Driven by the principles of I4.0, these advancements encouraged the industries to re-evaluate traditional practices and embrace more data-centric, automated workflows (Khan *et al*., 2023). Hence, the construction industry integrated digital technologies, including the Internet of Things (IoT), Big Data, Augmented Reality (AR), Virtual Reality (VR), Building Information Modelling (BIM), Artificial Intelligence (AI), Blockchain, Robotics, Drones and other related advancements as a response to I4.0. (Srivastava *et al*., 2022). Integration of I4.0 in construction industry yields enormous benefits for the construction industry, including reduced rework, reduced coordination problems, better communication between various stakeholders, reduced document errors, fewer claims, reduced paperwork, reduction in time and cost overrun, and reduction in lifecycle cost among the many benefits (Pakhale & Pal, 2020), and hindered due to technological incapacity among industry practitioners, their inherent resistance to change, inadequate technological infrastructure, and deficiencies in the legal framework and its enforcement (Karunaratne & Abeynayake, 2023). Most significantly, I4.0 technologies are capable of making both positive and negative impacts on the sustainability of the construction industry in the CPM context (Balasubramanian *et al*., 2022).

Globally, numerous studies have examined digitalisation in the construction industry (D'Alberto et al., 2025; Johari et al., 2024). However, existing research on I4.0 and sustainability has predominantly focused on social aspects (Calvetti et al., 2020; Sherratt et al., 2020), with limited attention given to a comprehensive TBL perspective that integrates economic, environmental, and social dimensions. Nevertheless, scholars have emphasised the importance of adopting a TBL approach, as the impacts of I4.0 may vary or even conflict across these dimensions (Balasubramanian et al., 2022). In addition, the application of digitalisation within CPM remains underexplored (Marnewick & Marnewick, 2022), especially within the Sri Lankan context. Accordingly, this study aims to explore the sustainability impacts of I4.0 in construction project management in Sri Lanka, and was achieved through identifying the implications on TBL sustainability from the implementation of I4.0 applications in CPM practices in Sri Lanka, as well by identifying the strategies to enhance sustainable digitalising CPM.

# 2. LITERATURE REVIEW

## 2.1 SUSTAINABILITY THROUGH A TRIPLE BOTTOM LINE (TBL) LENS

Sustainability is a holistic concept concerned with long-term resource management and its impacts (Saunders & Hughes, 2018). The widely recognised definition from the Brundtland Report (1987) describes it as meeting present needs without compromising future generations. Over time, sustainability has evolved beyond environmental concerns to include economic and social dimensions (Choi & Ng, 2011; Ford & Despeisse, 2016). Accordingly, it is understood through the Triple Bottom Line (TBL), balancing environmental, economic, and social aspects (Holden et al., 2014).

Environmental sustainability focuses on maintaining ecological balance and responsible resource use; economic sustainability emphasises long-term growth while preserving

resources; and social sustainability addresses the impacts of business and technological activities on people (Choi & Ng, 2011).

## 2.2 SUSTAINABILITY IMPLICATIONS OF DIGITALISATION IN THE CONSTRUCTION INDUSTRY

Sustainability concepts play a crucial role in construction projects (Stanitsas *et al*., 2021). The construction industry has a significant impact on the environment, contributing to the generation of two to three billion tonnes of building waste annually due to its high global consumption of natural resources (Jain, 2021). Additionally, the industry holds economic and social significance, contributing 5–7% to the Gross Domestic Product (GDP) in many countries (Alaloul *et al*., 2021), and employing millions of people (Babalola & Aigbavboa, 2022). Consequently, a strong link exists between construction and the three pillars of sustainability i.e. (i) economy, (ii) society, and (iii) environment (Goh *et al*., 2020). Integrating I4.0 technologies in the construction industry impacts both positively and negatively for sustainability (Wang & Guo, 2022). Therefore, adopting a TBL perspective is essential, as the sustainability impacts of I4.0 technologies may conflict across economic, environmental, and social dimensions (Balasubramanian *et al*., 2022). Figure 1 illustrates the positive and negative implications on TBL sustainability from I4.0 applications in construction.

***Economic - Positive Implication***
- Reduced cost of construction projects and operational costs at site
- Reduced project completion time
- Improved project tracking and scheduling
- Reduced material misplacement
- Increased productivity and efficiency of projects
- Reduced costly design variations at advanced stages of projects
- Reduced human bias and subjectivity in decision-making
- Reduced delays and unforeseen costs in construction

***Economic - Negative Implications***
- Increased cost of implementation of I4.0 applications
- Uncertain return on investment
- Increased cost of security on I4.0 applications
- Increased cost of recruiting, training and retaining the technology professionals
- Increased costs of subscriptions and upgrades relevant to I4.0 applications
- Costly delays and disruptions to the construction process due to technology failures

***Social – Positive Implications***
- Improved onsite workers' mental and physical well-being
- Improved security and safety
- Improved transparency and trust
- Improved accountability of all stakeholders
- Improved large-scale training
- Reduced manual errors and reworks
- Improved workforce skills
- Increased stakeholder communication and collaboration
- Increased employee productivity
- Reduces the need for manpower by automating a number of site inspection processes and defect management processes
- Creation of new jobs

***Social – Negative Implications***
- Increased data privacy issues
- Increased data breaches
- Increased digital surveillance of employees and reduce the employment relationships
- Inequalities at the workplace on wages and career advancements
- Increased job losses

***Environmental – Positive Implications***
- Reduced resource consumption and wastage in construction
- Reduced energy consumption in construction
- Reduced paper-based documentation
- Reduced environmental footprint from construction
- Enhanced end-of-life recovery of materials/ components
- Reduced carbon dioxide emission in construction
- Reduced environmental accidents due to early detection and predictive analytics

***Environmental - Negative Implications***
- Increased e-waste generation
- Increased energy usage for I4.0 applications

*Figure 1: Literature findings (implications of industry 4.0 applications in CPM practices on TBL sustainability)*
*(Source: Balasubramanian et al., 2022)*

Environmental sustainability involves preserving natural systems and ensuring resource use does not exceed ecological limits (Moghayedi et al., 2021). Industry 4.0 (I4.0) technologies present both positive and negative environmental implications. Positively, they enable process optimisation, efficient resource use, reduced waste, and lower energy consumption through real-time data and analytics (Ford & Despeisse, 2016; Balasubramanian et al., 2022). However, they may also increase energy demand and generate electronic waste (Ford & Despeisse, 2016).

Economic sustainability focuses on maintaining long-term financial stability (Balasbaneh & Sher, 2026). Digitisation contributes positively by translating environmental efficiencies into cost savings, including reduced labour, inspection, and administrative costs, thereby lowering overall construction expenses (Balasubramanian et al., 2022).

Social sustainability ensures equitable access to resources, opportunities and services, while upholding and justly distributing human rights to enhance the quality of life in society (Pieterse, 2011). Social sustainability has both positive and negative implications. The positive implications include the improved health and safety of workers (Holden *et al*., 2014). This is promising, because construction is one of the sectors that constitute the largest percentages of worker death by accidents and injuries. Moreover, Construction 4.0 will generate several new types of jobs, especially jobs in science and technology (Ejsmont *et al*., 2020). However, there are several adverse societal implications of I4.0. More discourse from an ethical and humanitarian perspective is required on the potential loss of jobs of unskilled blue-collar workers and their future role in the sector due to I4.0 (Yılmaz & Bakış, 2015). An increase in the surveillance of employees raises questions about employee freedom and privacy. More discourse is required on the data-related privacy, cyber-security, and data breaches surrounding I4.0 (Balasubramanian *et al*., 2022).

# 3. RESEARCH METHODOLOGY

This study examines the effective implementation of sustainable digitalisation in CPM, aligned with the three pillars of sustainability. A mixed-method approach was adopted, combining quantitative analysis to identify positive and negative TBL implications, and qualitative analysis to explore strategies for sustainable digitalisation in CPM. Accordingly, expert interviews and questionnaire surveys were employed as key research strategies. Data collection and analysis formed the core of the methodology (Chalmers & Armour, 2019), conducted in two phases as outlined below.

### 3.1.1 Phase I: Expert Interviews

Expert interviews were conducted with five professionals experienced in I4.0 applications in construction and CPM to refine the sustainability implications identified in the literature, with specific relevance to the Sri Lankan context. In selecting the experts, a problem and expertise-centred approach is appropriate than a convenience approach (Von Soest, 2022). Existing literature on expert interviews provides limited guidance regarding an exact sample size (Saunders & Townsend, 2016). Instead, the authors suggest that the sample should be sufficiently large to achieve data saturation while remaining small enough to facilitate in-depth analysis. Accordingly, emphasis is placed on justifying the adequacy of the selected sample rather than adhering to a predetermined number of participants. Therefore, employing purposive sampling, this study engaged five experts who satisfied the established selection criteria. The sample size was deemed adequate

upon reaching data saturation, with priority given to the depth and richness of insights rather than the quantity of participants. The respondent profiles are presented in Table 1.

*Table 1: Expert respondent profile*

| Respondent | Designation | Experience (Years) | Educational Qualification | Professional Qualification | Knowledge area | |
|---|---|---|---|---|---|---|
| | | | | | CPM | I4.0 |
| **E1** | Project Manager | 28 | B.Sc. Eng, M.Sc. | Chartered Engineer | Well aware | Well aware |
| **E2** | Project Manager | 25 | B.Sc. Eng | Chartered Engineer | Well aware | Well aware |
| **E3** | Project Manager | 20 | B.Sc. Eng | Chartered Engineer | Well aware | Well aware |
| **E4** | Project Manager | 16 | B.Sc. Eng | Chartered Engineer | Well aware | Well aware |
| **E5** | Assistant Project Manager | 10 | B.Sc. Eng | Chartered Engineer | Well aware | Well aware |

### 3.1.2 Phase II: A questionnaire survey

A questionnaire survey was conducted among 38 construction professionals (CPs) experienced in I4.0 applications and CPM, selected through snowball sampling. The sample size is considered sufficient for exploratory quantitative analysis within a specialised professional group. The data collection tool for the questionnaire survey, the semi-structured questionnaire was developed under 02 main sections, Section 1 in identifying the positive and negative implications on TBL sustainability from the I4.0 applications in CPM practices in Sri Lanka and Section 2 to identify the strategies for enhance sustainable digitalising CPM. Section 1 included a Likert scale (1–5, from “Extremely Low” to “Extremely High”) to prioritise sustainability implications. Further, the refined list of positive and negative implications on TBL sustainability from the I4.0 applications in CPM practices in Sri Lanka. Section 2 comprised of open-ended questions to identify strategies for sustainable digitalisation in CPM. Additionally, the questionnaire was assessed for validity. Content validity was established through the evaluation of the questionnaire by five experts, who reviewed the items for their appropriateness, relevance, and adequacy in representing the constructs under investigation (Hossan et al., 2025). Furthermore, the qualitative data underwent member checking, whereby survey participants were given the opportunity to review and verify the accuracy of the transcribed data and emerging themes, ensuring that their views were authentically represented (Soysal & Türkmen, 2024). In parallel, inter-coder reliability was assessed within the research team by having two researchers independently code the qualitative data and subsequently compare their coding outcomes to evaluate consistency (Hossan et al., 2025). Further, following the authors, any discrepancies identified were resolved through collaborative discussions until consensus was reached. Collected data were analysed using manual and descriptive methods, with the RII applied for quantitative analysis.

# 4. RESEARCH FINDINGS, ANALYSIS, AND DISCUSSION

## 4.1 EXPERT INTERVIEW FINDINGS AND ANALYSIS

### 4.1.1 Implications on TBL Sustainability from The Implementation of I4.0 Applications in CPM Practices In Sri Lanka

The positive and negative TBL sustainability implications identified through the literature were refined for the Sri Lankan context via expert interviews. Table 2 presents the finalised implications.

In relation to the positive economic implications, E2 emphasised that incorporating I4.0 applications in CPM practices allows faster and more informed decision making as it provides access to real-time data and analytics that enables faster and more informed decision-making, allowing project managers to respond swiftly to changing project requirements, market conditions, and stakeholder preferences, ultimately resulting in timely project completion. E4 stated that "*I4.0 applications have the capability to reduce the construction and operation costs as when I4.0 applications are integrated with the CPM processes it enables a minimal labour-intensive environment*". According to E3, this integration enhances predictive maintenance, which shall minimise cost of maintenance, and manage disputes arising due to poor payment and documentation practices. As per E1, predictive analytics facilitated through the I4.0 applications shall identify the potential risks early and allow proactive mitigation strategies there by avoiding costly disruptions. Negatively, E3 highlighted 'the complexity of integration and interoperability' that described the difficulty of connecting, coordinating, and enabling different digital technologies, systems, software platforms, and stakeholders to work together seamlessly within CPM particularly under I4.0. In relation to positive social implications, E5 stated the fact that integrating I4.0 applications and CPM practices increases the employee productivity where it enables the flexible work arrangements to improve work-life balance. In relation to negative social implications, experts highlighted that digital surveillance of employees in a troublesome manner disrupts the work pattern of employees leading to dissatisfaction, resistance and reduces professionalism.

## 4.2 SURVEY FINDINGS AND ANALYSIS

The RII scores reflect the level of importance assigned to each implication. A 60% RII value is taken as the benchmark, and implications with scores below this threshold are not considered applicable to the Sri Lankan construction industry. Table 2 illustrates the ranked list of implications on TBL sustainability from the I4.0 applications in CPM practices in Sri Lanka.

*Table 2: Positive and negative implications on TBL sustainability from the I4.0 applications in CPM practices in Sri Lanka*

| Expert Findings | 5 | 4 | 3 | 2 | 1 | RII | Rank |
|---|---|---|---|---|---|---|---|
| ***Implications on Environmental Sustainability*** | | | | | | | |
| ***Positive*** | | | | | | | |
| Reduced resource consumption and wastage | 16 | 12 | 6 | 3 | 1 | 0.75 | 3 |
| Reduced energy consumption | 18 | 12 | 5 | 2 | 1 | 0.80 | 2 |
| Reduced carbon emissions, specifically CO2 emissions | 21 | 11 | 4 | 2 | 0 | 0.85 | 1 |

| Expert Findings | 5 | 4 | 3 | 2 | 1 | RII | Rank |
|---|---|---|---|---|---|---|---|
| Greater end-of-life recovery of materials/ components | 11 | 12 | 8 | 5 | 2 | 0.65 | 4 |
| Reduced Environmental accidents due to early detection and predictive analytics | 8 | 11 | 9 | 6 | 4 | 0.55 | 5 |
| ***Negative*** | | | | | | | |
| Greater e-waste | 10 | 13 | 8 | 5 | 2 | 0.73 | 2 |
| High energy intensity for large storage and computing power requirements | 16 | 12 | 6 | 3 | 1 | 0.81 | 1 |
| ***Implications on Economic Sustainability*** | | | | | | | |
| ***Positive*** | | | | | | | |
| Reduce the cost of construction, operation and maintenance of the project | 14 | 15 | 6 | 3 | 0 | 0.81 | 7 |
| Improvement in tracking and scheduling | 21 | 12 | 4 | 1 | 0 | 0.88 | 1 |
| Avoid costly design variations at advanced stages of the project | 22 | 11 | 4 | 1 | 0 | 0.88 | 1 |
| Lower human bias and subjectivity in decision-making | 16 | 14 | 6 | 2 | 0 | 0.83 | 6 |
| Reduced delays, reworks and unforeseen costs | 18 | 13 | 6 | 1 | 0 | 0.85 | 5 |
| Project completion as scheduled | 20 | 12 | 5 | 1 | 0 | 0.87 | 3 |
| Avoid and mitigate disputes that occur due to poor payment and defective documentation | 19 | 13 | 4 | 2 | 0 | 0.86 | 4 |
| ***Negative*** | | | | | | | |
| Increased cost of implementation | 22 | 11 | 4 | 1 | 0 | 0.88 | 1 |
| Uncertain return on investments | 16 | 13 | 7 | 2 | 0 | 0.83 | 4 |
| The incurrence of costs related to security | 10 | 13 | 11 | 4 | 0 | 0.75 | 7 |
| The incurrence of costs related to recruiting and retaining technology professionals and training | 19 | 12 | 5 | 2 | 0 | 0.85 | 2 |
| The incurrence of costs related to subscription charges and upgraded costs | 18 | 13 | 5 | 2 | 0 | 0.85 | 3 |
| Over-reliance on technology can lead to costly delays and disruptions in the case of technology failure | 12 | 14 | 9 | 3 | 0 | 0.78 | 6 |
| The complexity of integration and interoperability | 14 | 14 | 7 | 3 | 0 | 0.81 | 5 |
| ***Implications on Social Sustainability*** | | | | | | | |
| ***Positive*** | | | | | | | |
| Improved workers mental and physical well-being | 13 | 14 | 8 | 3 | 0 | 0.79 | 8 |
| Improved security and safety at site | 16 | 13 | 7 | 2 | 0 | 0.83 | 6 |
| Improved transparency and trust | 20 | 12 | 5 | 1 | 0 | 0.87 | 2 |
| Improved accountability of all stakeholders | 19 | 12 | 6 | 1 | 0 | 0.86 | 3 |
| Enhances employee skill level through training programs | 14 | 14 | 8 | 2 | 0 | 0.81 | 7 |
| Reduced manual errors and reworks | 21 | 12 | 4 | 1 | 0 | 0.88 | 1 |
| Improved communication and collaboration through digital platforms | 18 | 13 | 5 | 2 | 0 | 0.85 | 4 |

| Expert Findings | 5 | 4 | 3 | 2 | 1 | RII | Rank |
|---|---|---|---|---|---|---|---|
| Reduced manpower requirement by automating several site inspection processes and defect management processes | 17 | 13 | 6 | 2 | 0 | 0.84 | 5 |
| ***Negative*** | | | | | | | |
| Increased data privacy issues | 13 | 14 | 7 | 4 | 0 | 0.79 | 5 |
| Diminish opportunities for face-to-face interaction and human connection | 15 | 14 | 6 | 3 | 0 | 0.82 | 3 |
| Increased digital surveillance of employees | 16 | 14 | 6 | 2 | 0 | 0.83 | 2 |
| Inequalities at the workplace in terms of wages and career advancements (with employees with ICT knowledge tending to get paid more) | 18 | 13 | 5 | 2 | 0 | 0.85 | 1 |
| Increased job losses | 14 | 14 | 7 | 3 | 0 | 0.81 | 4 |

The integration of I4.0 technological advancements, including autonomous robots, simulation, horizontal and vertical system integration, AI, the IoT, cybersecurity, cloud storage, additive manufacturing, augmented reality, and big data analytics, into the construction industry has the potential to enhance performance significantly, enabling up to 30% faster production and a 25% increase in efficiency (De Oliveira et al., 2026). Beyond productivity gains, these technologies play a crucial role in promoting environmentally responsible, socially equitable, and economically viable industrial practices (Khan et al., 2025). Therefore, it is essential to examine their impact on the three core pillars of sustainability, environmental, economic, and social, within the various industrial contexts including the construction sector. Globally, there is a growing emphasis on improving the sustainability of the construction industry, driven by persistent challenges such as high carbon emissions, escalating construction costs, compromised health and safety standards, and low productivity levels (Balasubramanian et al., 2022).

I4.0 applications shall address the TBL sustainability concerns in CPM through enhanced waste reduction, optimised energy usage in buildings, optimised energy consumption in building operation, worker health and safety at sites, and lifespan of the buildings (Khan et al., 2025). The authors specified that IoT and AI improves the energy efficiency by reducing the carbon footprint. CPs strongly supported this benefit, as reflected by "reduced carbon emissions, specifically $CO_2$ emissions" receiving the highest RII score of 0.85. Considering the increased concerns over climatic changes occurring in Sri Lanka over the recent decades (Fonseka et al., 2025), CPs consider the massive responsibility of the industry to engage in reducing the environmental footprint resultant through the construction activities. Relating to the negative impacts, the study emphasised greater e-waste and high energy usage for the advanced technologies. Supporting this, Balasubramanian *et al*. (2022) specifically stated the high energy demand for computer-based applications, AI and big data analytics. Further, CPs highlighted the challenges associated with the limited e-waste management and recycling facilities available in Sri Lanka. They noted that many obsolete IoT devices used on construction sites are ultimately disposed of as landfill waste. Additionally, CPs identified that battery-powered technological equipment contributes to the accumulation of toxic battery waste, as proper disposal and recycling mechanisms are not widely practised within the Sri Lankan context. Mainly, experts emphasised that the positive environmental and social

implications are getting converted to positive economic implications. This is justified through the findings of Balasubramanian et al. (2022) that the resource savings from I4.0 technologies are pioneering the effective management of the construction cost, and also the enhanced site safety enables effective worktime reducing the downtimes. Anyhow, all the experts highlighted the higher upfront cost of implementing I4.0 applications, where CPs identified this as the most severe negative implication related to the Sri Lankan context. E3 stated that when considering the developing nature of the Sri Lankan economy affording on these costly advanced technologies by the construction industry is challenging. Franco et al. (2022) emphasised capability of I4.0 technologies in making positive implications on the social sustainability in CPM through initiative such as improving the health and safety of workers, reduced work accidents, and replacement of manual works with digital activities. CPs re-emphasised the reduced manual errors and reworks as a positive implication by ranking it as the highest positive implication with a RII of 0.88. Experts established the possibility of utilising drone technology in structuring construction, mapping, and monitoring. Also, by considering the nature of blockchain technology, E2 highlighted its potential in enhancing the data transparency and trust among stakeholders. CPs stated that the use of Industry 4.0 technologies, such as drones at Sri Lankan construction sites, significantly enhances site monitoring, reduces rework, and promotes transparency among stakeholders, thereby addressing many of the challenges associated with manual project management processes. Negatively, I4.0 endeavours shall impact by threatening the job roles of the professionals (Khan et al., 2025). Anyhow, the spotlight of the Sri Lankan context was the probable inequalities at the workplaces in terms of wages and the career advancements, and the possibility of employees to rely more on digital technologies.

## 4.3 STRATEGIES FOR ENHANCE SUSTAINABLE DIGITALISING CPM

Questionnaire survey was further utilised in identifying the effective strategies for sustainable digitalising of CPM, addressing economic, social, and environmental considerations. In terms of **environmental** considerations, CPs emphasised the appropriateness of *conducting comprehensive risk assessments* to identify and mitigate negative impacts associated e-waste generation, improper disposal of electronic and battery waste, and also the carbon emissions from the technological infrastructure. Additionally, R9 and R20 emphasised the importance of *promoting sustainability and updating regulations* to support the deployment of sustainable technologies. The particular strategy shall be promoted through incentivising sustainability efforts and promoting collaboration and knowledge-sharing among industry peers and partners. On the **economic** front, respondents emphasised the *need for effective financial planning and investment in research and development to overcome potential challenges associated with digitalisation*, as proposed by R1 and R4. Further, the CPs emphasised that effective financial planning shall be utilised in addressing many negative implications of economic sustainability such as reducing the cost of construction, operation and maintenance of the project, reducing delays, reworks and unforeseen costs, and avoiding and mitigating disputes between the parties involved. Moreover, R3 and R5 highlighted the importance of *educating stakeholders about the economic benefits and productivity gains of I4.0 applications* compared to traditional project management practices.

From a **social** perspective, emphasis was placed on *enhancing cybersecurity to mitigate data breaches*, with R1 suggesting that the *government could reduce implementation costs by lowering taxes on I4.0 equipment and data-related fees*. Additionally,

*comprehensive training and education programs*, as advocated by R2 and R5, were highlighted to equip workers at all levels with the necessary digital literacy skills, which shall address the data privacy issues due to unawareness. *Engagement with stakeholders*, as suggested by R3 and R4, emerged as a crucial aspect, involving top-level management support, training and development initiatives, and providing opportunities for implementing novel technologies. This strategy shall become useful in overcoming the negative impacts of I4.0 implementation, such as diminished opportunities for face-to-face interaction and human connection, and also the issues with increased digital surveillance of employees. Overall, the insights provided by the respondents underscore the interconnectedness of economic, social, and environmental factors in the adoption of sustainable digitalisation practices in CPM. By addressing these aspects holistically, stakeholders can work towards achieving greater efficiency, cost-effectiveness, and sustainability in construction projects, thereby contributing to positive outcomes for both the industry and the environment.

## 5. CONCLUSIONS

This study examined the positive and negative sustainability implications of digitalising CPM through I4.0 technologies in the Sri Lankan construction industry using a TBL perspective. The findings indicate that digitalisation enhances project efficiency, resource optimisation, and decision-making, while introducing environmental, financial, and workforce-related challenges. Environmentally, key benefits include reduced resource use, improved waste management, and early risk detection, though these are offset by increased energy demand and electronic waste. Economically, improved tracking, scheduling, timely delivery, and reduced rework support project performance, whereas high implementation costs, uncertain returns, integration complexity, and skills shortages remain significant barriers. Socially, digitalisation improves transparency, accountability, safety, and error reduction, but raises concerns regarding job displacement, inequality, surveillance, and data privacy. Construction practitioners shall utilise the I4.0 technologies effectively in their projects and mitigate associated risks while managing its economic, environmental and social impacts on the CPM practices. Further, the construction organisations shall utilise the results to shape digital transformation strategies that optimise TBL performance and ensure sustainable implementation of I4.0 in CPM. Future research should adopt longitudinal approaches to better understand the long-term sustainability impacts of I4.0-enabled CPM practices.

## 6. REFERENCES

Alaloul, W.S., Musarat, M.A., Rabbani, M.B.A., Iqbal, Q., Maqsoom, A. & Farooq, W. (2021), Construction Sector contribution to Economic stability: Malaysian GDP distribution, *Sustainability*, *13*(9), 5012. https://doi.org/10.3390/su13095012.

Alvarenga, A., Matos, F., Godina, R. & Matias, J.C.O. (2020), Digital transformation and knowledge management in the public sector, *Sustainability*, *12*(14), 5824. https://doi.org/10.3390/su12145824.

Amri, T. A., Khetani, K. P., & Marey-Perez, M. (2021). Towards Sustainable i4.0: Key skill areas for Project Managers in GCC Construction Industry. *Sustainability*, *13*(15), 8121. https://doi.org/10.3390/su13158121.

Babalola, I.H. & Aigbavboa, C.O. (2022), Evaluating communication features of human resource management practices: The construction industry in Lagos State, Nigeria, *Businesses*, *2*(4), 471–485. https://doi.org/10.3390/businesses2040030.

Balasbaneh, A. T., & Sher, W. (2026). A Systematic Literature review of Internet of Things (IoT) applications in Sustainable Construction Project management. *Sustainability*, *18*(5), 2614. https://doi.org/10.3390/su18052614.

Balasubramanian, S., Shukla, V., Islam, N. & Manghat, S. (2022), Construction industry 4.0 and sustainability: An enabling framework, *IEEE Transactions on Engineering Management*, 711–19. https://doi.org/10.1109/tem.2021.3110427.

Calvetti, D., Magalhães, P.N.M., Sujan, S.F., Gonçalves, M.C. & De Sousa, H.J.C. (2020), Challenges of upgrading craft workforce into Construction 4.0: Framework and agreements, *Proceedings of the Institution of Civil Engineers - Management Procurement and Law*, *173*(4),158–165. https://doi.org/10.1680/jmapl.20.00004.

Chalmers, J., & Armour, M. (2018). The Delphi Technique. In *Handbook of Research Methods in Health Social Sciences*,1–21. https://doi.org/10.1007/978-981-10-2779-6_99-1.

Choi, S. & Ng, A. (2011), Environmental and economic dimensions of sustainability and price effects on consumer responses, *Journal of Business Ethics*, *104*(2), 269–282. https://doi.org/10.1007/s10551-011-0908-8.

D'Alberto, G., Raj, K., Tiburcio, V. A., & Coraglia, U. M. (2025). Innovative procedures and tools for the digitalisation of management construction processes in PA: A systematic scoping review. *Buildings*, *15*(19), 3457. https://doi.org/10.3390/buildings15193457

De Oliveira, J., Schreiber, D., & Jahno, V. D. (2025). Sustainability in civil construction through industry 4.0 and BIM technologies. *Automation in Construction*, *182*, 106729. https://doi.org/10.1016/j.autcon.2025.106729.

Ejsmont, K., Gladysz, B. & Kluczek, A. (2020), Impact of industry 4.0 on sustainability—Bibliometric literature review," *Sustainability*, *12*(14), 5650. https://doi.org/10.3390/su12145650.

Folgado, F., Calderón, D., González, I., & Calderón, A. (2024). Review of industry 4.0 from the perspective of automation and supervision systems: Definitions, architectures and recent trends. *Electronics*, *13*(4), 782. https://doi.org/10.3390/electronics13040782.

Fonseka, P. U., Zhang, H., Premasiri, R., Samarasuriya, C., & Rathnayake, U. (2025). Assessing microclimatic influences in Colombo metropolitan area (CMA) amidst global climate change: A comprehensive study from 1980 to 2022. *Environmental Monitoring and Assessment*, *197*(2), 199. https://doi.org/10.1007/s10661-025-13648-9

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Franco, J.D.A.B., Domingues, A. M., De Almeida Africano, N., Deus, R. M., & Battistelle, R. A. G. (2022). Sustainability in the civil construction sector supported by industry 4.0 technologies: Challenges and opportunities. *Infrastructures*, *7*(3), 43. https://doi.org/10.3390/infrastructures7030043

Goh, C. S., Chong, H., Jack, L., & Faris, A. F. M. (2019). Revisiting triple bottom line within the context of sustainable construction: A systematic review. *Journal of Cleaner Production*, *252*, 119884. https://doi.org/10.1016/j.jclepro.2019.119884

Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our Common Future revisited. *Global Environmental Change*, *26*, 130–139. https://doi.org/10.1016/j.gloenvcha.2014.04.006

Hossan, D., Wolfs, B., Jesmin, N.M.S., & Petkovic,M. (2025). Questionnaire Validity and Reliability: A Review with Practical Guidelines. *Journal of Entrepreneurship, Business and Economics*, *13*(1), 135–186. https://www.scientificia.com/index.php/JEBE/article/view/230

Hübner, D., Moghayedi, A., & Michell, K. (2022). The impact of industry 4.0 technologies on the environmental sustainability of commercial property by reducing the energy consumption. *IOP Conference Series Earth and Environmental Science*, *1101*(6), 062018. https://doi.org/10.1088/1755-1315/1101/6/062018

Ifeanyi, E. I., Kenechi, P. I., & Nonso, I. E. (2025, May 24). Construction project management goal-outcome aperture: Evidence from Enugu, Nigeria. *Journal of Environmental Management and Safety*, *16*(2), 206-223. https://doi.org/10.83032/jems.vol16no2.579

Jain, M. S. (2021). A mini review on generation, handling, and initiatives to tackle construction and demolition waste in India. *Environmental Technology & Innovation*, *22*, 101490. https://doi.org/10.1016/j.eti.2021.101490

Johari, M. S., Mahmud, S. H., Mohamed, S. F., Misnan, M. S., Kamarudin, T., Dzahir, M. A. M., & Utama, W. P. (2024). Digitalization: Potentials of digital technology in construction industry. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *50*(1), 136–150. https://doi.org/10.37934/araset.50.1.136150

Karunaratne, B.C.T.M. and Abeynayake, D.N., 2023. Potential impacts of blockchain technologyimplementation on construction contract management in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara,K.G.A.S., Ramachandra, T. and Ranadewa, K.A.T.O. (eds). Proceedings of the 11th World ConstructionSymposium, 21-22 July 2023, Sri Lanka. [Online]. pp. 860-872. DOI:https://doi.org/10.31705/WCS.2023.69. Available from: https://ciobwcs.com/papers/

Khan, I. S., Ahmad, M. O., & Majava, J. (2023). Industry 4.0 innovations and their implications: An evaluation from sustainable development perspective. *Journal of Cleaner Production*, *405*, 137006. https://doi.org/10.1016/j.jclepro.2023.137006.

Khan, M. I., Yasmeen, T., Khan, M., Hadi, N. U., Asif, M., Farooq, M., & Al-Ghamdi, S. G. (2025). Integrating industry 4.0 for enhanced sustainability: Pathways and prospects. *Sustainable Production and Consumption*, *54*, 149–189. https://doi.org/10.1016/j.spc.2024.12.012

Marnewick, C., & Marnewick, A. L. (2022). Digitalization of project management: Opportunities in research and practice. *Project Leadership and Society*, *3*, 100061. https://doi.org/10.1016/j.plas.2022.100061

Moghayedi, A., Awuzie, B., Omotayo, T., Jeune, K. L., Massyn, M., Ekpo, C. O., Braune, M., & Byron, P. (2021). A Critical Success Factor Framework for Implementing Sustainable Innovative and Affordable Housing: A Systematic Review and Bibliometric analysis. *Buildings*, *11*(8), 317. https://doi.org/10.3390/buildings11080317

Pakhale, P. D., & Pal, A. (2020). Digital project management in infrastructure project: a case study of Nagpur Metro Rail Project. *Asian Journal of Civil Engineering*, *21*(4), 639–647. https://doi.org/10.1007/s42107-020-00224-4

Pieterse, E. (2011b). Recasting urban sustainability in the South. *Development*, *54*(3), 309–316. https://doi.org/10.1057/dev.2011.62

Saunders, A. M., & Hughes, M. (2018). Overcoming Sustainability Displacement: The challenge of making sustainability accessible in the here and now. In *CSR, sustainability, ethics & governance* (pp. 39–53). https://doi.org/10.1007/978-3-319-71449-3_3

Sherratt, F., Dowsett, R., & Sherratt, S. (2020). Construction 4.0 and its potential impact on people working in the construction industry. *Proceedings of the Institution of Civil Engineers - Management Procurement and Law*, *173*(4), 145–152. https://doi.org/10.1680/jmapl.19.00053

Soysal, Y., & Türkmen, S. (2024). Reinterpreting the member checking validation strategy in qualitative research through the Hermeneutics lens. *Qualitative Inquiry in Education Theory & Practice*, *2*(1), 42–63. https://doi.org/10.59455/qietp.19.

Srivastava, A., Jawaid, S., Singh, R., Gehlot, A., Akram, S. V., Priyadarshi, N., & Khan, B. (2022). Imperative role of technology intervention and implementation for automation in the construction industry. *Advances in Civil Engineering*, *2022*(1). https://doi.org/10.1155/2022/6716987

Stanitsas, M., Kirytopoulos, K., & Leopoulos, V. (2020). Integrating sustainability indicators into project management: The case of construction industry. *Journal of Cleaner Production*, *279*, 123774. https://doi.org/10.1016/j.jclepro.2020.123774

Von Soest, C. (2022). Why do we speak to experts? Reviving the strength of the expert interview method. *Perspectives on Politics*, *21*(1), 277–287. https://doi.org/10.1017/s1537592722001116

Wang, K., & Guo, F. (2022). Towards Sustainable Development through the Perspective of Construction 4.0: Systematic Literature Review and Bibliometric Analysis. *Buildings*, *12*(10), 1708. https://doi.org/10.3390/buildings12101708

Yılmaz, M., & Bakış, A. (2015). Sustainability in construction sector. *Procedia - Social and Behavioral Sciences*, *195*, 2253–2262. https://doi.org/10.1016/j.sbspro.2015.06.312

Zheng, J., & Qiang, M. (2022). Understanding the changes in construction project managers' competences through resume data mining. *Journal of Civil Engineering and Management*, *28*(4), 305–319. https://doi.org/10.3846/jcem.2022.16579

Zhu, H., Hwang, B., NGO, J., & Tan, J. P. S. (2022). Applications of smart technologies in construction project management. *Journal of Construction Engineering and Management*, *148*(4). https://doi.org/10.1061/(asce)co.1943-7862.0002260

Ramasingha, K.S., Soorige, D. and Natasha, K.A.D.M., 2026. Temperature and humidity control in operating theatres: BMS vs. Thermostat systems. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1637-1650. DOI: https://doi.org/10.31705/WCS.2026.119. Available from: https://ciobwcs.com/papers/

# TEMPERATURE AND HUMIDITY CONTROL IN OPERATING THEATRES: BMS VS. THERMOSTAT SYSTEMS

**K.S. Ramasingha[1], S.D.A. Soorige[2] and K.A.D.M. Natasha[3]**

## *ABSTRACT*

*Maintaining proper temperature and humidity in operating theatres (OTs) is essential for infection control, patient safety, and equipment performance. This study examines the effectiveness of environmental monitoring and control practices in Sri Lankan hospitals, comparing building management system (BMS)-enabled facilities with traditional thermostatically controlled settings. Although international standards such as ASHRAE 170 recommend temperatures of 20–24°C and relative humidity of 40–60%, implementation is inconsistent. A multi-case study approach was used, involving two BMS-enabled and two non-BMS hospitals. Findings show that although BMS systems enable real-time monitoring, issues such as delayed responses, threshold deviations, and energy saving compromises impact compliance. Non-BMS setups lack centralized monitoring, rely on inconsistent manual adjustments, and offer limited transparency. Common challenges across all scenarios include technical errors, limited staff awareness, and behavioural impacts such as frequent door openings and comfort-based overlaps. The study highlights the need for targeted strategies across both system types. Key recommendations include staff training, engineering-clinical collaboration, visual compliance indicators, and adoption of IoT-based monitoring in non-BMS environments. This research addresses a gap in OT environmental management in Sri Lanka and suggests practical, system-specific solutions to improve safety and compliance.*

***Keywords:*** *ASHRAE 170; Building Management Systems; Indoor Environmental Control; Operating Theatre; Temperature and Humidity*

## 1. INTRODUCTION

Indoor Environmental Quality (IEQ) refers to the performance of the indoor environment (Patnaik et al., 2017) and includes factors affecting occupant well-being, such as indoor air quality, lighting, thermal comfort, acoustics, drinking water, ergonomics, and electromagnetic exposure (Mujeebu, 2019). Among these, temperature and humidity are key determinants of indoor air quality, along with ventilation, airflow, and pollutant levels (Türk, 2022). Inadequate temperature and humidity can reduce air quality and contribute to sick building syndrome (Fang et al., 2004), while maintaining proper levels is

[1] Property Management Coordinator, Sales & Handover, Shangri-La Group, Sri Lanka, skalani316@gmail.com
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, sooriged@uom.lk
[3] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, miyukin@uom.lk

particularly critical in specialized environments such as healthcare, pharmaceutical, and microbiological facilities (Vijayalakshmi et al., 2022).

Proper temperature and humidity control in healthcare facilities is crucial for infection prevention, patient comfort, and equipment integrity (G & Balaji, 2023; Kumar et al., 2024). Temperature and humidity requirements in hospitals are complex, varying by medical procedure and the function of each area (G & Balaji, 2023; Sadrizadeh & Loomans, 2016). Operating theaters (OTs) are critical hospital environments requiring precise temperature and humidity control to prevent infection rather than for comfort (Mohta, 2010; Katz, 2016). Major deviations from proper environmental conditions can reduce efficiency, harm surgical outcomes, and increase morbidity and mortality risk. Moreover, there are standards for operating room air conditioning (Mohta, 2010). According to Sánchez-Barroso and Sanz-Calcedo (2019), UNE 100713:2015, ASHRAE 170-2017, and EN 16244 are common, globally recognized standards used to evaluate OT environmental performance. Heating, Ventilation, and Air Conditioning (HVAC) control temperature, humidity, and air quality, playing a crucial role in maintaining optimal conditions in hospital OT (Hussain et al., 2020). However, in complex facilities such as hospitals, HVAC systems alone are insufficient to maintain optimal temperature and humidity levels. Advanced technologies play a crucial role in continuously monitoring and regulating these environmental parameters within the desired range. Building Management System (BMS) provides an integrated platform to collect real-time data from various building systems and issue control commands to the installed technologies (Vcelak et al., 2017). Furthermore, the use of IoT sensors enhances this process by providing a cost-effective way to automatically measure and control temperature and humidity by transmitting data to a secure server, enabling continuous monitoring and precise environmental control throughout the facility (Darji, 2021). Although BMS has been popular globally for many years, its use in Sri Lanka remains limited, with only a few facilities implementing it (Kumara et al., 2016). Hospitals in Sri Lanka largely rely on standalone thermostats for HVAC control, making it essential to evaluate OT temperature and humidity practices under both BMS-integrated and independent systems to assess current effectiveness and technology performance.

Many studies worldwide examine thermal comfort, indoor air quality, and temperature-humidity control systems, highlighting the role of HVAC systems, indoor environmental conditions, and advanced technologies such as BMS (Bearg, 2019; Mazzei et al., 2005; Zeng et al., 2026). Limited research exists on process-cooling environments like hospital OT. However, while areas such as indoor environmental control parameters, HVAC system performance, and energy efficiency have been extensively studied in the global literature, comparatively less attention has been given to the application and performance of BMS in OTs (Ahmadzadehtalatapeh, 2014; Balaras et al., 2007; Hussain et al., 2020;).

OTs require strict standards for sterilization, air exchange, filtration, and pressure to minimize infection risk and ensure safe surgery (Fredrick & Kumaran, 2018). Despite the importance of these parameters, there is a lack of focused studies assessing the efficiency of temperature and humidity control mechanisms in operating rooms, especially in the Sri Lankan context. This research gap becomes more pronounced when considering the performance differences between facilities that use integrated BMS for environmental monitoring and those that rely solely on standalone thermostat-based HVAC controls. Furthermore, there is a lack of empirical studies that evaluate and compare the ability of these control approaches to maintain compliance with prescribed temperature and relative

humidity requirements under actual operating conditions. This gap is particularly evident in healthcare facilities within developing and tropical regions, where environmental control demands are high, and building automation adoption varies considerably. Even though BMS have become widely adopted globally, their adoption remains limited in the Sri Lankan context (Kumara et al., 2016). Most hospitals still rely on standalone thermostats, highlighting the need to assess their effectiveness in maintaining standard OT conditions.

Accordingly, this study will have 3 objectives: 1. To study the current regulations related to maintaining temperature and humidity requirements for OTs. 2. Understand the current situation of compliance to identified standards and investigate the potential causes of deviations in BMS and traditional thermostat-controlled environments. 3. Propose expert strategies for enhancing compliance with established standards in OTs in Sri Lankan healthcare facilities. The findings of this study explain how various IEQ controls, such as thermostat control and BMS, affect the effectiveness of compliance in OTs. It also highlights implications for healthcare facility managers, engineers, decision-makers, and users of healthcare facilities in selecting and implementing appropriate environmental control strategies to enhance compliance, operational performance, and environmental management in critical healthcare spaces. Ultimately, the study contributes to the limited body of knowledge on OT environmental control in Sri Lanka, addressing a research area that has received relatively little attention in the existing literature.

# 2. LITERATURE REVIEW

## 2.1 TEMPERATURE AND HUMIDITY MONITORING AND CONTROLLING IN OTS

The air conditioning system of OTs should provide high comfort for patients and the surgical team by avoiding patient hypothermia, medical team discomfort, and anaesthetic gas pollution, controlling microclimatic parameters such as temperature, humidity, and air velocity (Cannistraro & Cannistraro, 2016). Key areas like ICUs, pharmacies, and OTs need an integrated monitoring system for temperature and humidity (Guo et al., 2016). Carefully controlled temperature and humidity are required to balance the needs of the surgical team and the patient (Katz, 2016).

According to Brock (1975), most surgeons prefer 18.5–21 °C, some 21–22 °C, with 21 °C being the optimal ambient temperature, though universally acceptable conditions are difficult to achieve. ASHRAE 170 recommends 20–24 °C, a range supported by multiple studies, though surgical teams often favour lower temperatures in practice (Ufat et al., 2017). Moreover, several studies demonstrated that RH often exceeds the acceptable range given by the ASHRAE 170 (Accelix, 2022; Mustafa et al., 2019). Therefore, proper monitoring and control are significant in OTs' temperature and humidity control. Katz (2016) notes that OTs have strict environmental needs, where small changes can affect safety and comfort. AC systems must meet NABH and government standards to prevent risks like hypothermia and anesthetic gas exposure (Mishra et al., 2021), though global guidelines vary, making review of local and international standards essential. The table below summarizes recommended temperature and humidity ranges.

*Table 1: Standard requirements for OTs*

| Standard | Temperature | Humidity |
|---|---|---|
| ASHRAE 170 | 20°C -24 °C | 20% -60% |
| Centers for Disease Control and Prevention (CDC) | 20°C -23°C | 30% -60% |
| Joint Commission International (JCI) | 20°C -24 °C | 20% -60% |
| Hospital Infection Prevention Control Manual-Sri Lanka | 20°C -24 °C | 40% -60% |

### 2.2 TEMPERATURE AND HUMIDITY MONITORING AND CONTROL TECHNOLOGIES

There are various monitoring and controlling techniques used for temperature and humidity control, such as IoT-enabled monitoring systems, BMSs, control algorithms, and smart systems.

IoT-enabled HVAC monitoring systems significantly improve operating room environmental control by enabling real-time monitoring of key parameters such as temperature, humidity, and pressure (Yojana, 2021). These systems issue automatic alerts when values exceed safe limits, ensuring timely interventions. Advanced IoT frameworks combine optimization and demand response strategies, achieving 20%-40% energy savings, while maintaining comfort (Giron et al., 2023). In addition, they support cloud-based data processing and remote monitoring, which is particularly beneficial in critical areas such as intensive care units (Rajith et al., 2018).

Building Management Systems (BMS) are an essential tool for enhancing energy efficiency and promoting sustainability in healthcare settings (Sharma & Alshtshati, 2024). They enable centralized oversight of building operations by utilizing sensor-based technologies to monitor critical environmental factors such as temperature and humidity in real time (Valinejadshoubi et al., 2020). BMS helps ensure adherence to standards like ASHRAE 170 by maintaining accurate environmental control within healthcare facilities (Setyonugroho et al., 2021). BMS effectively monitor and manage energy use, making them suitable for both small- and large-scale buildings (Harris & Madomercandy, 2007).

Recent studies have focused on smart HVAC control in operating rooms to improve air quality, comfort, and energy efficiency. Fuzzy logic controllers (FLC) effectively manage inputs such as temperature and humidity, improving system reliability and comfort (Saritas et al., 2007). CFD simulations help optimize performance while maintaining pollution standards (Wang et al., 2021). IoT-based systems enable real-time air quality monitoring and mobile alerts, improving environmental control and reducing energy use (Yojana, 2021).

## 3. METHODOLOGY

This study focused on examining the reality of the established concept that building management systems (BMS) are more effective than independent thermostat controls. Hence, this research was conducted across four hospitals that operate general surgery rooms, as defined by the ASHRAE 170 operating room classification. This study consisted of 3 phases, including a literature survey, 4 hospital case study evaluations, and expert interviews to validate the findings of case studies. The literature survey helped in realizing the current standards and regulations related to maintaining temperature and humidity requirements for OTs. The four case studies helped to understand the current

situation of compliance with identified standards and investigating the potential causes of deviations in BMS and traditional thermostat-controlled environments. Finally, interviews with experts helped to propose strategies for enhancing compliance with established standards in OTs in Sri Lankan healthcare facilities. The four hospitals studied had centralized air-conditioning systems with modulating controls. Cases A and B were equipped with BMS-enabled real-time monitoring and maintained historical temperature and humidity records, while Cases C and D relied on basic thermostat controls without BMS and lacked historical data. In each case, one member of the technical staff and one member of the medical staff were interviewed to obtain case-specific insights. Table 3 summarises the profile of case-study respondents.

*Table 2: Profile of respondents*

| Respondent Identity | Hospital Name | Department or professional background |
|---|---|---|
| R1 | Case A | Engineering Staff Person-HVAC Controlling |
| R2 | Case A | Medical Staff –OT User |
| R3 | Case B | Engineering Staff Person-HVAC Controlling |
| R4 | Case B | Medical Staff – OT User |
| R5 | Case C | Engineering Staff Person-HVAC Controlling |
| R6 | Case C | Medical Staff – OT User |
| R7 | Case D | Engineering Staff Person-HVAC Controlling |
| R8 | Case D | Medical Staff – OT User |

The five semi-structured interviews with subject experts, who had extensive experience in hospital indoor environmental quality management and building automation systems, were conducted to validate the case study findings. Each interview lasted approximately 30 minutes. A purposive sampling approach was followed in the selection of experts. The expert interviews were limited to five due to the recurrence of the same opinions and responses, detecting data saturation in the validation process. Table 3 summarises the profile of experts involved in the study.

*Table 3: Profile of experts*

| Respondent Identity | Years of Experience | Profile descriptions |
|---|---|---|
| E1 | 10 + | Engineering Manager of the leading Pvt sector hospital. |
| E2 | 3+ | Assistant maintenance engineer of a Pvt sector hospital with experience in the automation industry. |
| E3 | 15+ | Director of the leading automation company. |
| E4 | 3+ | HVAC commissioning engineer with experience in the automation industry. |
| E5 | 20+ | HVAC consultant. |

The data collected in both phases was analysed using manual content analysis as it is a qualitative study that and required systematically reviewing interview transcripts. The authors believed that human interpretation would achieve the most appropriate

contextually relevant results. Hence, the responses were manually reviewed, coded, and grouped into categories based on common themes and patterns.

# 4. FINDINGS

Findings are divided into two areas as case study findings and findings of the expert interviews.

## 4.1 CASE-WISE ANALYSIS

### 4.1.1 Case A

Case A is a private hospital where OT environmental conditions are controlled through a centralized BMS with a dedicated AHU, modulating controls, and duct sensors, enabling real-time 24/7 monitoring. A knowledge gap between technical and clinical staff was observed, which may affect communication and decision-making. However, both R1 and R2 emphasized that the HVAC system must operate continuously (24/7) to maintain the required temperature and humidity levels. As per respondents, temperature and humidity deviations were minimal, though R1 noted slight fluctuations during hot, humid months when the setpoint is set at the upper margin. BMS readings show stable temperature but frequent humidity fluctuations, though overall conditions meet standards. R1 and R2 confirmed that BMS supports effective environmental control, with R1 noting its multi-sensor, automatic adjustments outperform conventional thermostats, even amid budget and operational constraints. While BMS, limited sensors, and actuators restrict its full potential. R1 recommended expanding to IoT-based BMS, particularly in critical areas, to enhance environmental control, safety, and efficiency.

### 4.1.2 Case B

Case B is a private hospital that has a centralized BMS to control the environment. The OT has its own AHU with adjustable controls, and the hospital can monitor environmental conditions continuously (24/7). However, temperature and humidity data are only recorded three times a day manually by the BMS operator. R3 showed general awareness of temperature and humidity standards, referencing ASHRAE and national guidelines, indicating efforts to align with accepted practices. In contrast, R4 demonstrated limited awareness, relying on the BMS operator and past practices rather than defined standards. Medical staff also reported discomfort with temperature settings. Respondents noted recent temperature and humidity deviations due to technical issues. While continuous HVAC operation is required for a sterile environment, R3 highlighted challenges such as staff preferences (often requesting ~18°C), frequent door openings, and balancing energy demand, all of which affect maintaining standard conditions. As a result, the HVAC system tends to maintain lower temperatures to suit surgical preferences rather than standards. While significant fluctuations and instability were observed in both temperature and humidity, the humidity frequently exceeded limits, indicating poor dehumidification. Despite having a BMS, poor sensor accuracy and system programming, staff behavior, and operational practices limited its ability to maintain required environmental conditions.

### 4.1.3 Case C

Case C is a private hospital without a BMS to control the OT environment. The OT has a dedicated AHU with modulating controls. However, temperature is managed using a

basic thermostat system. Respondents showed a clear knowledge gap: R5 had strong awareness of ASHRAE 170 and CDC guidelines, emphasizing maintaining 20–24 °C and humidity below 60%, while R6 had limited knowledge and relied on the traditional practice of 18 °C. Current practices followed relied on historical norms rather than formal standards, highlighting the need for better communication and training to ensure operating room safety and compliance. Interviews and observations revealed critical deficiencies in operational practices related to environmental controls in OT. Both R5 and R6 acknowledge that there was a lack of systematic monitoring, particularly regarding the accuracy and reliability of environmental data. R5 noted that temperature and humidity are logged only by surgical staff, with no historical records for the engineering team, highlighting a disconnect between clinical and engineering teams and a lack of monitoring transparency. In Case C, OT temperature is logged manually twice daily, risking inaccuracy, while HVAC systems are turned off when unused, violating ASHRAE 170 standards. Lack of real-time monitoring and stable conditions compromises infection control and patient safety. Staff noted the need for a BMS, though budget constraints hinder implementation.

#### 4.1.4 Case D

Case D is a semi-government hospital where a there is no BMS available to control the thermal comfort in the OT. The OT has a dedicated AHU with modulating controls; however, temperature is managed using a basic thermostat, and a centralized BMS is not in operation. Respondents showed limited understanding of ASHRAE standards for operating rooms. R7 and R8 highlighted a significant knowledge gap in both technical and medical staff, with R7 showing low-confidence estimates (18–20 °C) and R8 unaware of formal standards, relying on 18 °C, indicating risks to environmental control and patient safety. The current practice for monitoring temperature and humidity in the selected OT appears to be informal and lacks a structured protocol. R7 noted that engineering teams are not proactive; OT staff check thermostats and request maintenance only when issues arise, causing potential delays in resolving environmental problems. R8 noted that temperatures are logged daily in a general book without a formal monitoring system, limiting trend analysis, standards compliance, and preventive maintenance. Limited engineering oversight and lack of routine humidity monitoring in Case D reveal high risks of temperature and humidity deviations, with low staff awareness posing threats to efficiency, patient safety, and infection control.

# 5. ANALYSIS

## 5.1 CROSS-CASE ANALYSIS

This section presents a cross-case analysis of Cases A, B, C, and D, comparing similar cases to identify common practices and contrasting cases to highlight gaps and context-specific challenges, providing insights into the effectiveness of temperature and humidity monitoring in OTs.

### 5.1.1 Cross-Case Analysis of Case A and Case B

The cross-case analysis of case A and case B revealed that the availability of BMS supports centralized control of OT conditions and real-time monitoring and control of temperature and humidity due to historical trend logs providing better decision-making by allowing analysis of temperature and humidity behaviour trends and patterns, while

manual recording limited responsiveness and data accuracy. When proper data recording is lacking, medical officers appear to influence temperature controls based on personal preferences, affecting indoor environmental quality. Also, the presence of BMS, system design limitations, sensor placement, number of sensors used, and programming errors can limit the effectiveness of the BMS system in maintaining temperature and humidity within acceptable ranges. User behaviour, training, and awareness of temperature and humidity control are among the technical factors that affect maintaining effective temperature and humidity.

### 5.1.2 Cross-Case Analysis of Case C and Case D

Cross-case analysis of cases C and D revealed that when BMS was not available, and manual thermostat control was available, the medical staff relied on routine and past practices rather than formal standards. The hospital lacks structured OT training and protocols, increasing risks to patient safety and limiting compliance with ASHRAE 170. It was also observed that when a BMS was absent, the engineering team was less involved in temperature and humidity control. Case C maintains manual temperature logs, though their accuracy is questionable, while Case D has no records. The lack of record-keeping prevents predictions, making engineering interventions mostly reactive. Case C also risks sterile conditions by shutting down HVAC during non-surgical hours. User behaviour, lack of training and awareness of regulatory standards (especially among clinical staff), and minimal involvement of engineering personnel contribute to poor environmental control. In both cases, staff prioritize personal or patient comfort over required environmental standards due to low awareness. Both also lack real-time monitoring, alerts, and trend analysis, allowing temperature and humidity deviations to go undetected and increasing risks to patient safety and operational efficiency.

## 5.2 CROSS-CASE ANALYSIS OF BMS AND THERMOSTAT CONTROL IN OT FOR TEMPERATURE AND HUMIDITY CONTROL

Table 4 is a summary of the characteristics of four cases.

*Table 4: Summary of case studies*

| Case | System Type | Monitoring Method | Temp Control Approach | RH Control Approach | Key Feature |
|---|---|---|---|---|---|
| Case A | BMS | Continuous (5-sec data) | Automated control | Automated control | High-level monitoring |
| Case B | BMS | Continuous monitoring | Advanced BMS control | Integrated RH control | Optimised system settings |
| Case C | Thermostat | Manual/3 readings/day) | Local thermostat-based | Limited RH control | Low-frequency monitoring |
| Case D | Thermostat | Manual/spot checks | Manual adjustment | Basic RH control | Reactive control system |

Cross-case analysis shows BMS-enabled OTs comply better with ASHRAE 170 than those using decentralized thermostatic controls. The findings are presented in Table 5.

*Table 5: Cross-case analysis summary*

| Criteria | BMS-enabled OTs | Thermostat enabled OTs |
|---|---|---|
| Compliance status to ASHRAE 170 | Partial and Full compliance | Failure to comply |
| Infrastructure and Monitoring Capability | Real-time monitoring, precise control, and alerts, ensuring compliance and safety. | Rely on manual adjustments and periodic logging, risking efficiency and patient safety. |
| Standard temperature and humidity requirements | Considerably acceptable temperature and humidity conditions | Low compliance, frequent deviations |
| Monitoring Accuracy & Responsiveness | Improved monitoring accuracy and responsiveness | Very low, manual, infrequent, and often inaccurate recording |
| Operational Practices Impact | Predictive control | Reactive control |

According to these analyses, the superior performance in Case A reflects the benefits of real-time data and automated trend analysis. However, in places like Case B, even within BMS-enabled hospitals, human factors, technical factors , and underutilization of system capabilities can neglect the technological advantages. On the other hand, the thermostat-operated OTs showed poor performance and compliance, increasing risks to patient safety and infection control.

## 5.3 VALIDATION AND RESPONSES OF EXPERTS

The findings from the case study analysis were validated through expert review, and strategies were developed to address the identified issues.

E1, E2, and E3 experts acknowledged that BMSs offer significant advantages in maintaining environmental conditions in OTs. They highlighted that BMS enables real-time monitoring, automatic alerts, and early detection, which are crucial for maintaining temperature and humidity within surgical standards. As E1 noted, "BMS provides continuous data that helps take action before conditions go far beyond acceptable ranges." Similarly, E2 and E3 pointed out that BMS platforms allow for remote diagnostics and data logging, making them very effective for preventive maintenance. However, E4 and E5 raised a warning about the practical limitations and risks associated with over-reliance on BMS for critical environments such as OTs. E4 emphasized that full override control by the BMS during technical malfunctions can become a liability due to the inability to make manual adjustments. E5 reinforced this concern by stating that, regardless of the benefits, many hospitals in SL still preferred basic thermostat controls in operating rooms because of their simplicity and direct manual control. According to E5, "*Most operating rooms are not connected to a BMS, as basic thermostat control is preferred for its reliability and ability to allow immediate adjustments without relying on engineering teams or software".* This confirmed the situation in cases B, C, and D, where surgical needs were prioritized over standard temperature and humidity. E1 noted that OT temperature and humidity deviations, even with real-time monitoring, are often intentional due to surgical needs or energy-saving measures, but when setpoints are configured correctly, the BMS automatically modulates the chilled water valve and dampers to maintain desired conditions. This automatic adjustment mechanism works equally well in both BMS-enabled systems and thermostatically controlled systems, E1 explained. However, the main limitation of thermostatically controlled environments is

the lack of centralized monitoring, as only OT staff can view or change setpoints, making it invisible to the engineering team, limiting proactive response, which would make compliance difficult. E3 highlighted that humidification and dehumidification systems often require reheating after lowering the temperature, causing long-term deviations. E4 added that even with correct setpoints, system response delays, especially during load or occupancy changes leading to temporary deviations. All respondents agreed that medical staff behaviour can hugely impact temperature and humidity control. A summary of the reasons for non-compliance within OTs highlighted by the experts, is presented in Table 6.

*Table 6: Reasons for non-compliance as per experts*

| Potential causes | E1 | E2 | E3 | E4 | E5 |
|---|---|---|---|---|---|
| Surgical procedure requirements outside the standard range | ✓ | ✓ | ✓ | | ✓ |
| Energy-saving practices | ✓ | ✓ | | | |
| Delay in system response (dehumidification/reheating) | | | ✓ | ✓ | |
| Manual override limitations in BMS | | | | ✓ | ✓ |
| Lack of centralized monitoring in thermostat-controlled systems | ✓ | ✓ | ✓ | | ✓ |
| Technical faults/system lag | | | | ✓ | ✓ |
| Staff behaviour (door opening, comfort prioritization) | ✓ | ✓ | ✓ | ✓ | ✓ |
| Faulty or delayed humidification/dehumidification design | | | ✓ | | |

Based on these findings, experts proposed strategies to address temperature and humidity control challenges. Table 7 summarises the recommended strategies for both BMS-enabled and thermostat-controlled operating theatre environments.

*Table 7: Strategies by experts*

| Strategies for BMS-Enabled Environments | Strategies for Thermostat-Controlled Environments |
|---|---|
| Enhance real-time centralized monitoring with automated alerts and fault detection. | Implement accurate digital thermostats for improved manual control. |
| Improve responsiveness using modulating valves, dampers, and reheating loops. | Conduct regular manual monitoring and data logging protocols. |
| Establish scheduled preventive maintenance and automated sensor calibration alerts. | Use standalone humidifiers/dehumidifiers to control humidity independently. |
| Enable fail-safe manual override options to maintain control during BMS faults. | Train clinical and support staff on manual thermostat operation and proper usage. |
| Provide training for staff on BMS interface, alert handling, and collaborative protocols. | Establish clear communication between clinical staff and engineers for quick response. |
| Leverage AI and data analytics for predictive trend analysis and HVAC optimization. | Maintain backup sensors and manual alarm systems for early fault detection. |

The findings of the analysis are presented in Figure 1.

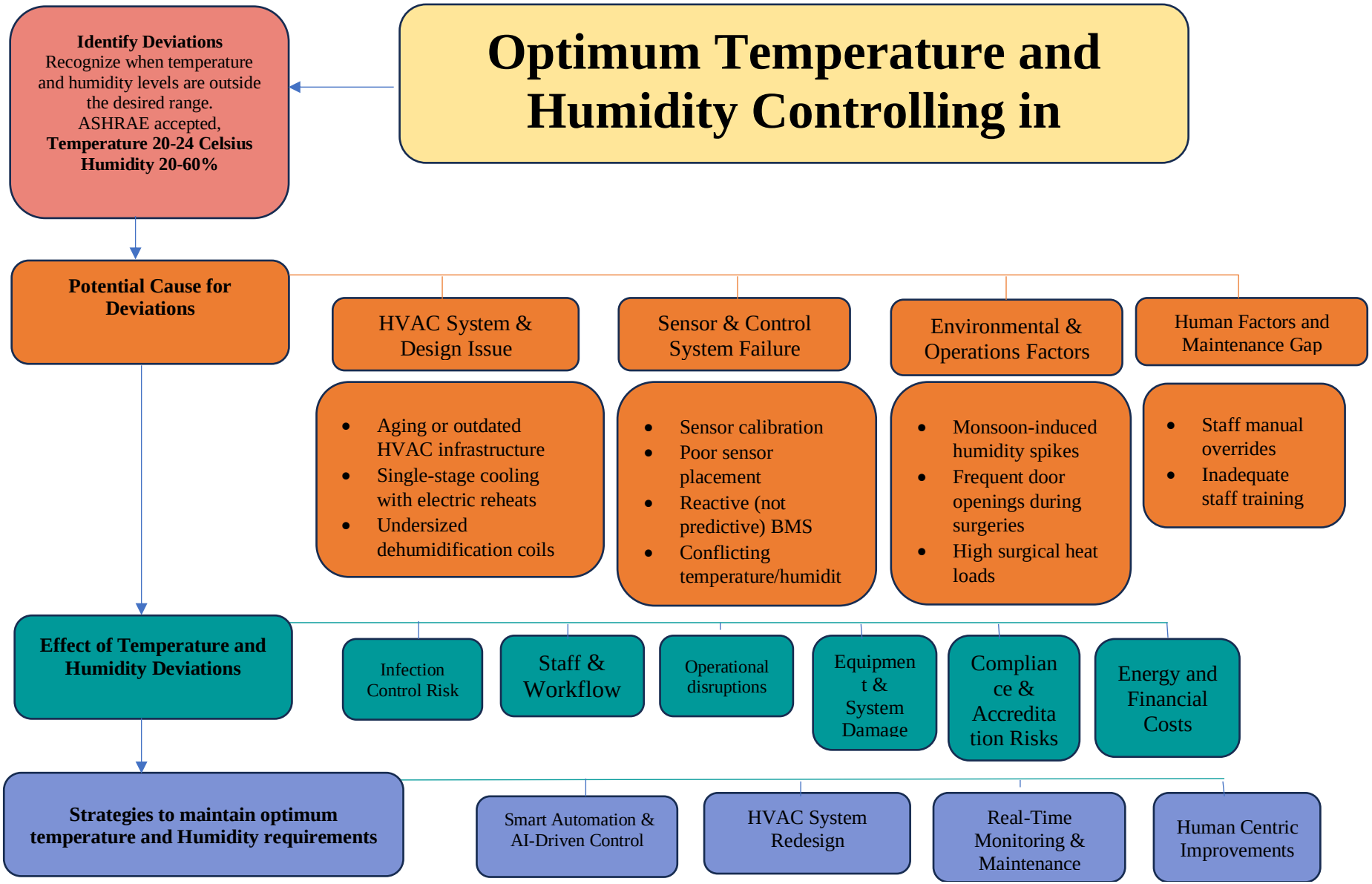



*Figure 1: Summary of study*

## 6. CONCLUSIONS

The literature revealed that many international standards, including ASHRAE, CDC, and JCI, recommend maintaining operating room temperature between 20°C and 24°C and relative humidity between 20% and 60% to ensure infection control, thermal comfort, and optimal equipment performance. Sri Lankan guidelines align with JCI, ASHRAE, CDC standards and the Hospital Infection Prevention and Control Manual, but implementation varies across hospitals. All guidelines align with ASHRAE standards, identifying temperature (20–24°C) and humidity (40–60%) as the benchmark ranges.

Two BMS-controlled hospitals were assessed, revealing that despite sensor-based systems, there are instances where temperature and humidity standards were unmet due to multiple factors. Furthermore, despite mandatory requirements for monitoring temperature and humidity, non-BMS facilities that relied on thermostat control showed a similar situation. It was further revealed that deviations from recommended temperature and humidity levels in operating rooms are caused by multiple interrelated causes. In BMS-enabled environments, factors such as delayed system response times, technical errors, energy-saving configurations, and limited flexibility in manual overrides were identified as major contributing factors to non-compliance. In contrast, thermostatically controlled systems faced challenges mainly due to a lack of centralized monitoring, being reactive rather than preventive in maintenance work, and poorly designed humidity/humidity reduction settings. In addition, in both system types, human factors such as frequent door openings, personal comfort adjustments, and lack of awareness among staff were significant behavioural contributors to environmental instability. These findings emphasize the importance of both technical robustness and disciplined operational practices in achieving consistent temperature and humidity compliance in operating rooms.

The proposed strategies by the experts were focused on both technical improvements and operational improvements that were tailored to the Sri Lankan healthcare context. For BMS-enabled environments, the experts recommended system-level improvements such as improved fault detection, integration of AI for predictive control, responsive dehumidification loops, and improved user interface training for clinical and engineering staff. In thermostatically controlled settings, the strategies emphasized the need for semi-automated control improvements, centralized data logging, and strict protocols for manual adjustments. In both systems, common recommendations included strengthening staff awareness, implementing maintenance schedules, and minimizing behavioural disruptions such as door openings. The practical implications of this study highlight that maintaining temperature and humidity compliance in OTs depends not only on the control system used but also on system operation, maintenance, and user behaviour. Relevant hospital managers should assess BMS and thermostat systems based on actual performance, as both may show similar compliance levels in practice. The findings also emphasize the need for continuous monitoring, proper maintenance, and staff awareness to ensure stable environmental conditions. The future research could examine staff collaboration on HVAC compliance, indoor air quality compliance in Sri Lankan healthcare facilities, and the role of AI-enabled BMS in improving temperature and humidity control in operating theatres.

# 7. REFERENCES


Accelix. (2022, January 18). Maintenance with and without a CMMS - eMaint CMMS Software. Retrieved from https://www.emaint.com/a-day-in-the-life-of-maintenance-with-and-without-a-cmms/

Ahmadzadehtalatapeh, M. (2014). Improving the Energy Performance of HVAC Systems in Operating Theatres by Using Heat Recovery Devices. *International Journal Of Renewable Energy Research*, *4*(3), 586–592. https://dergipark.org.tr/en/pub/ijrer/article/168059

ASHRAE. (2020). *Ventilation of Health Care Facilities*. www.ashrae.org

Balaras, C. A., Dascalaki, E., & Gaglia, A. (2007). HVAC and indoor thermal conditions in hospital operating rooms. *Energy and Buildings*, *39*(4), 454–470. https://doi.org/10.1016/J.ENBUILD.2006.09.004

Bearg, D. W. (2019). Indoor air quality and HVAC systems. In *Indoor Air Quality and HVAC Systems*. Routledge. https://doi.org/10.1201/9780203751152/INDOOR-AIR-QUALITY-HVAC-SYSTEMS-DAVID-BEARG

Cannistraro, G., & Cannistraro, M. (2016). Hypothermia risk, monitoring and environment control in operating rooms. *International Journal of Heat and Technology*, *34*(2), 165–171. https://doi.org/10.18280/ijht.340202

European Standards. (n.d.). *91.140.30 Ventilation and air-conditioning systems*. Retrieved June 13, 2026, from https://www.en-standard.eu/ics-codes/91-construction-materials-and-building/91-140-installations-in-buildings/91-140-30-ventilation-and-air-conditioning-systems/

European Committee for Standardization. (2018). Ventilation in hospitals - Coherent hierarchic structure and common terms and definitions for a standard related to ventilation in hospitals (CEN/TS 16244:2018). https://bsigroup.com

Fang, L., Wyon, D. P., Clausen, G., & Fanger, P. O. (2004). Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. *Indoor Air*, *14*(7), 74–81. https://doi.org/10.1111/j.1600-0668.2004.00276.x

Fredrick, T., & Kumaran, M. (2018). Operation theaters and sterilization requirements — Design consideration and standards for infection control. *TNOA Journal of Ophthalmic Science and Research*, *56*(2), 84. https://doi.org/10.4103/tjosr.tjosr_62_18

Guo, B., Wang, X., Zhang, X., Yang, J., & Wang, Z. (2016). Research on the Temperature & Humidity Monitoring System in the Key Areas of the Hospital Based on the Internet of Things. *International Journal of Smart Home*, *10*(7), 205–216. https://doi.org/10.14257/ijsh.2016.10.7.21

G, V., & Balaji, G. (2023). Impact of indoor temperature and humidity in IAQ of healthcare buildings. *Civil Engineering and Architecture*, *11*(3), 1273–1279. https://doi.org/10.13189/cea.2023.110313

Harris, D., & Madomercandy, R. (1988). Building management systems. *Facilities*, *6*(5), 10–16. https://doi.org/10.1108/eb006443

Hussain, T., Agarwal, P., & Hafiz, A. (2020). HVAC systems and environmental controls in hospital operation theatres.*Smart innovation, systems and technologies*,675–684). https://doi.org/10.1007/978-981-15-2647-3_63

Katz, J. D. (2016). Control of the environment in the operating room. *Anesthesia & Analgesia*, *125*(4), 1214–1218. https://doi.org/10.1213/ane.0000000000001626

Kumara, W. H. C. D., Waidyasekara, K. G. A. S., & Weerasinghe, R. P. N. P. (2016). Building management system for sustainable built environment in Sri Lanka. *Built Environment Project and Asset Management*, *6*(3), 302–316. https://doi.org/10.1108/BEPAM-02-2015-0004

Kumar, V., Upmanu, V., Chauhan, R. P. S., Sharma, N., Kumar, B. V., & Zadoo, M. (2024). Real-Time Environmental Monitoring and Control for Ensuring Optimal Temperature and Humidity Conditions for Patient Comfort and Medical Equipment Integrity. In *2024 3rd International Conference on Sentiment Analysis and Deep Learning (ICSADL)* 558–562. https://doi.org/10.1109/icsadl61749.2024.00097

Mazzei, P., Minichiello, F., & Palma, D. (2005). HVAC dehumidification systems for thermal comfort: a critical review. *Applied Thermal Engineering*, *25*(5–6), 677–707. https://doi.org/10.1016/J.APPLTHERMALENG.2004.07.014

Mishra, T., Singh, R., Giri, V., Chakraborty, J., & Sorabh, N. (2021). Air-Conditioning system in surgical and Critical Care: a review. *Lecture Notes in Mechanical Engineering*, 661–672. https://doi.org/10.1007/978-981-16-0159-0_58

Mohta, M. (2010). If air conditioning is not functioning. *Indian Journal of Anaesthesia*, *54*(6), 580. https://doi.org/10.4103/0019-5049.72657

Abdul Mujeebu, M. (2019). Introductory Chapter: Indoor Environmental Quality. In Indoor Environmental Quality. IntechOpen. https://doi.org/10.5772/intechopen.83612

Patnaik, A., Kumar, V., & Saha, P. (2018). Importance of indoor environmental quality in green buildings. In V. Singh, S. Yadav, & R. Yadava (Eds.), *Environmental pollution Water Science and Technology Library*, 77, 53–64. Springer. https://doi.org/10.1007/978-981-10-5792-2_5Rajith, S. Soki and M. Hiroshi, "Real-time optimized HVAC control system on top of an IoT framework," *2018 Third International Conference on Fog and Mobile Edge Computing (FMEC)*, Barcelona, Spain, 2018, 181-186, doi: 10.1109/FMEC.2018.8364062.

Sadrizadeh, S., & Loomans, M. G. L. C. (2016). Thermal comfort in hospital and healthcare facilities: a literature review. *IAQVAC 2016, The 9th International Conference on Indoor Air Quality*, 1–12. https://research.tue.nl/en/publications/thermal-comfort-in-hospital-and-healthcare-facilities-a-literatur/

Sánchez-Barroso, G., & Sanz-Calcedo, J. G. (2019). Evaluation of HVAC design Parameters in High-Performance Hospital Operating Theatres. *Sustainability*, *11*(5), 1493. https://doi.org/10.3390/su11051493

Setyonugroho, W., SesotyaUtami, S., ArlinaDewi, Listiowati, E., Hanifah, & Baskara, S. A. (2021). Green Choice: an opportunity to make a cost saving and improve healthcare quality for hospital management. *Journal of Cardiovascular Disease Research*, *12*(2), 329–336. http://www.jcdronline.org/index.php?mno=80086

Sharma, V., & Alshatshati, S. (2024). Optimizing energy efficiency in healthcare facilities: The pivotal role of building management systems. *Journal of Artificial Intelligence Machine Learning and Data Science*, *2*(1), 209–2013. https://doi.org/10.51219/jaimld/vibhu-sharma/70

Sri Lanka College of Microbiologists. (2021). *Hospital Infection Prevention Control Manual-Sri Lanka*. https://slmicrobiology.lk/wp-content/uploads/2021/10/Hospital-Infection-Prevention-and-Control-Manual.pdfv

Türk, B. (2022). Important factors affecting the quality of indoor air and a bibliometric analysis. *Sakarya University Journal of Science*, *26*(3), 608–619. https://doi.org/10.16984/saufenbilder.996443

Ufat, H., Kaynakli, O., Yamankaradeniz, N., & Yamankaradeniz, R. (2017). Investigation of the number of particles in an operating room at different ambient temperatures and inlet velocities. *International Journal of Ventilation*, *17*(3), 209–223. https://doi.org/10.1080/14733315.2017.1392107

Valinejadshoubi, M., Moselhi, O., Bagchi, A., & Salem, A. (2020). Development of an IoT and BIM-based automated alert system for thermal comfort monitoring in buildings. *Sustainable Cities and Society*, *66*, 102602. https://doi.org/10.1016/j.scs.2020.102602

Včelák, J., Vodička, A., Maška, M., & Mřna, J. (2017, July 10). Smart building monitoring from structure to indoor environment. *2017 Smart Cities Symposium Prague, SCSP 2017 - IEEE Proceedings*. https://doi.org/10.1109/SCSP.2017.7973859

S. Vijayalakshmi, M. Marimuthu, B. Paranthagan, V. S. Kumar, S. Sanjay and A. Vikash, "Monitoring and saving humidity &temperature through the Internet of Things," *2022 International Virtual Conference on Power Engineering Computing and Control: Developments in Electric Vehicles and Energy Sector for Sustainable Future (PECCON)*, Chennai, India, 2022, 1-6, doi: 10.1109/PECCON55017.2022.9851155.

Wang, F., Permana, I., Rakhsit, D., & Azizah, R. S. (2021). Thermal performance improvement and contamination control strategies in an operating room. *Journal of Advanced Thermal Science Research*, *8*, 30–40. https://doi.org/10.15377/2409-5826.2021.08.4

Yojana, A. C. (2021). IoT system to control the air quality in operating room. *Turkish Journal of Computer and Mathematics Education (TURCOMAT)*, *12*(3), 5726–5732. https://doi.org/10.17762/turcomat.v12i3.2248

Zeng, Q., Shagar, M., Fatemifar, K., Pishdad, P., & Yang, E. (2026). Utilizing Building Automation Systems for Indoor Environmental Quality Optimization: A Review of the Current Literature, Challenges, and Opportunities. *Buildings*, *16*(6), 1267. https://doi.org/10.3390/BUILDINGS16061267/S1

Fernando, S. and Samarawickrama, S., 2026. Temporary built environments in Sri Lankan film production design. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1651-1663. DOI: https://doi.org/10.31705/WCS.2026.120. Available from: https://ciobwcs.com/papers/

# TEMPORARY BUILT ENVIRONMENTS IN SRI LANKAN FILM PRODUCTION DESIGN

**S. Fernando[1] and S. Samarawickrama[2]**

## *ABSTRACT*

*A temporary built environment refers to a spatial arrangement intentionally created or modified for limited duration use, where design decisions are shaped by reversibility, adaptability, and planned disassembly rather than permanence. While this concept is well-established within architectural discourse, comparable spatial conditions are evident in film production design, where environments are constructed, transformed, and dismantled to meet the temporal demands of filmmaking. Despite these visible parallels, film production design has rarely been examined through the broader architectural discourse on temporary built environments. This study investigates Sri Lankan cinema to examine how film production design functions as a form of temporary built-environment practice. A qualitative interpretive approach was adopted, drawing on structured interviews with four experienced Sri Lankan production designers. The analysis was guided by three spatial dimensions identified in architectural literature: temporality, material construction, and experiential narrative organization. The findings confirm that cinematic environments operate through these interrelated conditions while also exhibiting a distinctive characteristic specific to production design: dual functionality combined with operational flexibility. Film sets function simultaneously as representational architecture and as technical infrastructure, requiring continuous spatial adjustment during filming. The study argues that Sri Lankan film production design constitutes a specialized form of temporary built environment practice. By demonstrating how temporally bounded spatial systems operate beyond conventional architectural typologies, the paper expands the discourse on the built environment to include mediated and industrial spatial practices.*

***Keywords:*** *Perceptual Authenticity; Production Design; Spatial Design; Sri Lankan Cinema; Temporary Built Environments.*

## 1. INTRODUCTION

Knowledge developed within one disciplinary field can illuminate parallel practices in another, particularly where shared spatial or material concerns exist (Cross, 2006; Till, 2009). Within architecture and urban design, the concept of temporary built environments is well established, referring to spatial arrangements intentionally created for limited durations yet fully functional during their period of occupation (Kronenburg, 2007; Bishop & Williams, 2012). Such environments are typically defined by temporality, reversibility, adaptability, and planned disassembly rather than long-term permanence (Brand, 1994). Temporary pavilions, exhibition structures, and event-based installations

[1] Post Graduate Student, Department of Integrated Design, University Moratuwa, Sri Lanka, shermilafernando82@gmail.com
[2] Senior lecturer, Department of Integrated Design, University Moratuwa, Sri Lanka, sumanthris@uom.lk

demonstrate how architectural practice accommodates transience while maintaining structural coherence and operational functionality.

Comparable spatial conditions can be observed in film production, where environments are constructed, adapted, and dismantled according to the temporal requirements of filmmaking. Scholars examining the relationship between cinema and architecture have argued that cinematic environments operate through spatial logics comparable to architectural practice, positioning film sets as constructed spatial artefacts rather than merely visual backdrops (Neumann, 1996; Penz & Thomas, 1997; Bruno, 2002). Within the collaborative structure of filmmaking, production design is responsible for shaping the visual and spatial world of the narrative through the creation and transformation of sets, locations, and environmental contexts (LoBrutto, 2002; Barnwell, 2020). Although these environments are temporary in duration, they must appear materially stable, spatially coherent, and experientially convincing in order to sustain narrative credibility on screen (Bordwell & Thompson, 2019).

The historical relationship between architecture and film production design further reinforces this connection. Many early set designers and art directors were trained in architecture or related spatial disciplines, bringing architectural drawing conventions and spatial planning methods into cinematic practice (Neumann, 1996; Bergfelder et al., 2007). In several European film industries, the role was even described using architectural terminology: set designers in Germany were sometimes credited as "architects," while in France the term "architect-decorator" was used to describe those responsible for the spatial design of film environments. These historical practices illustrate how architectural knowledge informed early studio set construction and contributed to the development of cinematic spatial design. Consequently, much of the historical and theoretical literature on production design has approached cinematic space through architectural representation and visual construction (Affron & Affron, 1995; Ramírez, 2004). However, while this scholarship acknowledges architectural influence, it rarely examines film sets explicitly as forms of temporary built environments within built-environment discourse.

This parallel suggests a productive conceptual overlap between architectural temporary structures and cinematic spatial fabrication. In both domains, environments are deliberately constructed to function within defined time frames while maintaining structural integrity and perceptual coherence. However, despite these visible similarities, temporary built environments have been predominantly theorised within architectural discourse, with limited engagement beyond conventional building typologies (Kronenburg, 2007; Bishop & Williams, 2012). While cinema–architecture relationships have been explored from aesthetic and representational perspectives (Neumann, 1996; Penz & Thomas, 1997), film production design has rarely been examined as a material and operational form of temporary built environment practice. This disciplinary separation has restricted recognition of cinematic environments as legitimate temporary built environments and has left practitioner-based spatial knowledge underexplored, particularly in Global South contexts such as Sri Lanka.

While production design encompasses multiple visual components including props, costumes, and graphic elements the present study focuses specifically on spatial set construction, location transformation, and environmental dressing, as these elements most directly correspond to the architectural notion of temporary built environments. By

narrowing the analytical scope to spatial environments rather than broader aesthetic elements, the paper establishes a clearer dialogue between architectural spatial theory and cinematic design practice.

Against this conceptual background, the present study aims to examine how early Sri Lankan film production design practices can be understood through the defining characteristics of temporary built environments. Sri Lankan cinema provides a particularly relevant case study, as production design frequently involves adaptive reuse of existing locations, minimal permanent intervention, and context-responsive spatial modification under economic and material constraints.

Adopting a qualitative research approach, the study combines cross-disciplinary literature analysis with structured narrative interviews conducted with four award-winning Sri Lankan production designers selected through archival credit observations and professional recognition. The interview data were analysed using thematic analysis guided by spatial dimensions identified in built-environment literature. Through this methodological framework, the paper investigates how cinematic environments may be understood as temporary built environments, thereby contributing to broader architectural discussions of temporality and adaptive spatial practice.

### 1.1 RESEARCH OBJECTIVES

In order to address the identified gap between architectural discussions of temporary built environments and cinematic spatial practices, this study establishes the following objectives to guide the theoretical and empirical investigation.

The objectives of the study are:

- To examine how temporary built environments are conceptualized within architectural discourse and film production design scholarship.
- To investigate how temporary cinematic environments are constructed and operated within Sri Lankan film production practice.
- To analyze cinematic spatial practices through the dimensions of temporality, material construction, and experiential–narrative organization.
- To contribute to built environment discourse by positioning film production design as a form of temporary built environment practice.

## 2. LITERETURE REVIEW AND CONCEPTUAL FRAMEWORK

This section brings together the key ideas that shape the conceptual foundation of this study. It begins by outlining how temporary built environments are understood within architectural scholarship, and then turns to film production design to explore how similar spatial concerns emerge within cinematic practice. Rather than treating architecture and film as separate domains, the review places them in conversation, highlighting shared questions of temporality, material construction, perception, and event-based spatial organization. By drawing these strands together, the section establishes a comparative conceptual framework that guides the analysis of temporary spatial environments within Sri Lankan film production.

## 2.1 TEMPORALITY AS A SPATIAL CONDITION IN ARCHITECTURE AND FILM.

Temporality has long been examined within architectural discourse as a defining condition of certain spatial practices. Temporary built environments are understood as spatial settings intentionally created for limited durations, yet fully functional during their period of occupation (Kronenburg, 2007; Bishop & Williams, 2012). Unlike permanent structures associated with longevity and continuity, temporary environments foreground adaptability, reversibility, and planned disassembly as central design principles (Brand, 1994). Mehrotra (2014) further conceptualizes ephemeral urbanism as a cyclical spatial phenomenon shaped by processes of appearance and disappearance, positioning temporality as a productive spatial logic rather than a deficiency (Mehrotra & Vera, 2017). Similarly, Till (2009) challenges permanence as architecture's dominant value, arguing that buildings must be understood in relation to time, uncertainty, and change.

Comparable temporal conditions can be observed within film production design. Film sets and transformed locations are constructed specifically for the duration of production and are dismantled or restored upon completion. Although inherently time-bound, these environments must function operationally and visually throughout filming. Scholars exploring cinema architecture relationships note that film sets are not merely representational backgrounds but constructed spatial artefacts operating through architectural logics (Neumann, 1996; Penz & Thomas, 1997). Thus, both architectural temporary structures and cinematic environments share a foundational condition: they are spatial systems defined by duration yet required to perform coherently within that limited timeframe.

## 2.2 MATERIAL CONSTRUCTION AND STRUCTURAL CREDIBILITY

Architectural discussions of temporary environments emphasize material flexibility, portability, and structural sufficiency rather than monumentality (Kronenburg, 2007). Temporary structures may employ lightweight systems, modular components, and reusable materials, yet they remain materially convincing and structurally stable during use (Brand, 1994). The emphasis is not on permanence but on achieving adequate performance within defined temporal parameters.

Film production design similarly requires environments to achieve material credibility. Production designers translate narrative concepts into constructed spatial form, coordinating architecture, décor, texture, and colour to produce coherent environmental worlds (LoBrutto, 2002; Barnwell, 2020). While sets may employ temporary materials or non-load-bearing constructions, they must appear materially stable and spatially believable on screen. Bordwell and Thompson (2019) argue that mise-en-scène including setting functions to sustain narrative coherence and perceptual realism. Therefore, both architectural temporary structures and cinematic environments negotiate a balance between material construction and functional appearance, albeit for different purposes.

## 2.3 PERCEPTION, EXPERIENCE, AND EVENT-BASED SPATIAL MEANING

Temporary environments in architecture are frequently discussed in relation to event-based occupation and experiential engagement. Tschumi (1996) conceptualizes architecture as an event-oriented practice in which spatial meaning emerges through action and uses rather than permanence. Similarly, Mehrotra (2014) emphasizes the atmospheric and participatory qualities of ephemeral urbanism, where spatial value

derives from lived experience rather than longevity. Bishop and Williams (2012) further note that temporary environments such as festivals, exhibitions, and short-term urban interventions are structured around anticipated activities, deriving purpose from facilitating human interaction within defined temporal boundaries.

Cinematic environments operate through comparable spatial principles. In film production design, space is not constructed for long-term habitation but for narrative activation, where spatial environments are designed to support storytelling and guide audience perception (McLean, 2007). Sets are designed to accommodate character movement, camera positioning, and dramatic action, organizing spatial form according to story requirements (Barnwell, 2005; LoBrutto, 2002). At the same time, production design shapes the emotional and psychological dimensions of narrative space through environmental composition cinematic environments (Barnwell, 2020; Bordwell & Thompson, 2019). Film sets must generate mood, atmosphere, and symbolic meaning while remaining perceptually coherent within the frame. As Neumann (1996) observes, cinematic space operates at the intersection of architectural construction and visual experience.

In both architecture and film, therefore, temporality is not defined solely by duration but by the activation of space through event and perception. Architectural temporary structures facilitate real-world events, while cinematic environments facilitate narrative events; yet in both cases, spatial meaning arises through human engagement and temporal progression rather than static occupation. This convergence reinforces the conceptual alignment between temporary built environments and film production design as practices structured around experiential and event-based spatial organisation.

## 2.4 COMPARATIVE SPATIAL FRAMEWORK

Temporary built environments have been extensively theorised within architectural discourse, whereas film production design literature addresses similar spatial concerns in a more dispersed manner, without explicitly framing cinematic environments through the conceptual lens of temporary built environments. By bringing these two disciplinary perspectives into dialogue, Table 01 synthesises the shared spatial conditions identified across both fields. Architectural scholarship consistently highlights temporality, material construction, and experiential or event-based spatial meaning as defining characteristics of temporary built environments. The comparative framework presented in Table 1 demonstrates that these same spatial conditions also operate within cinematic environments.

*Table 1: Comparative spatial dimensions of temporary built environments in architecture and film production design.*

| Spatial Dimension | Architectural Temporary Built Environments | Cinematic Spatial Practice (Production Design) | Key References |
|---|---|---|---|
| Temporal Condition | Time-bound structures; planned dismantling; reversibility; cyclical transformation. | Sets constructed for limited filming duration; dismantling or | Kronenburg (2007); Bishop and Williams (2012); Neumann (1996) |

| Spatial Dimension | Architectural Temporary Built Environments | Cinematic Spatial Practice (Production Design) | Key References |
|---|---|---|---|
| | | restoration after production. | |
| Material Condition | Lightweight systems; modular construction; structural adequacy within limited lifespan. | Set fabrication; adaptive material use; structural stability for filming. | Brand (1994); Barnwell (2020); LoBrutto (2002) |
| Experiential–Narrative Condition | Atmosphere; experiential engagement; event-based spatial meaning; activation through human use. | Narrative credibility; mood creation; perceptual realism; spatial organisation around character movement and action. | Mehrotra (2014); Tschumi (1996); Bordwell and Thompson (2019); Wille (2015); Barnwell (2005) |

This synthesis establishes a comparative conceptual foundation for the empirical investigation that follows, in which Sri Lankan cinema is examined as a focused case study to assess how the architectural principles of temporary built environments are enacted through film production design practice. By situating the analysis within Sri Lankan cinematic practices, the study illustrates how temporally bounded spatial systems function within a distinct cultural and industrial context, thereby extending architectural discussions of temporary built environments beyond conventional building typologies.

# 3. RESEARCH METHODOLOGY

This study investigates how principles associated with temporary built environments are enacted within Sri Lankan film production design practice. The research is guided by the comparative spatial framework developed in the literature review, which identified three core dimensions of temporary built environments: temporality, material construction, and experiential–narrative organisation. Rather than generating new theoretical categories inductively, the study examines how these established spatial principles are manifested within practitioner accounts of cinematic set construction. A qualitative interpretive approach was adopted to access professional knowledge embedded in production design practice and to interpret cinematic environments as temporally bounded spatial systems.

## 3.1 RESEARCH DESIGN AND ANALYTICAL ORIENTATION

The study adopts a qualitative interpretive research design grounded in a concept-guided analytical framework. The objective is not to measure production efficiency or evaluate technical performance, but to understand how spatial decision-making processes reflect the defining characteristics of temporary built environments. The research seeks to interpret how practitioners conceptualize duration, reversibility, material substitution, and perceptual coherence within the operational realities of filmmaking.

The empirical investigation forms part of a broader doctoral study documenting the evolution and working practices of production designers in Sri Lankan cinema. Within the scope of this paper, the research integrates cross-disciplinary theoretical perspectives derived from architectural discourse with practice-based qualitative inquiry. This

integration enables cinematic spatial environments to be examined through the lens of built-environment theory while remaining grounded in practitioners' experiential knowledge. The analytical orientation is deductive: the spatial dimensions identified in the literature review provide the interpretive structure through which interview material is examined.

## 3.2 PARTICIPANT SELECTION AND SAMPLING STRATEGY

A purposive sampling strategy was employed to ensure that participants possessed substantial professional experience and long-term creative involvement in Sri Lankan cinema. Selection criteria focused on practitioners who had participated in multiple feature-length productions, received national-level professional recognition, and maintained sustained engagement in production design across different industrial phases. These criteria ensured that the selected participants had accumulated extensive experiential knowledge of spatial construction under varying economic, technological, and aesthetic conditions.

Through this process, four veteran production designers, identified in this study as Designer A, Designer B, Designer C, and Designer D, were selected as expert participants. Collectively, their careers span several decades of Sri Lankan film production, enabling reflection on both continuity and transformation in temporary spatial practice. Their experience across studio-based productions and location-based filmmaking provided a rich basis for examining how principles of temporary built environments operate across diverse production contexts.

## 3.3 DATA COLLECTION PROCEDURES

Data were collected through semi-structured qualitative interviews focusing specifically on spatial aspects of production design. Interview discussions addressed duration planning, dismantling and restoration processes, modification of existing locations, material selection and fabrication strategies, and the spatial organisation of sets in relation to narrative and technical requirements. While an interview guide ensured consistency across participants, conversations were allowed to develop narratively so that practitioners could articulate reflective accounts of their lived professional experiences.

Interviews were conducted in participant-selected environments, primarily their homes or workspaces, in order to encourage open and detailed discussion. With informed consent, all interviews were audio-recorded and subsequently transcribed verbatim. The transcription process preserved terminology, emphasis, and descriptive nuance relevant to spatial interpretation, ensuring that practitioner accounts could be examined accurately in relation to the conceptual framework.

## 3.4 ANALYTICAL STRATEGY: FRAMEWORK-GUIDED SPATIAL INTERPRETATION

The analytical strategy was deductive and framework-guided. Rather than employing open thematic coding to generate emergent categories, the analysis examined interview transcripts in relation to the three spatial dimensions established in the literature review: temporality, material construction, and experiential–narrative organization. Transcripts were read repeatedly to identify passages in which participants described time-bound construction processes, reversible interventions, material negotiation strategies, perceptual considerations, and narrative-driven spatial adjustments.

Extracted segments were interpreted as manifestations of temporary built environment principles within cinematic practice. This approach enabled practitioner knowledge to be translated into spatial categories consistent with architectural theory, while avoiding the imposition of unrelated analytical constructs. The purpose of the analysis was therefore not to produce independent themes, but to assess how established temporary built environment characteristics operate within film production design.

During the interpretive process, two additional recurrent characteristics dual functionality of space and operational flexibility emerged consistently across participant accounts. These were not treated as independent emergent themes, but as refinements that extend the comparative framework when applied to cinematic environments. Together, this framework-guided qualitative interpretation enables film production design to be examined as a structured and operational form of temporary built environment practice.

# 4. FINDINGS: TEMPORARY SPATIAL PRACTICES IN SRI LANKAN CINEMA.

This section interprets practitioner interviews through the three spatial dimensions identified in the architectural literature on temporary built environments: temporality, material construction, and experiential–narrative organisation. The analysis confirms that these three conditions are clearly operative within Sri Lankan film production design.

However, beyond these architecturally derived dimensions, the interviews consistently revealed one additional spatial characteristic specific to cinematic practice: the dual and operationally flexible nature of constructed space. This feature, while aligned with the conceptual framework developed from temporary built environment scholarship, emerges as a distinctive intensification within production design.

## 4.1 TEMPORALITY: DURATION AND REVERSIBILITY

Architectural temporary built environments are defined by limited duration, planned disassembly, and reversibility. Practitioner accounts demonstrate that cinematic environments operate under comparable temporal logic. All four designers consistently described duration as a primary planning parameter. As Designer B explained, “We first consider how long the set needs to remain. The materials depend on that timeframe”.

Unlike permanent construction, cinematic sets are calibrated precisely to filming schedules. Structural sufficiency is measured against the required period of operation rather than long-term endurance. In location-based productions, temporality is reinforced through reversibility. Existing houses are frequently modified for filming purposes, but these interventions remain temporary and must be removed without permanently altering the original environment. As Designer C explained, “When we work inside a real house, after filming the house must return exactly to how it was”.

Fixings are minimized, surface treatments are removable, and added elements are detachable. This mirrors architectural temporary installations where occupation is provisional and restoration is expected. Studio-based practice intensifies this cyclical logic. Sets are fabricated for dismantling: “The panels, windows, and doors are stored separately, but the space itself never remains the same (Designer B).”

Material elements may persist, but spatial configuration does not. In both architectural and cinematic contexts, temporality is embedded structurally rather than treated as an afterthought.

### 4.2 MATERIAL CONSTRUCTION: SUBSTITUTION AND STRUCTURAL SUFFICIENCY

Architectural temporary structures frequently rely on lightweight systems and modular components while maintaining functional adequacy. A parallel material strategy is evident in cinematic construction. Production designers consistently emphasized that economic limitations should not compromise perceptual credibility. As Designer A emphasized, “The audience must never perceive those limitations”.

Lightweight substrates, plywood frames, and composite materials are used to simulate masonry, concrete, or earthen walls. Surface layering plastering, texturing, ageing transforms temporary assemblies into perceptually stable architectural elements.

What distinguishes cinematic material practice is the calibrated relationship between structural adequacy and visual illusion. Sets must support performers, lighting equipment, and technical crews safely, yet they are constructed for controlled dismantling. Reuse is systematic: panels are dismantled, stored, and reassembled in new spatial configurations.

This aligns closely with architectural discussions of flexible and portable temporary systems, but cinematic practice intensifies material mobility by combining substitution, simulation, and cyclical reuse within rapid production timelines.

### 4.3 EXPERIENTIAL–NARRATIVE ORGANISATION: PERCEPTUAL ACTIVATION

Architectural temporary environments are frequently structured around events and experiential activation. Cinematic environments similarly derive meaning through narrative activation rather than permanence. Practitioners repeatedly emphasised the importance of perceptual authenticity within cinematic space. As Designer D noted, “If the audience feels that the space is artificial, then the illusion is broken”.

The interviews further revealed that selective spatial completion functions as a defining strategy within production design practice. As Designer A explained, “We build what the camera sees. Behind the camera, things can remain open”.

Unlike conventional architecture, cinematic space is framed and mediated through camera perception. It does not require complete architectural enclosure but must instead appear spatially convincing within the cinematic frame. Spatial organisation is therefore adjusted according to narrative and technical requirements. As Designer C stated, “Sometimes we move a wall because the scene requires it”.

Thus, experiential coherence supersedes architectural realism. Space is organised around action, framing, and emotional tone. In this sense, cinematic practice aligns with architectural event-based theories but operates through perceptual framing rather than direct physical occupation.

### 4.4 PRODUCTION DESIGN–SPECIFIC EXTENSION: DUAL FUNCTIONALITY AND OPERATIONAL FLEXIBILITY

While the three spatial dimensions align closely with architectural temporary built environments, one additional condition emerged consistently from practitioner accounts: the dual and operationally flexible nature of cinematic space.

Cinematic environments operate simultaneously at two levels: (1) As representational architecture within the narrative frame, (2) As technical infrastructure for production operations. As designer A and C explained: "The space must look complete on camera, but behind the camera it is completely different."

Walls may be partial, ceilings removable, and structural supports concealed outside the frame. A single constructed element may function both as narrative surface and as anchor for lighting or camera equipment. Furthermore, spatial flexibility is embedded in construction: "We must always think about where the camera will go (Designer D)."

Movable panels, detachable roof sections, and modular framing systems allow continuous adjustment during filming. While architectural temporary structures are designed for adaptability, cinematic environments require dynamic intra-use modification within a single production cycle.

This dual functionality and operational flexibility represent an intensification of temporary built environment logic. They are not separate from the framework but extend it within the industrial and performative conditions of filmmaking.

The deductive analysis confirms that Sri Lankan film production design operates through the three core dimensions associated with architecturally temporary built environments. At the same time, cinematic practice introduces a distinct extension: space functions simultaneously as representational architecture and as adaptive production infrastructure.

This layered and operationally flexible spatial condition distinguishes production design as a specialized form of temporary built-environment practice. Figure 01, 02 and 03 illustrates selected examples from Sri Lankan film production environments, demonstrating the key spatial conditions identified through the interview findings, including temporality, material construction, experiential–narrative organization, and operational flexibility. Together, these examples visually demonstrate how temporary cinematic environments function simultaneously as narrative spaces and active production infrastructures.

a) Studio-based temporart interior living room set construction

b) Experiential -narrative beach bar construction and crew functionality during the filming process

*Figure 1: Examples of temporary cinematic environments in Sri Lankan film production practice (Author's archive)*

*Figure 2: Examples of temporary cinematic environments in Sri Lankan film production practice (Author's archive)*

*Figure 3: Examples of temporary cinematic environments in Sri Lankan film production practice (Author's archive)*

Table 02 subsequently presents a comparative summary of the spatial dimensions identified in the interview findings.

*Table 2: Comparative summary of spatial dimensions identified in the interview findings*

| Spatial Dimension | Architectural Temporary Built Environments | Cinematic Spatial Practice (Production Design) |
|---|---|---|
| Temporality | Limited duration; planned disassembly; reversibility. | Time-bound sets; restoration of locations; cyclical studio reconfiguration |
| Material Construction | Lightweight systems; modularity; structural sufficiency. | Material substitution; surface simulation; reusable panels; visual credibility. |
| Experiential Organisation | Event-based activation; atmosphere; human occupation | Narrative activation; perceptual framing; selective completion |
| Production-Specific Extension | Adaptability and flexibility | Dual functionality and operational flexibility within active filming |

## 5. DISCUSSION AND CONCLUSIONS

This study examined whether Sri Lankan film production design can be interpreted through the conceptual framework of temporary built environments established within architectural discourse. The findings confirm that the three defining spatial dimensions identified in the literature review, namely temporality, material construction, and experiential narrative organisation, are clearly operative within cinematic practice. Duration functions as a governing design parameter in set planning. Reversibility and dismantling are embedded in both location transformation and studio fabrication. Material strategies prioritise structural sufficiency and perceptual credibility within defined timeframes. Cinematic environments therefore operate as temporally bounded yet fully functional spatial systems rather than improvised constructions.

The analysis also demonstrates that film production design intensifies these architectural principles under the industrial conditions of filmmaking. Structural adequacy is calibrated not for long term occupation but for concentrated operational use. Material substitution and surface simulation reveal a distinction between material permanence and perceptual permanence, showing how architectural credibility can be achieved through calibrated sufficiency rather than mass or longevity. Spatial organisation is activated through narrative framing, where selective completion and camera mediation replace full architectural enclosure. In this sense, cinematic environments align closely with event based temporary environments in architecture while operating through mediated perception rather than direct physical occupation.

Beyond the three dimensions derived from architectural theory, one additional characteristic emerged consistently from practitioner accounts: dual functionality combined with operational flexibility. Cinematic environments operate simultaneously as representational architecture within the frame and as technical infrastructure for production. Concealed structural systems accommodate lighting, camera movement, and crew circulation, while visible surfaces sustain narrative coherence. Spatial assemblies are designed to permit adjustment during filming, not only dismantling after use. This layered and responsive condition extends architectural discussions of adaptability by demonstrating how temporary spatial systems can remain structurally coherent while undergoing continuous modification during occupation.

By situating Sri Lankan cinema within the broader discourse on temporary built environments, this study broadens the conceptual scope of temporary built environments beyond conventional architectural typologies such as pavilions, exhibitions, and installations. Film production design demonstrates that temporally bounded spatial systems can be materially efficient, structurally reliable, experientially activated, and operationally flexible within constrained economic and industrial contexts. Recognizing cinematic production design as a legitimate form of temporary built environment practice contributes to a more expansive understanding of how time-based spatial infrastructures function across disciplines.

Future research may extend this investigation through detailed case studies of specific Sri Lankan films, production designers, or studio practices in order to examine how temporary spatial environments vary across historical periods, genres, and production conditions. Comparative studies between studio-built sets and transformed real locations may further contribute to understanding adaptive spatial practices within Sri Lankan

cinema. Such investigations would also support the documentation of practitioner-based spatial knowledge within local film production culture.

## 6. REFERENCES


Affron, C., & Affron, M. J. (1995). *Sets in motion: Art direction and film narrative*. Rutgers University Press. https://archive.org/details/setsinmotionartd0000affr/page/n7/mode/2up

Barnwell, J. (2005). *Production design: Architects of the screen*. Wallflower Press. https://www.nottingham.ac.uk/scope/documents/2005/october-2005/book-rev-oct-2005.pdf

Barnwell, J. (2020). *Production design: Architects of the screen* (2nd ed.). Wallflower Press.

Bergfelder, T., Harris, S., & Street, S. (2007). *Film architecture and the transnational imagination: Set design in 1930s European cinema*. Amsterdam University Press. https://doi.org/10.5117/9789053569801

Bishop, P., & Williams, L. (2012). *The temporary city* (1st ed.). Routledge.

Bordwell, D., & Thompson, K. (2019). *Film art: An introduction* (12th ed.). McGraw-Hill Education.

Brand, S. (1994). *How buildings learn: What happens after they're built* [DX Reader version]. Viking. https://archive.org/details/howbuildingslear00bran/page/n5/mode/2up

Bruno, G. (2002). Film, architecture, and the movement of spectators: The architecture of cinematic space. *Screen*, *43*(2), 195–205. https://doi.org/10.1093/screen/43.2.195

Cross, N. (2006). *Designerly ways of knowing* (1st ed.). Springer.

Kronenburg, R. (2007). Flexible: Architecture that responds to change. *Open House International*, *30*(2), 59-65. https://doi.org/10.1108/OHI-02-2005-B0008

LoBrutto, V. (2002). *The filmmaker's guide to production design*. Allworth Press. https://archive.org/details/filmmakersguidet00lobr_0/page/n3/mode/2up

McLean, S. T. (2007). *Digital storytelling: The narrative power of visual effects in film*. The MIT Press. https://doi.org/10.7551/mitpress/2432.001.0001

Mehrotra, R. (2014). *Ephemeral urbanism: Cities in constant flux* [Primera Edition]. Harvard University Graduate School of Design. https://catalog.princeton.edu/catalog/99102889483506421

Mehrotra, R., & Vera, F. (2017). Ephemeral urbanism: Looking at extreme temporalities. In T. Hass & H. Westland (Eds.), *The post-urban world* (1st ed.). Routledge. *https://doi.org/10.4324/9781315672168*

Neumann, D. (Ed.). (1996). *Film architecture: Set designs from metropolis to blade runner*. Prestel-Verlag.

Penz, F., & Thomas, M. (1997). *Cinema and architecture: Méliès, mallet-stevens, multimedia*. British Film Institute.

Ramírez, J. A. (2004). *Architecture for the screen: A critical study of set design in Hollywood's Golden Age.* McFarland & Company. https://archive.org/details/architecturefors0000rami/page/n5/mode/2up

Till, J. (2009). *Architecture depends*. MIT Press. https://mitpress.mit.edu/9780262518789/architecture-depends/

Tschumi, B. (1996). *Architecture and disjunction*. MIT Press. https://arch5350su14.wordpress.com/wp-content/uploads/2014/07/tschumi_architecture-and-disjunction.pdf

Wijerathne, H.M.P.M.K. and Hirudini, S.M., 2026. The effect of house plan types on house plan usage pattern transitions in upper middle-class residences: Case in Aniwatte, Kandy. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1664-1678. DOI: https://doi.org/10.31705/WCS.2026.121. Available from: https://ciobwcs.com/papers/

# THE EFFECT OF HOUSE PLAN TYPES ON HOUSE PLAN USAGE PATTERN TRANSITIONS IN UPPER MIDDLE-CLASS RESIDENCES: CASE IN ANIWATTE, KANDY

**H.M.P. Madhushani K. Wijerathne[1] and S.M Hirudini[2]**

## *ABSTRACT*

*This research aims to explore the effect of house plan types on residents' spatial usage pattern transitions over time with reference to upper-middle-class suburban residences, with a case study of Aniwatte East, Kandy. The houses are intended as permanent architectural forms, the extended period of occupancy results in a change of spatial intensity and spatial usage. The study is limited to upper-middle-class suburban houses in Kandy, as this specific socio-economic and contextual category remains underexplored in research. Through literature review physical parameters which affect house plan and the social parameters which affect usage patterns were identified. This research used a mixed-method approach for the case study of ten houses. Spatial data and usage data were collected via measured drawings, observations, and photographic records and interviews with the residents. The houses were analyzed across three phases, from the original plan, early occupancy, and current status, using both physical factors related to circulation, spatial utilization, material adaptability, durability, and furniture arrangement, analyzing with temporal parameters addressing the interval and frequency of house type transformation. The research identified six house types based on space use intensity. The results showed a trend from higher to lower intensity of use, indicated by the centralization of daily activities within a functional zone and increasing dormancy of peripheral areas. This change occurs mainly through interior rearrangement rather than structural alterations, preserving the original architectural form. The study provides insights for architects and housing professionals to create more adaptable and sustainable homes for upper-middle-class suburban residents.*

***Keywords:*** *Residences, Transition, Upper-Middle-Class, Suburban, Kandy*

## 1. INTRODUCTION

The study explores the realization and aspiration of house types through the transition between the initial and final house-type conditions and their usage patterns. Architecture in suburban Sri Lankan residences is influenced by cultural aspirations and values. Architecture in suburban areas such as Aniwatte, near Kandy, upper middle-class houses have often been designed as permanent objects, as opposed to meeting changing family

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, madhushaniwijerathne01@gmail.com
[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, mihirih@uom.lk

needs. This dichotomy between static design and changing household that there is space for improvement in terms of architectural adaptability, whereby houses may change in usage patterns while their physical structures remain unchanged. This can be better understood by examining these houses as multi-level entities consisting of frameworks, replaceable parts, and furniture.

The main concern of this study is that these suburban houses are static structures that, although meeting short-term needs, are not flexible enough to adapt to long-term needs. This means that as family needs change, such as in the case of reduced family size, these homes may remain unchanged, leading to inefficiencies. The lack of intrinsic flexibility could also cause problems in the utilization of space and energy. For example, unused rooms could be underutilized, and the core spaces become cramped. identifying this, the current research aims to examine how the physical design of the UMC houses of Aniwatte facilitates adaptability. The literature on Sri Lankan housing, mainly focuses on low-income settlements or informal sectors (Warakapitiya *et al.*, 2024), and there are few studies on houses in the upper middle class in suburban areas. As far as, the literature does not include all the dimensions of physical design, such as spatial configuration, volumetric properties, and materials and their transitions.

For the present research, a mixed-methods case study approach was employed to achieve the objectives, focusing on ten upper middle-class houses in Aniwatte East, Kandy. The data collection combined architectural plan analysis, on-site observation, archival records, and resident interviews (to track spatial changes). The selected houses were analysed at three stages of evolution: the original design (Design stage), early occupation (changes during construction stage), and the current stage (changes during usage).

## 1.1 RESEARCH AIM AND OBJECTIVES

The research aim is to examine how different house plan types influence the transition patterns of house plan usage over time in upper middle-class residences. The objectives of the study are: (i) to examine the spatial, volumetric, and material configurations of the selected houses; (ii) to identify the parameters of house plan elements, and transition; and (iii) to investigate the realization and aspiration of house types through the usage transition. The overall objective of the study is to improve the typology of house plans and thus enhance the flexibility of future house designs.

## 1.2 SCOPE AND LIMITATIONS

The proposed study will be limited to the upper-middle-class residential houses in Aniwatte East, a suburban area of Kandy. The proposed study will also be limited to the suburban area of Kandy and will thus exclude the lower-income groups of the population. The proposed study will also be limited to ten selected houses, and the period of transition will be around thirty-five years, so the findings are context-specific and not broadly generalizable. The proposed study will thus enable the researchers to compare the selected houses and thus analyze the spatial changes and usage patterns of the selected houses. The limitations caused by having only ten case study houses were mitigated by selecting a diverse set of cases (varying in construction period, family size and plan type), giving a proper cross section of the houses in the selected case study area. Since the typical case-study limitations remain, the results describe only the sampled cases. Therefore, the study findings are limited to similar socio-economic and geographic settings only.

# 2. LITERATURE REVIEW ON RESIDENTIAL ARCHITECTURE AND USAGE PATTERNS

House plans are dynamic spatial frameworks that change over time in response to evolving functional and social needs. Theories by Rapoport, Lawrence, Habraken, and Brand explain that while the structural shell remains stable, interior spaces adapt through reconfiguration and changing use. Flexible housing concepts further emphasize the importance of adaptability for long-term residential performance.

Family life-cycle changes significantly influence how domestic spaces are used over time. Events such as children growing up, migration, ageing, and reduced household size shift daily routines and cause some spaces to become underused while others remain active. Thus, house plan usage transition is shaped by both the architectural framework and changing family behaviors.

## 2.1 THEORETICAL FRAMEWORK

The study is based on a theoretical framework where architecture is treated as a dimension independent of other factors. The study is centred on the physical aspects of dwelling units, focusing on form, spatial interconnection, materials, and interior fit-out, using layered readings and their transition over time (Lawrence, 1987; Rapoport, 1969). This is achieved by means of plans, sectional drawings, diagrams, tables, etc., based on six basic parameters (P1-P6). The parameters P1-P4 analyse the spatial connection, materiality, and interior arrangement based on hierarchical levels such as primary structure, secondary structure, and furniture. The parameters P5-P6 analyse the temporal progression by focusing on the interval and periodicity of spatial and interior changes.

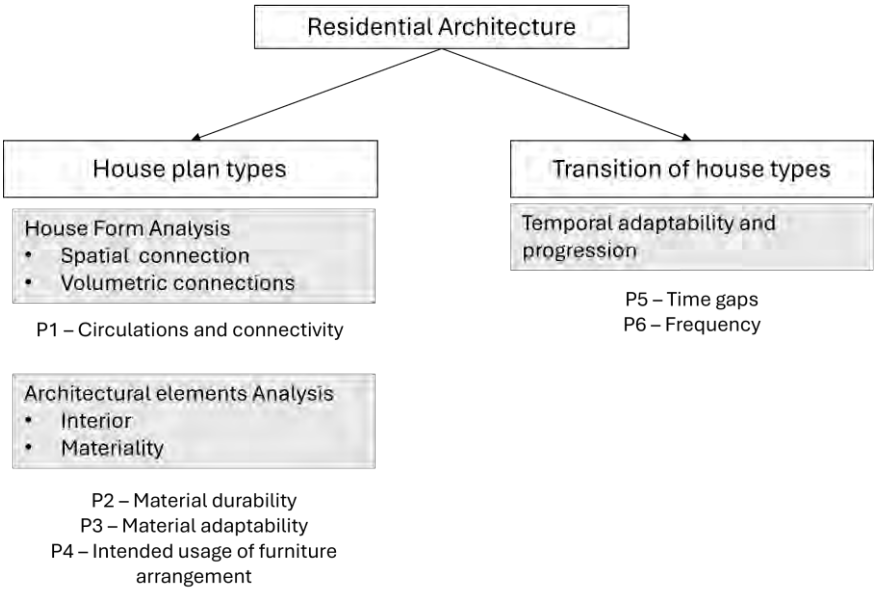



*Figure 1: Theoretical framework of the study*

## 2.2 PARAMETERS THAT AFFECT HOUSES PLAN TYPES

In accordance with the above framework, the following architectural parameters (P1–P4) and temporal parameters (P5–P6) were used to analyse the transitions:

*Table 1: Theory – Matrix chart for architectural parameters*

| Analytical focus | Spatial connection | | Materiality | Interior | House type transition | |
|---|---|---|---|---|---|---|
| Theory – parameters | **P1 – Circulation and space usage** | **P2 – Material adaptability** | **P3 – Material durability** | **P4 – Intended usage of furniture arrangement** | **P5 – Time Gaps** | **P6 – Frequency** |
| Family Life Cycle / Development (Lawson, 1988) | ✓ family routines reconfigure routes | ✓ spaces shift across life stages | ✓ families prioritize durable elements | ✓ furniture/layout adapts with family | ✓ family stages, spatial transition | ✓ recurring adjustments across stages |
| Open Building (Habraken, 1998) | ✓ support infill allows plan change | ✓ Building objective | ✓ base/supports emphasise longevity | ✓ infill and furniture easily modified | ✓ long-term phased change | ✓ infill systems - over time |
| Shearing Layers of Change (Brand, 1994) | ✓ Changing active circulation patterns | ✓ Adaptable material layers | ✓ layered durability | ✓ Frequent interior adaptations | ✗ | ✗ |
| Typology & Spatial Org (Panerai *et al*., 2004) | ✓ typological ordering shapes movement | ✓ typology can embed flexible modules | ✓ typological endurance supports longevity | ✓ interior hierarchy informs furnishing | ✓ typological - historical periods | ✗ |
| Flexible Housing (Schneider & Till, 2005; Till & Schneider, 2012) | ✓ designs allow adaptable paths | ✓ central to flexible housing discourse | ✗ | ✓ reconfigurable furniture recommended | ✓ temporal adaptability | ✓ flexibility capacity for repeated change |
| Materiality & Details (Brownell, 2014; Zumthor, 2006) | ✗ | ✓ details enable reversible adaptation | ✓ craft, finishes and longevity are central | ✓ details and finishes shape usability and longevity | ✗ | ✗ |

**P1: Circulation and Space Usage** – This parameter examines the relationship between the circulation and the utilization of the space. This parameter assesses how the circulation crosses the space. The interconnections of the space influenced daily routines. The more efficient, direct, and uninterrupted the circulation is, the more the space can be utilized. Fragmented circulation can result in isolated spaces with low functional potential.

**P2: Material Adaptability –** This parameter assesses the adaptability of the materials used in the space. Material adaptability allows reversible modifications, making it

possible to easily reinterpret spaces. Robust, warm finishes make it easier to adapt spaces, whereas rigid, fixed materials limit flexibility (Habraken, 1998). Material adaptability defines in the study ability to accommodate changing family needs (Schneider & Till, 2005; Till & Schneider, 2012).

**P3: Material Durability –** This parameter assesses the durability of the space. Durable space can be achieved by making sure the materials are strong. Strong materials can be used to make the interior. This can be achieved by using strong materials such as wood. On the other hand, a non-durable space can be abandoned due to the high cost of maintaining the space (Lawson, 1988).

**P4: Furniture Arrangement –** This parameter assesses the dynamic layer of the interior. Spaces that are constantly being rearranged are considered to have evolved (Panerai *et al.*, 2004). Adaptation is considered as A1 extensive change, A2 moderate change, and A3 minimal change. Adaptation is considered to have taken place when the interior is being constantly rearranged (Brownell, 2014; Zumthor, 2006).

**P5: Time gap -** This parameter assesses the time gap between the stages of spatial or functional transformation of the dwelling. This parameter assesses the period during which a spatial or functional transformation occurs.

**P6: Frequency -** This parameter assesses the recurrence of adaptive interventions within a defined time span. It considers how often spatial reorganization, material modification, or furniture rearrangement takes place within the architectural framework. Higher frequency reflects a greater capacity for repeated adjustment, while lower frequency indicates relative stability in spatial and interior conditions.

# 3. RESEARCH METHODOLOGY OF CASE STUDIES ON SELECTED HOUSES IN ANIWATTE

In addition, this section identifies the methodology applied in assessing the temporal evolution in selected upper middle-class houses in Aniwatte East. Ten houses with extended occupancy were used as a case study in assessing architectural evolution in Aniwatte East. The methodology applied in assessing architectural evolution is based on in-depth architectural analysis, which includes house plans, sections, site analysis, photographs, interviews, and sketches. Furthermore, this section identifies the basis on which the case houses were selected, a general overview of Aniwatte, and the methodology applied in assessing architectural transformations. All these methodologies form a basis for analyzing the dynamism of spaces (Habraken, 1998).

## 3.1 CASE STUDY SELECTION CRITERIA AND AREA

Kandy is a compact city with a limited core of residential areas, resulting in a high proportion of upper-middle class residents and professionals (doctors, engineers, etc.) living in proximate suburbs. Aniwatte East is one such area, with a population of approximately 1,200 people, divided into 245 households. It is approximately 2.5 kilometres from the city core. This has resulted in a large number of houses being under-occupied or rented out. This trend, where a house has fewer occupants, is the backdrop for this study on the role of architectural design. Ten upper-middle-class residential buildings, constructed or occupied between 1990 and 2010, were purposively selected to allow for depth analysis, depending on the willingness of the owners to allow access to

architectural plans, renovation histories, and interviews. Although the buildings have similar architectural features to those in the region, they vary in terms of plot size, floor numbers, roofing materials, and renovation levels, which allow for comparative analysis of differing architectural responses to similar residential conditions. Aniwatte East, 2.5 km from the center of Kandy, is a green suburb in close proximity to major schools and hospitals.

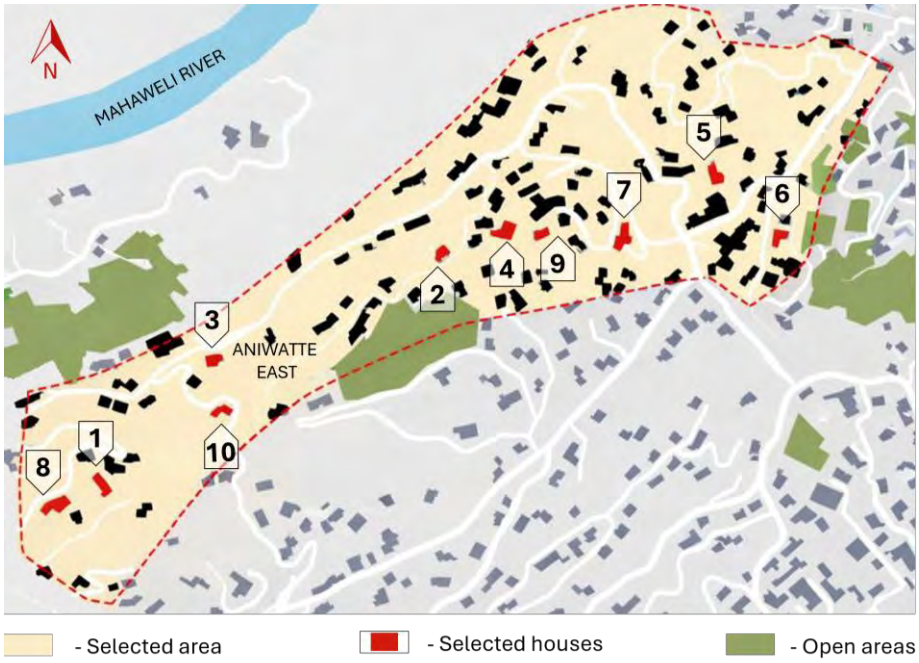



*Figure 2: Selected houses in Aniwatte east*

The study adopted a mixed-method case study approach representation of varying house plan configurations and house plan usage transitions. Semi-structured interviews were conducted with residents to document family life-course progression, spatial usage changes, renovation history, and reasons for physical adaptations. Qualitative data from interviews, observations, photographs, and archival records were integrated with quantitative comparative analysis through plan overlays, temporal transition charts, count-based change assessment across parameters (P1–P4), and cross-case typological classification, enabling both physical transition patterns and socio-demographic influences to be systematically interpreted.

## 3.2 METHODOLOGICAL FRAMEWORK

The methodology is based on the study of house changes and is structured into two analytical components: physical configuration analysis and temporal usage progression analysis. The first component includes house plan analysis and architectural elements analysis, which focuses on spatial connections, materiality, and interiority through readings of layers (P1-P4).

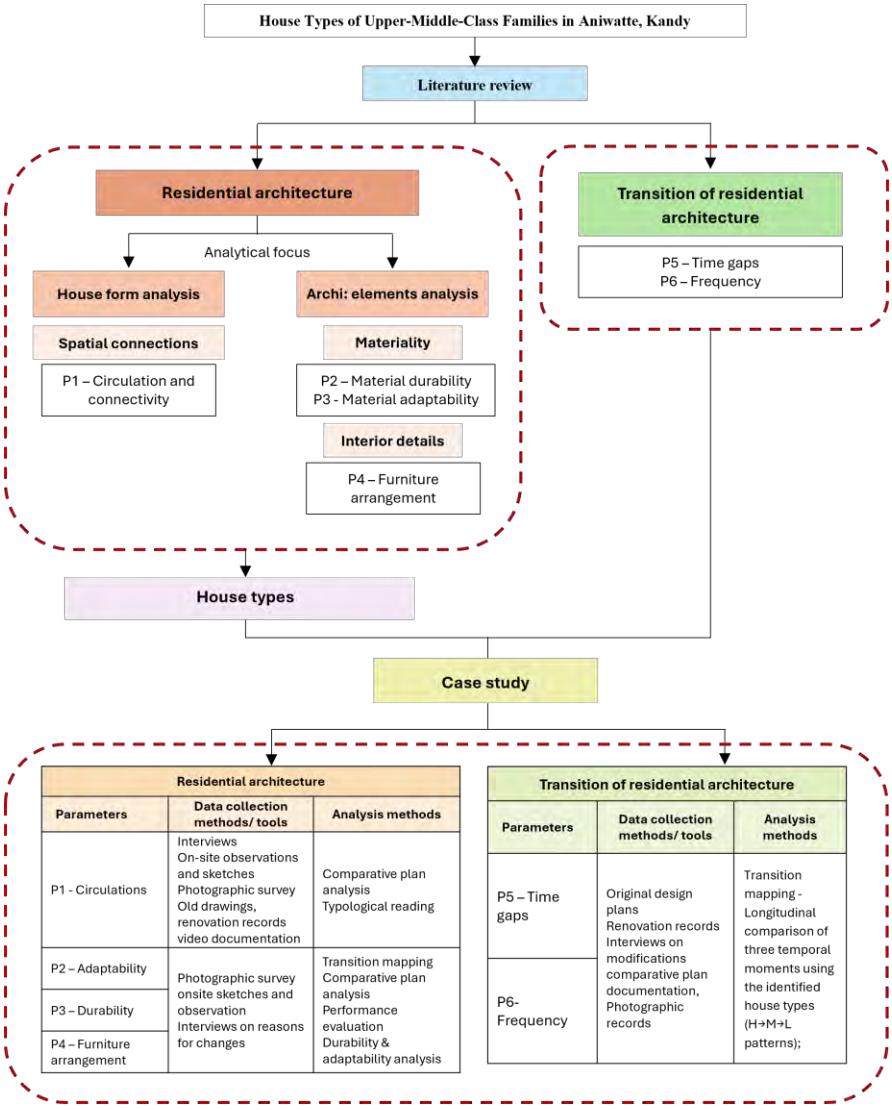



*Figure 3: Research design, methodological framework*

The data collection process is based on documentary study, direct observation, visual recording, architectural plans, and testimonies of inhabitants that identify the designed house and the house in use through interviews and walk-through documentation. The second component research temporal adaptability (P5-P6) by means of the chronological analysis of three temporal moments and identified house types across time bands. The analytical methods consist of comparative plan analysis, typological analysis, transition analysis, and interval/occurrence analysis.

### 3.2.1 House Plan and Architectural Elements Analysis

The focus of this phase analyses how each selected house's physical spatial configuration is organized and how it supports adaptation. The house is considered as a largely static structure composed of layered elements. Three points in time are examined: the initial design or purchase, an early phase of occupancy, and the current state. At each of these points, the floor plan and section are coded to show the locations of circulation cores, space utilization, materiality, and interior arrangement. Using the physical parameters

(P1–P4), spatial connection, material adaptability, material durability, and furniture arrangement are evaluated, establishing the basis for house-type identification.

#### 3.2.2 House-Type Transition and Temporal Usage Progression

This section is focused on the determination of house type progress across the time. In this case, the residences are seen as a mostly static structural framework with varying uses. A comparative examination of the same triad of time moments is conducted to identify the progression of the types of houses. Through the use of the time parameters (P5–P6), the time gap between the stages and the periodicity of spatial and interior changes are evaluated. In this phase, the connection between the physical configuration and the time adaptability of the spatial usage is solidified.

# 4. RESEARCH RESULTS

## 4.1 ANALYSIS OF HOUSE TYPES OF SELECTED FAMILIES

This area is focused on the architectural analysis of the selected upper middle-class houses. In this case, the analysis is conducted from the architectural or physical point of view by examining how the built form is configured and how its internal spatial connectivity evolves across three phases: the design or buying stage, the early occupation phase, and the current phase. The focus is the house as an architectural object, addressing, the dynamism of spaces, the materiality, adaptability, furniture arrangement and the layers of the fabric and the fit-out that define the level of physical change that is possible over time are examined (Brand, 1994; Habraken, 1998). In this analysis, the built form is examined as a hierarchy of physically distinct layers. As a key finding, the selected upper-middle-class houses demonstrate low material and furniture adaptability, as durable permanent elements such as teak and jack furniture limit future reconfiguration despite their long-term usability. In this area, the primary layer is comprised of the structural plan framework, the partitions, the floor plates, and the roof. The secondary layer is comprised of the fixed but replaceable items such as the joinery, the window systems, and the cabinetry.

The classification of house types into High (H), Moderate (M), and Low (L) usage was developed through a comparative count-based analysis rather than descriptive interpretation. Across parameters P1–P4, separate horizontal timeline bar charts were used to track functional changes, material adaptability, material durability, and furniture arrangement across the three stages. Based on the cumulative frequency of observed changes, houses were classified as Low (0–2 changes), Moderate (3–5 changes), and High (>5 changes), providing a more consistent and reproducible basis for typological classification.

### 4.1.1 House Types of Classification and Analysis

On the basis of the above analysis, houses were classified into six types based on two axes. The first axis (H/M/L) reflects overall spatial utilization (P1), where:

- H (High usage - > 5 changes): Many rooms are actively used daily. The circulation network is clear and multi-nodal.
- M (Moderate usage - 3-5 changes): Contraction is partial. Activity centers are concentrated primarily in key areas (living, kitchen), with some peripheral areas used to a less use.

- L (Low usage - 0-2 changes): Activity is concentrated in a few core rooms. Significantly large areas of the plan are dormant, often including large areas of upper floors and/or formal spaces.

The second axis (A1/A2/A3) reflects interior adaptation (P4), where:

- A1 (High adaptation - > 5 changes): Rooms have been substantially refurnished.
- A2 (Moderate adaptation - 3-5 changes): Moderate interior rearrangement. Furniture has been moved and/or added.
- A3 (Low adaptation - 0-2 changes): Rooms have not been refurnished. Original furniture layouts remain essentially intact.

Combining these yields the six empirical house types: H-A3, H-A2, M-A2, M-A1, L-A2, L-A1. Each type captures both spatial intensity and degree of interior change.

*Table 2: House Type Classification and Analysis*

| Case no. | Parameters | | | | Type |
|---|---|---|---|---|---|
| | P1 | P2 | P3 | P4 | |
| **01** | | | | | H – A2 |
| **02** | | | | | H – A3 |
| **03** | | | | | H – A2 |
| **04** | | | | | M – A2 |
| **05** | | | | | M – A2 |
| **06** | | | | | M – A1 |
| **07** | | | | | L – A2 |
| **08** | | | | | L – A2 |
| **09** | | | | | L – A1 |
| **10** | | | | | L – A1 |

- High, - Moderate, - Low, **H** – Highly functioning , **M** – moderate functioning, **L** – Lower functioning, **A1** – Higher intended usage, **A2** – Moderate intended usage, **A3** – Lower intended usage, - **H-A2** (Higher circulation and space usage moderate intended usage of furniture arrangement), - **H-A3** (Higher circulation and space usage low intended usage of furniture arrangement), - **M-A1** (Moderate circulation and space usage high intended usage of furniture arrangement), - **M-A2** (Moderate circulation and space usage moderate intended usage of furniture arrangement), - **M-A3** (Moderate circulation and space usage low intended usage of furniture arrangement), - **L-A1** (Low circulation and space usage high intended usage of furniture arrangement), - **L-A2** (Low circulation and space usage moderate intended usage of furniture arrangement)

#### 4.1.2.1 House Type 01: H-A3

For H-A3 residences, circulation is highly efficient and nearly all areas are used. The floor plan is integrated, with the kitchen, living room, and master bedroom well-connected. “A3” indicates that furniture remains in its original configuration (original seating, beds, storage intact), with only minor adjustments in placement. Thus, H-A3 is marked by high utilization and minimal interior change.

#### 4.1.2.2 House Type 02: H-A2

H-A2 residences also have active circulation and core areas acting as hubs but show moderate interior change. “A2” means one or two room usage changes (e.g. an extra bedroom converted into an office). These homes still have multi-room circulation, with stage-2 furniture rearrangements or additions, while the overall space configuration remains unchanged.

#### 4.1.2.3 House Type 03: M-A2

M-A2 residences have partially functioning circulation. The main living core (entrance, living/dining, kitchen) is used daily, while many secondary areas (formal living, formal dining, upper-floor guest rooms) are underutilized. Vertical circulation remains, but many corridors end as dead ends. “P4 = A2” indicates moderate furniture changes (such as adding chairs in underused spaces) without significant room reconfiguration.

#### 4.1.2.4 House Type 04: M-A1

Circulation in M-A1 is similar to M-A2 but with significant levels of interior adaptation. “A1” refers to the full repurposing and furnishing of idle spaces. In this type, the exterior remains the same, but the interior is adapted in stages with the addition of new pieces of furniture and cabinetry. Thus, M-A1 houses combine moderate levels of circulation efficiency with high levels of interior adaptation.

#### 4.1.2.5 House Type 05: L-A2

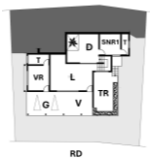
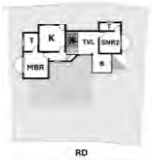
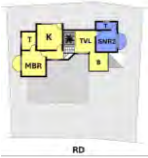
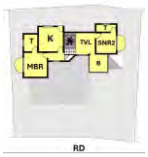
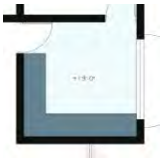
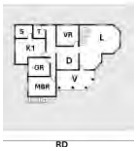
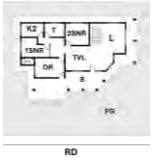
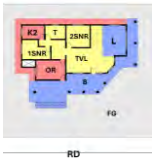
L-A2 houses have higher fragmentation, with the majority of the spaces, particularly on the upper levels and core, idle and disconnected. daily movement is confined to the designated spaces on the ground level, such as the kitchen, living room, or master bedroom. “P4 = A2” refers to moderate levels of adaptation. In this type, the idle spaces may be repurposed or reassigned. For example, the idle bedroom may be converted into a storage room. Thus, L-A2 houses combine low levels of spatial efficiency with moderate levels of interior change.

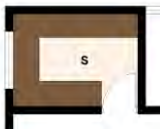
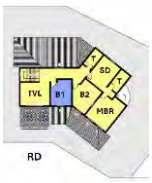
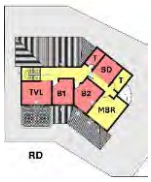
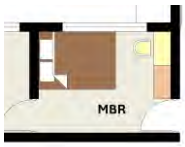
#### 4.1.2.6 House Type 06: L-A1

L-A1 houses have poor circulation efficiency, with daily movement limited to a couple of areas (typically the kitchen, living room, and perhaps one bedroom) and most spaces idle. “A1” refers to the full repurposing and furnishing of the idle spaces. Thus, L-A1 homes have weak circulation combined with significant interior adaptation.

The following table presents three representative case studies from the ten identified cases, based on the three major house plan types along the first axis of analysis. The cases were selected for their strong defining characteristics, distinctive spatial qualities, and diversity in occupant and household profiles.

*Table 3: House* type *- Based case study summary*

| Case No & type | Floor | Design/ buying Stage | Construction/ Renovated stage | Current Stage |
|---|---|---|---|---|
| | | ***2014*** | ***2015*** | ***2025*** |
| Type H – Case No 03 | Ground Floor Plan |  | | |
| | First Floor Plan |  |  |  |
| | MBR Interior | | | |
| | Son's RM 2 Interior | |  | |
| | | ***2003*** | ***2004*** | ***2025*** |
| Type M – Case No 06 | Ground Floor Plan @ +/- 0 level |  | | |
| | First Floor Plan @ 10'-0" level |  |  | |
| | Office room | | | |

| Case No & type | Floor | Design/ buying Stage | Construction/ Renovated stage | Current Stage |
|---|---|---|---|---|
| Type L – Case No 09 | Kitchen 2 | |   | |
| | | ***2001*** | ***2001*** | ***2025*** |
| | Ground Floor Plan @ +/- 0 & 3'-0" level | | | |
| | First Floor Plan @ 13'-0" level | |   |   |
| | MBR/ Store RM | | | |
| | Visitor's RM/ MBR | | |   |

- Mostly used spaces, - Rarely used spaces, - Underutilised spaces, **K** – kitchen, **D** – dining space, **L** – living room, **TVL** – tv lobby, **T** – toilet, **G** – garage, **S** – storage, **B** – balcony, **MBR** – master bedroom, **DR** – daughter's room, **SNR** – son's room, **GR** – grandparent's room, **VR** – visitor's room, **PLA** – play area, **SR** – servant's room, **OR** – office room, **RD** – road, **FG** – front garden, **RG** – rear garden, **SD** – study area, **LD** – laundry, **PA** – Prep area, **SA** – Seating area, **DRR** – Driver's room, **V** – Verandah**, C** – Couch, **STD –** Studio, **TR** – Terrace

## 4.2 ANALYSIS OF HOUSE TYPE TRANSITION OF SELECTED FAMILIES

An analysis of all the longitudinal data shows a pattern of contraction in spatial use for the selected houses. The transition table (Table 3) shows that the majority of the houses begin with an H-type configuration (either H-A2 or H-A3) and overtime transition to lower-intensity types. For example, Cases 07–10 each follow the full sequence from H to M to L. clearly demonstrating a clear progression towards a stepwise reduction in active spaces. These houses begin with high spatial activity and eventually concentrate activity within a limited core area. Cases 05-06 demonstrate a partial transition process from H to M, indicating a reduced spatial activity from their original configuration. Cases 01-03 maintain H-types over the entire longitudinal process, indicating high spatial activity; however, their trajectories suggest these houses may transition toward M-types if

observed further. Case 04 remains stable as an M-type, balancing moderate usage with moderate interior adaptation.

The identified transition pattern emerges through a combination of architectural conditions and socio-demographic changes across the family life cycle. Key contributing reasons: Children's educational progression and migration, which reduce spatial intensity as previously active bedrooms and study spaces become dormant once children relocate for higher education or overseas opportunities (e.g. Cases 07-10); Empty-nest transition and shrinking household size, which concentrate daily life within a smaller functional core while peripheral spaces become underutilised (e.g. Cases 07–10); Ageing and reduced mobility of parent occupants, which gradually limit vertical circulation and shift everyday use toward more accessible zones (e.g. Case 02, 07); and Changing family routines and intergenerational domestic needs, which result in the repurposing of spaces such as play areas, visitor rooms, and study areas (e.g. Case 01, 06). These observations suggest that the transition of house-plan types is influenced not only by physical architectural capacity, but also by evolving family structures and changing spatial demands over time.

*Table 4: House type transition*

| Case no. | House Types Transition | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *1985 - 1990* | *1980 - 1995* | *1995 - 2000* | *2000 - 2005* | *2005 - 2010* | *2010 - 2015* | *2015 - 2020* | *2020 - 2025* |
| **01** | | | | | | | P | H – A2 |
| **02** | | | | | Q | Q | H – A2 | H – A3 |
| **03** | | | | | P | P | H – A2 | H – A2 |
| **04** | | | | | | A | A | M – A2 |
| **05** | | | | P | H – A2 | H – A2 | H – A3 | M – A2 |
| **06** | | | P | P | H – A2 | M – A2 | M – A2 | M – A1 |
| **07** | A | Q | Q | Q | H – A2 | M – A2 | M – A2 | L – A2 |
| **08** | Q | A | P | H – A2 | H – A2 | M – A2 | M – A3 | L – A2 |
| **09** | P | P | P | P | P | H – A3 | M – A2 | L – A1 |
| **10** | A | A | A | Q | H – A3 | M – A2 | L – A1 | L – A1 |

- **H-A2** (Higher circulation and space usage moderate intended usage of furniture arrangement), - **H-A3** (Higher circulation and space usage low intended usage of furniture arrangement), - **M-A1** (Moderate circulation and space usage high intended usage of furniture arrangement), - **M-A2** (Moderate circulation and space usage moderate intended usage of furniture arrangement), - **M-A3** (Moderate circulation and space usage low intended usage of furniture arrangement), - **L-A1** (Low circulation and space usage high intended usage of furniture arrangement), - **L-A2** (Low circulation and space usage moderate intended usage of furniture arrangement)

Further, a quantitative analysis of the transition table confirms the identified patterns. Of the 10 cases, 4 cases reach L-type state, 3 cases end at the M-type state, and 3 cases remain at the H-type. This reveals a strong trend of reduced spatial utilization, as the majority of houses exhibit a movement toward reduced utilization levels. The letters (P, Q, A) in the table columns track the timing of these shifts, the key insight is that L-A1 and L-A2 appear as the final stage for most cases. This contraction pattern is consistent and directional, as they reduce the number of active-rooms over the course of the period. Therefore, the transition analysis confirms the identified trend of the houses exhibiting a

reduction of spatial intensity (from H to M to L) as the prominent typological narrative presented in the study.

### 4.3 FUTURE PROBABILITIES OF EVOLVING PATTERNS

Most families in the study begin their occupancy in H-A2 or H-A3 houses, reflecting high spatial intensity at the start of each case. These high-intensity house types have a high probability of transitioning through M-types and toward L-types as the family cycle progresses. In practical terms, this means that the majority of houses are likely to decrease their effective use of space over time. Indeed, according to Table 3, L-A1 and L-A2 serve as the terminal conditions in 40% of cases (Cases 07–10), making them the most common endpoint. Cases 05 and 06 terminate in M-A2 and M-A1 respectively, and Cases 01–03 stay in H-types. Thus, 7 out of 10 houses reach an M- or L-type by the final period, indicating that a downward shift in spatial usage is the norm. Notably, only one case (Case 06) continues beyond the first cycle as M-A1, which suggests a renewed cycle of adaptation. This case is effectively entering a second family cycle without declining to an L-type, showing that not all trajectories end at L-type. The persistence of Case 06 at M-A1 implies that additional interior adaptation (re-furnishing or repurposing rooms) can maintain a moderate circulation core even as spatial usage contracts. Overall, these future probabilities imply that aspiration for sustained high-intensity use is generally unmet; the realization is that most houses will follow the H to M to L path. Critically, this progression reflects behavioral adaptation rather than structural change: the physical framework of each house remains stable across cycles, and it is the patterns of occupancy and furniture arrangement that redefine the active spatial core over time. This observation is consistent with Habraken's (1998) open building concept, where the permanent structural framework remains stable while the changeable interior infill adapts over time. Similarly, Brand's (1994) shearing layers of change support this interpretation, as the observed transitions occur primarily within fast-changing interior layers rather than through alterations to the structural shell. The study findings agree with the findings of Hirudini and Yamada (2024), that house plans and their usage transit with time and the development of the family (Hirudini & Yamada, 2024). These findings advocate for an architecturally adaptable housing framework in which domestic spaces are conceived not as fixed permanent programs, but as flexible spatial systems capable of contraction, expansion, and functional reconfiguration in response to evolving family life cycles, changing occupancy patterns, and long-term socio-spatial transformations.

## 5. CONCLUSIONS

This study establishes a clear connection between house plan types and their long-term transition of upper-middle-class suburban residences. The study identified six empirical house types (H-A3, H-A2, M-A2, M-A1, L-A2, L-A1) that capture variations in circulation efficiency and interior change. The longitudinal analysis shows a dominant H to M to L transition pattern: houses start with high spatial intensity (H-types) and generally contract toward moderate (M-types) and then low intensity (L-types) over successive occupancy periods. This pattern was evident in Table 3, where most cases end in L-A1 or L-A2. Importantly, the contraction in space use is achieved through interior adaptation (rearranging or replacing furniture) rather than changing the building's structure. The external shell remains essentially unchanged, while certain rooms fall out of daily use and others are refurnished for new functions. This reinforces the theoretical

position of open building and shearing layers introduced as methods to achieve adaptability, which suggest that long-term adaptability of houses often occurs through interior reconfiguration rather than structural transformation. However, unlike pre-designed flexible housing models (Schneider & Till, 2005; Till & Schneider, 2012), the adaptability observed in this study appears to be activated primarily by family lifecycle changes and reduced occupancy rather than intentional design flexibility. These findings imply that upper-middle-class houses tend to consolidate activity into a smaller core (typically the kitchen, living area, and master bedroom) as families evolve. In practical terms, designers and homeowners should recognize that flexibility in furniture and interior layout is key to long-term adaptability. The typology and transition patterns developed here can inform strategies to prolong the functional life of such houses. Overall, the research highlights that without major interventions, most houses will follow the observed contraction trend, but thoughtful design can mediate this through adaptability in use rather than overhauling the structure.

## 6. ACKNOWLEDGEMENTS

The authors sincerely appreciate the house owners and all who assisted in facilitating data collection and supporting this research.

## 7. REFERENCES

Brand, S. (1994). *How buildings learn: What happens after they're built*. Viking Press.

Brownell, B. (2014). *Material strategies: Innovative applications in architecture*. Princeton Architectural Press.

Habraken, N. J. (1998). *The structure of the ordinary: Form and control in the built environment*. MIT Press.

Hirudini, S. M., & Yamada, K. (2024). Dynamism of house plans with reference to family conditions of lower-middle-class families in suburban western coast of Sri Lanka. *Buildings*, *14*(2), 522. 10.3390/buildings14020522

Lawrence, R. J. (1987). *Housing, dwellings and homes: Design theory, research and practice*. John Wiley & Sons.

Lawson, R. W. (1988). The family life cycle: A demographic analysis. *Journal of Marketing Management*, *4*(1), 13–32. https://doi.org/10.1080/0267257X.1988.9964057

Panerai, P., Castex, J., & Depaule, J. C. (2004). *Urban forms: The death and life of the urban block*. Architectural Press.

Rapoport, A. (1969). *House form and culture*. Prentice-Hall.

Schneider, T., & Till, J. (2005). Flexible housing: Opportunities and limits. *Architectural Research Quarterly*, *9*(2), 157–166. https://doi.org/10.1017/S1359135505000199

Till, J., & Schneider, T. (2012). Invisible agency. *Architectural Design*, *82*(4), 38–43. https://doi.org/10.1002/ad.1426

Warakapitiya, G. Y. D., Coorey, S. B. A., Perera, N. G. R., & Giridharan, R. (2024). Behavioural adaptations and housing modification: A case study of a low-income high-rise housing estate in Sri Lanka. In Y. G. Sandanayake, K. G. A. S. Waidyasekara, K. A. T. O. Ranadewa, & H. Chandanie (Eds.), *Proceedings of the 12th World Construction Symposium* (pp. 279–290). Ceylon Institute of Builders. https://doi.org/10.31705/WCS.2024.22

Zumthor, P. (2006). *Atmospheres: Architectural environments, surrounding objects*. Birkhäuser.

Fernando, M.H.R., Kulatunga, U., Gheethanjali, B. and Gunawardhana, D.N.T., 2026. The financial and social implications of construction site accidents in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1679-1692. DOI: https://doi.org/10.31705/WCS.2026.122. Available from: https://ciobwcs.com/papers/

# THE FINANCIAL AND SOCIAL IMPLICATIONS OF CONSTRUCTION SITE ACCIDENTS IN SRI LANKA

**M.H.R. Fernando[1], U. Kulatunga[2], B. Gheethanjali[3] and D.N.T. Gunawardhana[4]**

## *ABSTRACT*

*Construction site accidents are increasingly prevalent worldwide due to the dynamic and uncertain nature of the construction industry. Such accidents adversely affect overall productivity and performance while imposing significant consequences on construction firms, workers, and their families. Accordingly, this study aims to examine the financial and social impacts of construction site accidents in Sri Lanka. A quantitative research approach was adopted, and data were collected through a questionnaire survey from 68 respondents and analysed using the Statistical Package for the Social Sciences (SPSS). The findings indicate that construction site accidents lead to substantial financial burdens on organisations, including increased insurance premiums, compensation payments for injuries or fatalities, and additional costs associated with remedial and preventive measures to avoid recurrence. Furthermore, the study identifies deterioration of corporate reputation and loss of public trust as the most significant social consequences for construction organisations. At the societal level, an increase in debt was the most prominent financial impact arising from construction site accidents. From a family perspective, the loss of the primary income earner due to a site accident was the most severe social consequence. Although remedial mechanisms exist in Sri Lanka covered under the Workmen's Compensation Policy, the compensation provided is insufficient to adequately support affected families when compared with the comprehensive social security systems available in developed countries. Based on the findings, the study proposes practical recommendations aimed at minimising construction site accidents and mitigating their adverse financial and social impacts on both organisations and affected families.*

***Keywords:*** *Construction Sector; Financial Implications; Site Accidents; Social Implications; Sri Lanka.*

## 1. INTRODUCTION

The Construction Industry is a key sector that significantly contributes to economic growth, particularly in developing countries (Jayamal et al., 2023). Darshana (2017) noted that a considerable number of unskilled and inadequately qualified workers are employed on construction sites, which has led to an unacceptably high rate of workplace

[1] Senior Quantity Surveyor, Surath Wickramasinghe Associates, Sri Lanka, rruchi101@gmail.com
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Temporary Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anjana122000@gmail.com
[4] Head of the Research Support Services Division, Library, University of Moratuwa, Sri Lanka, Nayanig@uom.lk

accidents and safety-related incidents across the country. Compared to other industries, the construction sector is inherently more susceptible to accidents (Mohammadi et al., 2018). Further statistical evidence indicates that the probability of fatal accidents occurring in the construction sector is approximately three to four times higher than in other industries in developed countries, while in developing countries it is about three to six times higher (Melagoda & Rowlinson, 2022).

Such accidents often result in project delays, productivity losses, and adverse consequences for all stakeholders involved, either directly or indirectly (Lee et al., 2018). In addition, construction site accidents have wider societal implications, affecting not only workers but also their families and relatives, project owners, construction professionals, and companies (Arquillos et al., 2012). Moreover, site accidents could result in fatalities and severe injuries to workers while the families can suffer immense loss and agony as a result of these event (Choi et al., 2020). Accordingly, the financial complications and emotional health of the dependents may affect all dependents long after the death of the primary provider (Quadir et al., 2019). Construction accidents can further damage public trust and negatively influence perceptions of construction firms, contractors, and regulatory bodies responsible for enforcing safety regulations on construction sites.

Within the context of Sri Lanka, the ratio between non-fatal and fatal accidents has become high, indicating that fatal accidents are increasingly alarming in Sri Lanka (Dasandara & Dissanayake, 2021). In 2019 alone, the Sri Lankan construction industry recorded forty fatal accidents and fifty-nine non-fatal accidents (Melagoda & Rowlinson, 2022). Moreover, about 4000 workplace accidents occur annually in Sri Lanka (Thalgaspitiya et al., 2018). Furthermore, Accident and Orthopaedic Service of Sri Lanka National Hospital treated more than 102,000 accident patients in 2015, and occupational health risks are thought to be liable for 12% of whole injuries and 50% of entire serious accidents (Darshana, 2017). These challenges highlight the need for effective protective measures and preventive strategies to reduce accident occurrences on construction sites. Given the hazardous nature of the industry, numerous studies, publications, and scholarly works have examined construction site accidents, their causes (Birhane et al., 2020), accident types, and preventive approaches (Ahamed et al., 2011; Darshana, 2017). Identifying the economic and social implications of site accidents within the construction industry may support organisations in adopting proactive measures to mitigate potential losses. Numerous studies were conducted in other countries including Mthalane et al. (2008) have examined the social and economic impacts in South Africa whereas Okorie & Aigabavboa, (2016) examined the impacts in Nigeria. Further, Elsebaei et al. (2020a) has conducted a study on the impacts in Egypt construction sector. Moreover, Okorie & Adindu (2020) have analysed the impacts of site accidents on small and medium construction companies. However, limited studies have been carried out in investigating the social and financial impacts of construction site accidents on both construction workers' families and construction companies in Sri Lanka. Therefore, the aim of this research is to enhance health and safety practices in Sri Lanka by identifying the financial and social impacts of construction site accidents. To achieve this aim, initially a literature review was done to identify the economic and social impacts of site accidents on construction companies and affected families globally. Then, the impacts were analysed in Sri Lanka and classified the impacts based on their characteristics.

# 2. LITERATURE REVIEW

The literature review was done mainly analysing the journals, conference proceedings, news articles, books and relevant websites. The literature review is essential to identify the impact of site accidents on the construction sector and the society. Therefore, this chapter analyses the background of site accidents in the construction sector and it's social and financial impacts.

## 2.1 SITE ACCIDENTS IN THE CONSTRUCTION INDUSTRY

Workers engaged in site-related activities are continuously exposed to occupational hazards and injuries, rendering the construction industry one of the most dangerous and high-risk sectors due to its complex and dynamic nature, particularly in developing countries (Zeng & Yoon, 2022). In the Sri Lankan context, the construction industry ranks as the third largest contributor to fatal workplace injuries and accidents among all industries (Udawatta & Rameezdeen, 2012).

The primary causes of construction site accidents can be categorised into environmental, human, and mechanical factors (Chi & Han, 2013). Human factors encompass fatigue, negligence, and inadequate knowledge of safety practices, whereas mechanical factors involve the use of defective tools or malfunctioning equipment. Environmental factors include adverse weather conditions, insufficient lighting, slippery surfaces, falls from heights, trips caused by staircases or balconies lacking handrails or protective barriers, and inadequate safety training (Shamsuddin et al., 2015). Furthermore, occupational risk among non-executive construction workers is significantly higher than that of executive personnel due to the nature of their tasks and the conditions under which they operate (Wang et al., 2018). Approximately 70 to 80% of fatalities and 35 to 40% of accidents are attributed to incompetence or non-compliance with hygiene and safety regulations (Zelalem, 2015).

To address construction related accidents, one key practice is the strict monitoring of safety protocols and employee compliance at construction sites, as emphasised by Ambegaonkar (2020). Furthermore, the implementation of environmental protection measures and building safety practices has been recognised as a significant factor in reducing construction accidents (Shamsuddin et al., 2015). Employees and their representatives have obtained important new rights through amendments to occupational safety and health laws and regulations, including the ability to file complaints, request site wide inspections, access information, and explore new protective standards (David et al., 2020). Accordingly, construction organisations are advised to educate employees on the importance of safe practices and the impacts of site-related hazards (Elsebae et al., 2020a). In Sri Lanka, safety provisions include the adoption of security methodologies such as protective indicators and warning signals, restrictions on harmful narcotics and alcohol at workplaces, and the provision of safety manuals, first aid equipment, and handlers' booklets (Priyadarshani et al., 2013).

## 2.2 FINANCIAL AND SOCIAL IMPLICATIONS OF CONSTRUCTION SITE ACCIDENTS

The impacts associated with financial conditions can be identified as being linked to financial factors (Elsebaei et al., 2020b). The costs of occupational accidents can be classified into three main categories: direct costs, indirect costs, and quality-of-life costs

(Waehrer et al., 2007). According to this classification, direct costs include medical expenses, police and fire services, emergency transport, property damage, and the wages of injured workers. Indirect costs comprise production losses, wage losses, reductions in household productivity, and administrative expenses related to workers' compensation, wage replacement, and sick leave (Pillay, 2014). Okorie and Adindu (2020) identified the two most significant economic variables as reductions in family income and increases in indebtedness. The principal areas affected by site-related injuries at the family level include loss of household income, deterioration in living standards, limited access to finance and education, increased debt, and difficulties in meeting bill and loan obligations (Haupt & Pillay, 2016). The total financial burden of injuries cannot be fully quantified, as numerous implicit costs are difficult to measure beyond the most visible immediate expenses. Further, significant economic effect can be the resulting reduction in household earnings since the individual involved often had to quit the position or be demoted to a lower salary due to the injuries and damages (Haupt & Pillay, 2016). Further, according to Waehrer et al. (2007), construction accidents cost the United States $11.5 billion in 2002, fatal accidents accounted for $4 billion (40%), and non-fatal accidents accounted for $7 billion. Table 1 presents the financial cost impacts of site injuries and the associated legal implications for construction firms and the families of affected employees.

*Table 1: Financial implications of construction site accidents*

| Impact on Families | Impact on Firms |
|---|---|
| Deterioration of household living conditions | Production failure & job interruption |
| Loss of income resulting from death or injury | Damaged tools and equipment |
| Increased indebtedness leading to financial hardship. | Remedial measures to prevent a recurrence of the disaster. |
| Adverse impacts on educational expenditure and school dropout of children. | Compensation for affected employees |
| | Negative impact on the company's reputation |
| | Judicial protection charges on lawsuits |
| | Evacuation and machinery charges |
| | Emergency machinery cost |
| | Expenses in preparation with backups |
| | Growing expense of premiums |

Adopted from: Battaglia et al. (2014), Kadiri et al. (2014), Mthalane et al. (2008), Pillay (2014), Rauner et al. (2005).

According to Rafieyan et al. (2022), severe site accidents result in worker distress demonstrated through feelings of displacement, sadness, and shame, leading to organisation-wide emotional uncertainty. In examining the social impacts of site accidents on workers and their family members, psychological behaviour is found to change significantly following a serious accident, which can adversely affect family life (Barkhordari et al., 2019). Consequently, long-term emotional and cultural consequences may be experienced by family members, including trauma, anxiety, stress, and broader social harm.

The death or physical injury of a construction worker at a site can generate a highly negative public image of construction firms and may even lead to permanent business closure (Alzahrani & Emsley, 2013). Moreover, site-related injuries can create psychological strain among top management, supervisors, and employees, resulting in reduced morale across managerial and workforce levels. Additionally, fatal site accidents may trigger institutional conflicts and give rise to false allegations, leading to legal

investigations and diverting attention from other construction projects (Kadiri et al., 2014). Table 2 illustrates the social implications of site accidents for workers, family members, and construction organisations.

*Table 2: Social impacts of construction site accidents*

| Affected Families | Affected Firms |
|---|---|
| Loss or injury of primary earners.<br>Reduced quality of life and family mental health decline. | Loss of confidence among the workforces and public and client mistrust<br>Employee depression<br>Shortage of skilled and professional staff degrades organisational quality |
| Adopted From: Brauer (2006), Huang & Hinze (2006), Mthalane et al. (2008), Okorie and Aigbavboa (2016). | |

According to Table 2, construction site accidents have significantly affected firms in terms of social impacts, in addition to their effects on families. Such accidents adversely influence the mental health of the remaining employees and create fear and insecurity within the working environment. Considerable research was conducted globally on impacts of site accidents. The construction sector is significantly affected by the site accidents. In Sri Lanka, the site accidents is a major concern due to reduced safety measures. Therefore, proper research is necessary to identify the impacts on construction firms and affected families.

## 3. RESEARCH METHODOLOGY

The research process provides a systematic approach for defining research objectives, managing data, establishing a methodological framework, and disseminating findings (Godwill & Ozofor, 2015). This study adopted a quantitative research approach using a structured questionnaire survey to collect and analyse numerical data. Data collection was confined to the Sri Lankan construction industry to maintain contextual relevance and the population is restricted to executive-level employees. Accordingly, construction professionals from Sri Lankan construction firms were selected as respondents. Purposive sampling was employed to ensure the inclusion of executive-level personnel with relevant expertise and direct experience of construction site accidents, as alternative sampling methods could result in the selection of participants lacking the specific knowledge required to address the research objectives effectively and selected a sample of 80 respondents. Descriptive statistical analysis was used to evaluate the social and financial effects of construction site accidents, employing measures of central tendency, including the mean, median, and mode, as well as dispersion measures such as standard deviation. Inferential statistical methods, including regression analysis, correlation analysis, and hypothesis testing, were not adopted, as the primary objective of the study was not to examine relationships between variables or test hypotheses, but rather to identify and prioritise key factors. The collected data were analysed using the Statistical Package for Social Sciences (SPSS). Although questionnaires were distributed to 80 respondents, only 68 valid responses were returned and analysed. Table 3 presents the distribution of respondents according to organisational type, job position, and professional experience.

*Table 3: Summary of respondents' details*

| Type of Organisation | | Position of Respondents | | Experience | |
|---|---|---|---|---|---|
| Type | % | Position | % | Experience | % |
| Contractor Firm | 80.8 | Chairpersons/Managing Director | 4.4 | 0 to 5 yrs. | 26.5 |
| Engineering Firm | 13.2 | Directors | 16.2 | 5 to 10 yrs. | 17.6 |
| Employer Firm | 06.0 | CEO/General Manager | 22.1 | 10 to 15 yrs. | 19.1 |
| | | Project Manager | 17.6 | 15 to 20 yrs. | 23.5 |
| | | Engineer | 13.2 | Over 20 yrs. | 13.2 |
| | | Quantity Surveyor | 13.2 | | |
| | | Accountant | 13.2 | | |

According to Table 3, three main stakeholder groups were selected, as they are directly impacted by site accidents. Furthermore, 80% of the respondents were contractors. Contractors were purposively selected, as they are considered key stakeholders with direct connections to affected individuals and employees, and they tend to experience greater losses due to site accidents. Although client and consultant firms possess knowledge regarding site accidents and their impacts, contracting firms maintain closer engagement with affected parties.

# 4. DATA ANALYSIS AND FINDINGS

This chapter analyses the financial and social impacts of construction site accidents on companies and families using descriptive statistical methods, specifically the mean and standard deviation derived from the collected data. The financial and social implications for families and firms were derived from a review of the global literature, while the questionnaire survey facilitated the identification of additional impacts specific to the Sri Lankan context.

## 4.1 THE FINANCIAL IMPLICATIONS OF CONSTRUCTION SITE ACCIDENTS ON CONSTRUCTION COMPANIES

To evaluate the financial implications of construction site accidents on construction companies, fourteen indicators were used to assess this variable across the selected firms. The descriptive statistics obtained from these indicators are presented in Table 4.

*Table 4: The level of the financial impacts of construction site accidents on construction companies*

| Financial Impacts (Construction Company) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Increase in insurance premiums | 4.2647 | 0.44446 | 01 |
| Payments (fees) for settlements of injury or death claims | 4.25 | 0.74061 | 02 |
| Remedial actions to prevent the re-occurrence of the accident | 4.1471 | 0.67503 | 03 |
| Training costs for replacements | 4.1176 | 1.77486 | 04 |
| Costs of rescue operations and equipment | 4.0735 | 0.79769 | 05 |
| Reduced efficiency | 3.9412 | 0.66652 | 06 |
| Medical payments | 3.8971 | 0.57665 | 07 |
| Slackening of operations while accident causes are determined (safety investigation) | 3.7647 | 0.60143 | 08 |
| Loss of function and operations income | 3.75 | 0.95222 | 09 |

| Financial Impacts (Construction Company) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Emergency equipment expenditure | 3.6618 | 0.97139 | 10 |
| Legal fees for defence against claims | 3.5588 | 0.85313 | 11 |
| Damage to plant, equipment, and finished work | 2.7794 | 1.41258 | 12 |
| Loss of productivity | 1.9412 | 0.82647 | 13 |
| Disruption of current work | 1.9412 | 0.80821 | 14 |

Based on Table 4, the relative importance of the economic effects of construction site accidents to the construction firms is shown. Results show that insurance claims *(M* = 4.26, *SD* = 0.44) and compensation payments *(M* = 4.25, *SD* = 0.74) are of prime importance to the firms, which is an indication that the accident has a multiplying effect on the firm's finances. Preventive and corrective actions initiated after the occurrence of the accident are also important, which is an indication that additional investment is required to avoid a re-accident. Other operational effects, which are less important and reflect secondary economic effects, relate to decreased efficiency, suspension of operations to investigate the accident, and lost earnings. Productivity loss, damage to the work in progress, and disruption of work are of less importance and indicate that these are less serious effects than the other economic and legal requirements.

## 4.2 FINANCIAL IMPLICATIONS OF CONSTRUCTION SITE ACCIDENTS ON THE AFFECTED FAMILIES

To evaluate the financial implications of construction site accidents on the employee and the affected family, five indicators were used to assess this variable across the selected firms. The descriptive statistics obtained from these indicators are presented in Table 5.

*Table 5: The level of financial implications of construction site accidents on the affected families*

| Financial Implications (Family) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Increase in debts | 4.2353 | 0.79396 | 01 |
| Difficult to pay bills/ policies/ bonds | 4.0441 | 0.76165 | 02 |
| Decrease in family income | 4.0147 | 0. 32289 | 03 |
| Education and schooling expenses affected | 3.7941 | 0.98585 | 04 |
| Decrease in the standard of living | 3.7206 | 1.06288 | 05 |

The financial implications of construction accidents on affected families are reflected in reduced living standards, decreased household income, increased debt, difficulties in meeting financial obligations such as bills and insurance payments, and constraints on education related expenditures. Increased debt records the highest mean value (M = 4.23, SD = 0.793), while the reduction in living standards shows the lowest mean value (M = 3.72, SD = 1.06) among the assessed indicators.

Survey results indicate that rising debt imposes a substantial burden on affected families, as excessive borrowing is associated with poor credit ratings and limited access to loans at favourable interest rates. High interest borrowing further constrains household cash flow, thereby affecting overall financial stability and quality of life. In addition, construction accidents significantly influence children's education and schooling expenses in affected households (M = 3.79, SD = 0.98), as the mean value falls within the higher impact range. Based on the established decision rule, all indicators of the

financial impact of construction accidents on affected families are categorised as high ($3.5 < \bar{X} \leq 5$).

## 4.3 SOCIAL IMPACTS OF CONSTRUCTION SITE ACCIDENTS ON CONSTRUCTION COMPANIES

To evaluate the social impacts of construction site accidents on the construction firms, five indicators were used to assess this variable across the selected firms. The indicators were identified in the existing literature. The descriptive statistics obtained from these indicators are presented in Table 6.

*Table 6: Level of social impacts of construction site accidents on construction companies*

| Social Impacts (Construction Companies) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Loss of public confidence | 4.36765 | 0.48575 | 01 |
| Loss of customer satisfaction | 4.3088 | 0.46544 | 02 |
| Degradation of morale | 3.9559 | 0.50175 | 04 |
| Depression of employees and work fellows | 3.7353 | 0.61372 | 05 |
| Loss of company image | 3.7059 | 0.81146 | 06 |

Loss of public confidence (M = 4.37, SD = 0.49) ranks first, indicating that site accidents critically undermine stakeholder trust. This is followed by loss of customer satisfaction (M = 4.31, SD = 0.47), which highlights the negative influence of accidents on client perceptions and ongoing business relationships. This highlights the importance of accident prevention, as effective safety management enables construction companies to maintain public trust in the quality and safety of their operations. Adverse media coverage following accidents can erode public trust and generate significant social consequences for affected organisations.

Degradation of morale within organisations (M = 3.96, SD = 0.50) ranks fourth, suggesting notable psychological and motivational consequences among management and staff. Employee and coworker depression (M = 3.74, SD = 0.61) further demonstrates the emotional strain experienced within firms following site accidents. Loss of company image (M = 3.71, SD = 0.81) records the lowest mean value, though it remains within the high impact range. Overall, the results confirm that construction site accidents generate significant social consequences for construction companies, particularly in terms of public trust, customer satisfaction, and internal organisational wellbeing.

## 4.4 SOCIAL IMPACTS OF CONSTRUCTION SITE ACCIDENTS ON THE AFFECTED FAMILIES

Five main social impacts of construction site accidents on the affected families were analysed considering the level of impact on the families. Table 7, summarise the data analysed using SPSS software.

*Table 7: The level of social impacts of construction site accidents on the affected families*

| Social Impacts (Family) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Loss or injury to the family provider | 4.3382 | 0.97556 | 01 |
| Loss of workers to the community | 4.0588 | 0.47663 | 02 |
| Family depression | 3.9265 | 0.67617 | 04 |
| Reduced superiority of life for individual workers and families | 3.8824 | 0.76352 | 05 |

| Social Impacts (Family) | Mean | Std. Deviation | Rank |
|---|---|---|---|
| Loss of social welfare | 3.8235 | 0.66784 | 06 |

With the highest mean value (M = 4.34, SD = 0.98), the results show that loss or injury to the family provider is the most significant impact, highlighting the extreme socioeconomic vulnerability that families face. The loss of workers to the community (M = 4.06, SD = 0.48) comes next, indicating wider consequences at the community level. Additionally, family depression exhibits a high impact level (M = 3.93, SD = 0.68), suggesting that family members are experiencing significant psychological distress. Since financial support cannot compensate for the loss or disability of the primary income earner, it can be considered a critical component. Building site accidents can affect many families both financially and emotionally because many partners may become widows or widowers. Loss of social welfare and decreased quality of life for individual workers and families are additional indicators of the significant social burden caused by construction site accidents. In general, every indicator is in the high impact range.

Although the data were collected from executive-level employees, the questions were designed to capture information on the impacts experienced by both construction companies and affected families. As these respondents are responsible for providing incentives and relief to affected families, they possess adequate awareness of the families' financial conditions. Therefore, despite not being directly affected as family members, the respondents have sufficient exposure to evaluate and analyse the impacts accurately.

## 5. DISCUSSION

When considering the financial implications, according to Haupt & Pillay (2016), reduction in family income, and rise in indebtedness are the first and second most important factors affecting individuals or families from an economic standpoint. Whereas in Sri Lankan context, decrease in family income obtains the third position. Further, increase in debts and difficulties in paying utility bills obtained the first two positions respectively. Moreover, among the mentioned economic variable elements, the 'loss of firm productivity' and 'damage to plants/equipment' had the highest impact on many projects (Okorie & Adindu, 2020). However, in Sri Lanka it is considered as a minor impact whereas settlement to victims and increased insurance premiums were the main concerns.

When analysing the social implications, according to Kadiri et al. (2014), fatal accidents at the site can cause conflicts within institutions and create false allegations that can cause legal inquiries and distract attention to other building projects. However, it has no major impact on Sri Lankan construction firms. Moreover, in Sri Lanka, loss of workers to the community and loss of social welfare is identified as a unique social impact on affected families. Further, Okorie and Adindu (2020) reported that losing the family breadwinner and declining quality of life are the two most critical accident variables reported. Similarly, the interviews held by the researcher proved that the most effective social factor impacting families is the loss of the family provider.

In addition, a framework was developed using the empirical data to categorise accident-related impacts according to their severity and temporal progression. The framework was developed based on the characteristics of each impact and the development of the impacts. Accordingly, the impacts were classified as preventable and non-preventable impacts. Further, based on the development of impacts it is classified as immediate impacts,

cascading impacts and long-term impacts. The framework illustrates that a site accident initially gives rise to a set of immediate impacts, which represent the first layer of financial and operational burden on construction projects. These immediate impacts include injuries or fatalities among workers, loss or injury to the family provider, temporary or complete site shutdowns depending on accident severity, emergency response costs largely borne by the company, and medical treatment expenses incurred by either the worker or the employer. Once an accident occurs, such impacts are largely unavoidable and occur instantaneously.

Following the immediate stage, the framework highlights a series of cascading impacts that significantly affect both construction companies and workers. From an organisational perspective, site shutdowns often result in project delays and reduced productivity, leading to direct financial losses. In addition, injuries or fatalities typically place legal and financial responsibility on the contractor, resulting in compensation claims, increased insurance premiums, legal fees, medical expenses, formal investigations, and settlement payments. These cascading impacts can further contribute to financial instability, reputational damage, loss of public confidence, and, ultimately, the loss of skilled workers from the community. Okorie and Adindu (2020) reported that loss of firm productivity and damage to plant and equipment exerted the greatest influence across multiple projects. Furthermore, Brauer (2006) emphasised that the cumulative costs of accidents significantly reduce organisational profitability, particularly through expenses related to rescue equipment, rework, and corrective measures. Spangenberg (2009) also noted that fatal incidents can trigger internal organisational tensions characterised by blame and conflict, diverting managerial attention from core operational activities toward investigations and legal proceedings.

From the perspective of affected families, injuries or fatalities of the primary income earner generate significant cascading impacts. Reduced family income often leads to increased indebtedness and family depression, while long-term consequences include disruption to children's education and a decline in overall living standards. These findings align with Okorie and Adindu (2020), who reported that reductions in family income and increased indebtedness ranked as the most critical economic consequences of site accidents. They further highlighted the loss of the family breadwinner and declining quality of life as the most significant accident-related social variables.

In addition, the framework distinguishes between preventable and non-preventable impacts. Preventable impacts including injuries resulting from inadequate safety training, equipment-related accidents, and avoidable injuries highlight the potential for mitigation through improved safety management practices. In contrast, non-preventable or residual impacts, including natural disasters, fatalities despite safety controls, and unpredictable human error consequences, reflect the inherent risks associated with construction activities. This distinction underscores the importance of proactive safety strategies aimed at minimising preventable impacts while recognising that some residual risks remain unavoidable. Overall, by integrating empirical findings within a cascading impact perspective, the framework demonstrates that the true cost of construction site accidents extends well beyond direct medical and compensation expenses, affecting organisational sustainability, family wellbeing, and community resilience. This emphasises the need for comprehensive safety interventions that address both immediate risk reduction and long-term socioeconomic consequences.

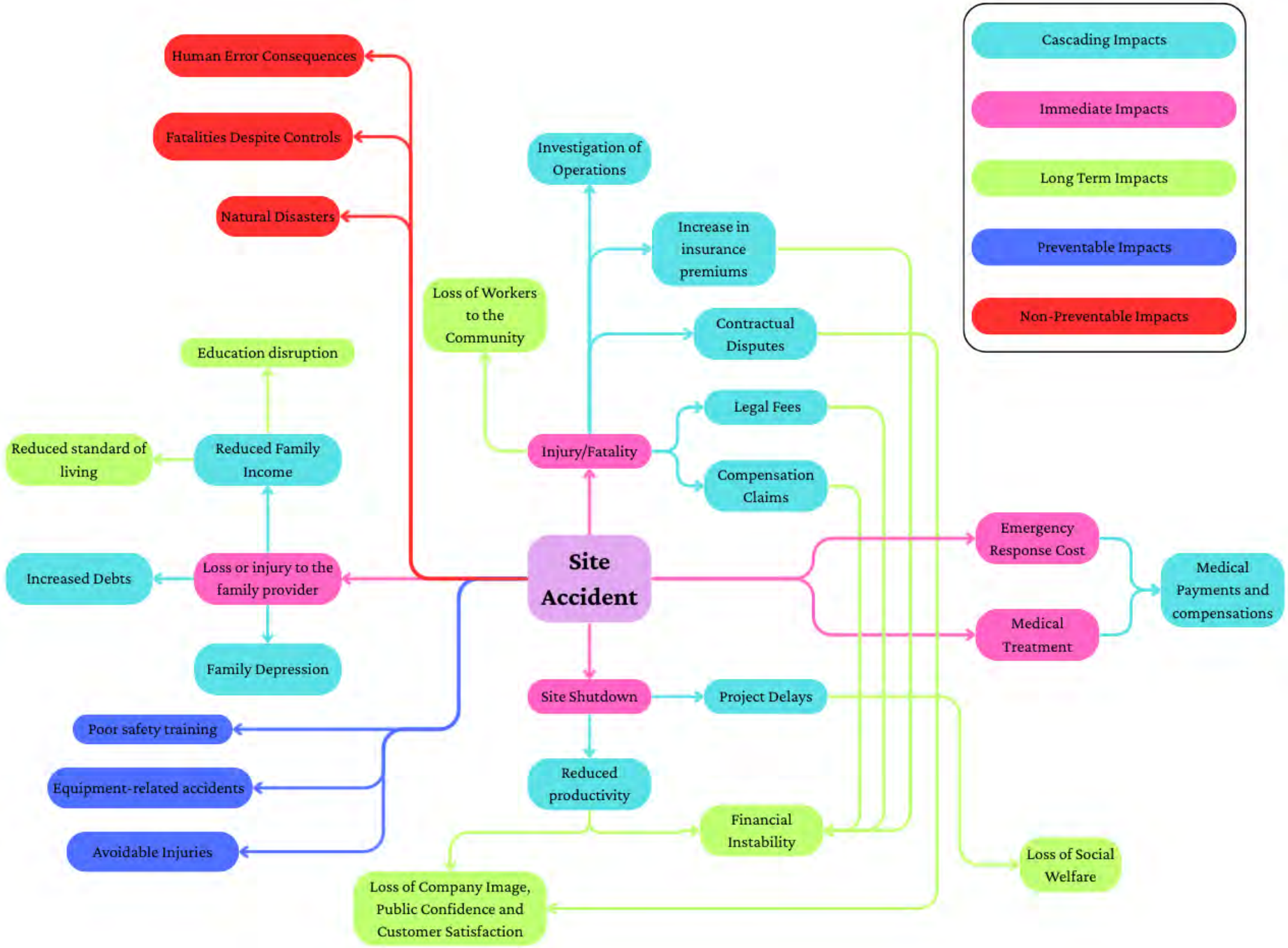



*Figure 1: Impacts of construction site accidents on companies and affected families*

## 6. CONCLUSIONS AND RECOMMENDATIONS

The Sri Lankan construction industry experiences a high frequency of site accidents, resulting in significant adverse impacts on construction firms and affected households. This study examined the financial implications of such accidents on organisations and families. Findings reveal that construction companies bear a greater financial burden than households, with increased insurance premiums representing the most significant cost. Overall, accident-related expenses substantially reduce firm profitability through costs related to equipment damage, rescue operations, rework, and corrective actions. In addition to organisational impacts, site accidents impose severe financial stress on affected families. Decline in household income, reduced living standards, increased debt levels, difficulties in meeting financial obligations, and rising education related expenses collectively contribute to significant financial hardship and all indicators measuring the financial impact on families were assessed as high. These findings demonstrate that construction accidents extend beyond individual victims to their families and have broader implications for the socio-economic stability of society. In cases where the injured worker is the primary income earner, disability often results in the loss of income and places substantial financial and emotional strain on the entire household.

Construction site accidents remain a critical health and safety issue both nationally and globally, with consequences that extend beyond affected individuals to the wider economy. To mitigate these impacts, the study recommends strengthening regulatory frameworks, enhancing training and educational programmes, adopting appropriate safety technologies, promoting collaborative approaches among stakeholders, and establishing effective support mechanisms for victims. The implementation of these measures can improve site safety, reduce accident occurrence, and minimise social and financial losses to firms and families, thereby contributing to a safer and more sustainable construction industry in Sri Lanka. Reliance on questionnaires distributed only to executive-level staff limits the diversity of perspectives. In addition, impacts on affected families were assessed through industry stakeholders, as victims were not directly interviewed or surveyed. Future research should examine the impacts of site accidents on other project stakeholders involving minor staff and workers, examine the psychological impacts of construction site accidents, evaluate existing preventive practices, with the aim of developing effective frameworks to reduce accident risks, policy development to support vulnerable groups, and awareness of construction site accidents among all stakeholders.

## 7. REFERENCES

Ahamed, M. S. S., Nafeel, A. F. M., Rishath, A. A. M., & Dissanayake, P. B. G. (2011). Site safety of Sri Lankan building construction industry. In *Proceedings of the International Conference on Structural Engineering, Construction and Management (ICSECM), Kandy, Sri Lanka* (pp. 1-12). http://dl.lib.mrt.ac.lk/handle/123/9444

Alzahrani, J. I., & Emsley, M. W. (2013). The impact of contractors' attributes on construction project success: A post construction evaluation. *International Journal of Project Management*, *31*(2), 313–322. https://doi.org/10.1016/j.ijproman.2012.06.006

Ambegaonkar, R. (2020). *The importance of safety on construction sites.* NY Engineers. https://www.ny-engineers.com/blog/the-importance-of-safety-on-construction-site

Arquillos, A. L., Romero, J. C. R., & Gibb, A. (2012). Analysis of construction accidents in Spain, 2003-2008. *Journal of Safety Research*, *43*(5–6), 381–388. https://doi.org/10.1016/j.jsr.2012.07.005

Barkhordari, A., Malmir, B., & Malakoutikhah, M. (2019). An analysis of individual and social factors affecting occupational accidents. *Safety and Health at Work*, *10*(2), 205–212. https://doi.org/10.1016/j.shaw.2019.01.002

Battaglia, M., Frey, M., & Passetti, E. (2014). Accidents at work and Costs Analysis: a field study in a large Italian company. *Industrial Health*, *52*(4), 354–366. https://doi.org/10.2486/indhealth.2013-0168

Birhane, G. E., Yang, L., Geng, J., & Zhu, J. (2020). Causes of construction injuries: a review. *International Journal of Occupational Safety and Ergonomics*, *28*(1), 343–353. https://doi.org/10.1080/10803548.2020.1761678

Brauer, L. R. (2006). *Safety and health for engineers* (2nd ed.). John Wiley & Sons. https://hsseworld.com/wp-content/uploads/2020/10/Safety-and-health-for-engineers.pdf.

Chi, S., & Han, S. (2013). Analyses of systems theory for construction accident prevention with specific reference to OSHA accident reports. *International Journal of Project Management*, *31*(7), 1027–1041. https://doi.org/10.1016/j.ijproman.2012.12.004

Choi, J., Gu, B., Chin, S., & Lee, J. S. (2020). Machine learning predictive model based on national data for fatal accidents of construction workers. *Automation in Construction*, *110*, 102974. https://doi.org/10.1016/j.autcon.2019.102974

Darshana, W. D. (2017). Improvement of health and safety in construction sites in Sri Lanka. *Engineer Journal of the Institution of Engineers Sri Lanka*, *50*(1), 53-70. https://doi.org/10.4038/engineer.v50i1.7244

Dasandara, S., & Dissanayake, P. (2021). Limiting reasons for use of personal protective equipment among construction workers: Case studies in Sri Lanka. *Safety Science*, *143*, 105440. https://doi.org/10.1016/j.ssci.2021.105440

David, S. J., Hansen, S., & Seminario-Amez, C. (2020). Firm-Level risk exposures and stock returns in the wake of COVID-19. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3707934

Elsebaei, M., Elnawawy, O., Othman, A. A. E., & Badawy, M. (2020a). Causes and impacts of site accidents in the Egyptian construction industry. *International Journal of Construction Management*, *22*(14), 2659–2670. https://doi.org/10.1080/15623599.2020.1819523

Elsebaei, M., Elnawawy, O., Othman, A., & Badawy, M. (2020b). Elements of safety management system in the construction industry and measuring safety performance – a brief. *IOP Conference Series Materials Science and Engineering*, *974*(1), 012013. https://doi.org/10.1088/1757-899x/974/1/012013

Godwill, E. A., & Ozofor, N. M. (2015). *Fundamentals of research Methodology: A holistic guide for research completion, management, validation and ethics*. Nova Science Publishers, Inc. https://eprints.gouni.edu.ng/2262/1/BOOK%207.pdf

Haupt, T. C., & Pillay, K. (2016). Investigating the true costs of construction accidents. *Journal of Engineering Design and Technology*, *14*(2), 373–419. https://doi.org/10.1108/jedt-07-2014-0041

Huang, X., & Hinze, J. (2006). Owner's role in construction safety: Guidance Model. *Journal of Construction Engineering and Management*, *132*(2), 164-173. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:2(174).

Jayamal, D., Gunarathne, N., & Perera, B. L. S. H. (2023). An exploratory study on abandoned construction projects in the Western Province, Sri Lanka. In: Y. G. Sandanayake, K. G. A. S. Waidyasekara, K.G.A.S., T. Ramachandra, & K. A. T. O. Ranadewa (Eds). *Proceedings of the 11th World Construction Symposium.* (pp. 123–134). https://doi.org/10.31705/WCS.2023.11

Kadiri, Z. O., Nden, T., Avre, G. K., Oladipo, T. O., Edom, A., Samuel, P. O., & Ananso, G. N. (2014). Causes and effects of accidents on construction sites (a case study of some selected construction firms in Abuja FCT Nigeria). *IOSR Journal of Mechanical and Civil Engineering*, *11*(5), 66-72. https://doi.org/10.9790/1684-11516672

Lee, B. H., Chen, J. C., & Fo, K. W. (2018). Accidents in construction sites: a study on the causes and preventive approaches to mitigate accident rate. *INTI Journal*, *1*(3), 1-12. http://eprints.intimal.edu.my/1136/.

Melagoda, D. G., & Rowlinson, S. (2022). The institutional framework of construction safety management: A case study of Sri Lanka. *IOP Conference Series Earth and Environmental Science*, *1101*(4), 042038. https://doi.org/10.1088/1755-1315/1101/4/042038

Mohammadi, A., Tavakolan, M., & Khosravi, Y. (2018). Factors influencing safety performance on construction projects: A review. *Safety Science*, *109*, 382–397. https://doi.org/10.1016/j.ssci.2018.06.017

Mthalane, D., Othman, A. A. E., & Pearl, R. G. (2008, March). The economic and social impacts of site accidents on the South African society. In *Proceedings of the 5th post graduate conference on construction industry development* (Vol. 1, p. 12). Pretoria, South Africa: Construction Industry Development Board.

Okorie, V. N., & Adindu, C. C. (2020). An exposition of the socio-economic impacts of construction site accidents in Nigeria. *Journal of Surveying, Construction and Property*, *11*(1), 38-47. https://doi.org/10.22452/jscp.vol11no1.4

Okorie, V. N., & Aigabavboa, C. O. (2016). The economic and social impacts of site accidents on the small and medium sized construction companies in Nigeria. In *ICIDA Conference*. https://ujcontent.uj.ac.za/esploro/outputs/conferencePaper/The-economic-and-social-impacts-of/9911428207691

Pillay, K. R. (2014). *The costs of construction accidents* (Doctoral dissertation, Cape Peninsula University of Technology). https://etd.cput.ac.za/handle/20.500.11838/1044

Priyadarshani, K., Gayani, K., & Sajani, J. (2013). Construction safety assessment framework for developing countries: a case study of Sri Lanka. *Journal of Construction in Developing Countries*, 18(1), 33-51. http://dl.lib.mrt.ac.lk/handle/123/10115

Quadir, M. M., Lee, Y. J., Hoque, R., Karim, M. M., & Alamgir, H. (2019). How are the surviving workers of the Rana Plaza factory collapse in Bangladesh doing: quality of life, participation restriction, income and occupation. *Disability and Rehabilitation*, *43*(3), 393–399. https://doi.org/10.1080/09638288.2019.1626494

Rafieyan, A., Sarvari, H., & Chan, D. W. M. (2022). Identifying and evaluating the essential factors affecting the incidence of site accidents caused by human errors in industrial parks construction projects. *International Journal of Environmental Research and Public Health*, *19*(16), 10209. https://doi.org/10.3390/ijerph191610209

Rauner, M. S., Harper, P. R., & Schwarz, B. (2005). Economic Impact of Occupational Injuries: Resource Allocation for Prevention Programs. *Central European Journal of Operations Research*, *13*(4).

Shamsuddin, K. A., Ani, M. N., Ismail, A. K., & Ibrahim, M. (2015). Investigation the Safety, Health, and Environment (SHE) protection in construction area. *International Research Journal of Engineering and Technology*, *2*(6), 624-636. https://www.irjet.net/archives/V2/i6/IRJET-V2I6101.pdf.

Spangenberg, S. (2009). An injury risk model for large construction projects. *Risk Management*, *11*(2), 111-134.

Thalgaspitiya, S. P., Liyanage, A. S., & Handapangoda, H. M. (2018). PW 1958 Occupational injuries in the north central province of Sri Lanka. *Injury Prevention*, *24*. https://doi.org/10.1136/injuryprevention-2018-safety.590

Udawatta, N., & Rameezdeen, R. (2012). Fatalities and non-fatalities in construction accidents (Version 1). Deakin University. https://hdl.handle.net/10536/DRO/DU:30088163

Waehrer, G. M., Dong, X. S., Miller, T., Haile, E., & Men, Y. (2007). Costs of occupational injuries in construction in the United States. *Accident Analysis & Prevention*, *39*(6), 1258-1266.

Wang, P., Wu, P., Wang, J., Chi, H. L., & Wang, X. (2018). A critical review of the use of virtual reality in construction engineering education and training. *International Journal of Environmental Research and Public Health*, *15*(6), 1204.

Zelalem, Y. (2015). *Study of Occupational Safety and Health Management in Building Construction Sites of Bahir Dar* (Doctoral dissertation, Bahir Dar University). https://sl1nk.com/nss0k16.

Zeng, Q., & Yoon, J. H. (2022). The Optimized Process for Effective Decision Makings to Minimize Fall From Height (FFH) Accidents on Construction Site. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 39, pp. 597-604). IAARC Publications. https://doi.org/10.22260/isarc2022/0084

Rajapakse, S.I. and Hirudini, S.M., 2026. The impact of location on threshold space architectural character: Study of Egoda Uyana, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1693-1706. DOI: https://doi.org/10.31705/WCS.2026.123. Available from: https://ciobwcs.com/papers/

# THE IMPACT OF LOCATION ON THRESHOLD SPACE ARCHITECTURAL CHARACTER: STUDY OF EGODA UYANA, SRI LANKA

**S.I. Rajapakse[1] and S.M. Hirudini[2]**

## *ABSTRACT*

*The Street-front threshold spaces constitute a critical architectural interface between private domestic interiors and public streets in lower–middle-income suburban settlements. While existing research frequently emphasizes their social and behavioural implications, limited attention has been given to their measurable physical configuration as architectural systems. This study examines the impact of location on threshold space architectural character in Egoda Uyana, Sri Lanka, with the aim of identifying design parameters that are applicable to tropical suburban settlement contexts. Using systematic field documentation, measured drawings, sectional analysis, typological classification, and spatial coding, the research identifies key location- identified parameters including accessibility and connectivity, functionality, territoriality, and threshold character- identified parameters including roof projection, material and edge treatment, permeability, and plinth level differentiation. The findings demonstrate that threshold character varies significantly according to spatial location within the street network. Linear street segments typically sustain modest semi-open transitional spaces that reinforce frontage continuity, whereas intersection nodes generate more articulated threshold configurations due to increased connectivity and multidirectional visibility. Progressive enclosure through high boundary walls and solid materials transforms transitional interfaces into defensive edges, disrupting spatial layering and environmental responsiveness. By studying the relationship between the location of the house threshold in a settlement and the threshold character, the study contributes design-based guidelines that reposition threshold spaces as measurable architectural infrastructures rather than residual margins. The design parameters offer design implications for housing design guidelines and incremental development strategies in lower–middle-income suburban settlements within tropical regions.*

***Keywords:*** *Architectural elements; Incremental housing; Morphology; Street-front interface; Threshold space; Tropical settlements*

## 1. INTRODUCTION

The suburban settlements in many South Asian cities are shaped by plot-based ownership structures, and gradual architectural transformation. In these environments, the street-facing frontage becomes a crucial spatial mediator between domestic life and public

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, si98rajapakse@gmail.com
[2] Senior Lecturer, Department of Architecture, University of Moratuwa, Sri Lanka, mihirih@uom.lk

circulation. The phrase 'threshold' refers to the ambiguity between opening and closure. 'Space' refers to architectural dimensions as determined by the physical experience of a person in motion and perception. So, the threshold spaces act as an in-between space between the private and public realm and balance the interrelationship between these two realms. So, threshold spaces mainly provide three functions such as separation, connection and communication (Gunathillaka & Coorey, 2014). This threshold space has different 'space-light' values, and the extended threshold space represents both internal and external qualities, gradually shifting from one to another (Tzortzi & Saxena, 2024). According to the definition adopted for this research, the threshold space not only acts as a transitional space but also as a territorial demarcation. The street-front threshold space manifested through verandas, semi-open porches, recessed entries, front yards, or boundary transitions such as forms an intermediate zone that negotiates privacy, visibility, and environmental buffering. Within Sri Lanka's lower–middle-income suburban neighbourhoods, threshold spaces historically functioned as climatically responsive and socially adaptable interfaces. However, contemporary pressures including densification, security concerns, commercialization, and lifestyle shifts have increasingly altered these transitional spaces, often compressing or enclosing them. Despite their importance in shaping the morphological continuity of the street, threshold spaces are frequently treated as secondary architectural elements rather than primary spatial infrastructures. Theoretical discourse in architecture and urban design has long recognized the importance of transitional spaces. Alexander et al. (1977) emphasized the necessity of articulated entrances and spatial gradation between realms. Ashihara (1983) discussed the aesthetic continuity of urban townscape through semi-public interfaces. Hillier and Hanson (1984) demonstrated how spatial configuration affects movement and visibility systems, suggesting that interface conditions significantly influence spatial integration. Boettger (2014) further conceptualized thresholds as structured transitional sequences that shape perception and experience. However, while such scholarship provides conceptual grounding, there remains limited systematic evaluation of threshold spaces as physically measurable architectural systems, particularly within lower–middle-income suburban contexts. Much of the literature prioritizes social performance, leaving morphological and architectural element-based parameters underexplored. The aim of this research is to investigate the impact of location on threshold space architectural character in a suburban settlement context. The study observes different locations of threshold spaces and how they gradually change the architectural character of each place. To reach this aim, the research sets the following objectives: identify threshold types based on the location and architectural characteristics of threshold spaces in a suburban neighbourhood context, and develop a design framework that offers practical implications for housing upgrading policies in a suburban context. The study primarily addresses the identification of the architectural characteristics that make certain thresholds more conducive to an everyday neighbourhood lifestyle. This study is geographically limited to the Egoda Uyana settlements in Moratuwa, focusing on lower-middle-income residential neighbourhoods situated near the New Galle Road and coastal edge. These areas represent a typical suburban residential context in Sri Lanka. The riverfront areas of Egoda Uyana are excluded from the study due to their differing spatial and environmental characteristics. It is characterized by moderate population density, and mixed housing morphologies within an evolving suburban fabric. This focus allows an in-depth study through on-site observation, mapping, and photographic study to understand the lived experience of threshold spaces in each location. The study is

applicable to the Sri Lankan context and may also be applicable to similar contexts in South Asia. However, the findings are not intended to be generalized to the global context.

# 2. LITERATURE REVIEW: RELATIONSHIP BETWEEN SETTLEMENT LOCATION AND THRESHOLD CHARACTER

## 2.1 THEORIES BETWEEN SETTLEMENT LOCATION AND THRESHOLD CHARACTER

The concept of the threshold occupies a significant position in architectural theory as a mediator between interior and exterior realms. Alexander et al. (1977) describe transitional spaces as essential components in establishing spatial hierarchy and experiential progression. Rather than abrupt separation, successful architecture incorporates gradation and layering between domains. So, the threshold space has two basic qualities as ambiguity and permeability (Prasetiyo & Fuad 2021). The configuration, openness, and functionality of thresholds are often influenced by the location of houses within the settlement structure, such as intersections, linear streets, or inner clusters. Understanding the relationship between settlement location and threshold character therefore provides an important theoretical basis for interpreting how architectural forms emerge from spatial context. Urban morphological studies suggest that the physical organization of settlements which includes street hierarchy, node positions, and block structures directly influences the form and usage of building frontages (Hillier & Hanson, 1984; Lynch, 1960). Houses located at prominent nodes or intersections typically develop more permeable and socially active thresholds, whereas dwellings located along linear or inward-facing streets tend to exhibit more controlled and privatized threshold configurations. This indicates that the architectural character of thresholds cannot be understood in isolation from the spatial structure of the settlement. The settlement location also influences the functional adaptation of building frontages. Alexander et al. (1977) argue that buildings located along active streets or intersections tend to incorporate semi-public transitional spaces that mediate between private interiors and the public domain. These spaces create opportunities for everyday encounters and contribute to the vitality of neighbourhoods. In contrast, houses positioned along quiet inner streets often prioritize enclosure and domestic privacy, resulting in more rigid boundary treatments such as high walls or fenced edges. From this literature review, it gives a set of parameters like Accessibility and connectivity, functionality, and territoriality to identify certain threshold locations in a settlement.

*Table 1: Location Identified parameters*

| Parameter | Sub parameters | Design parameters | Author |
|---|---|---|---|
| Accessibility and connectivity | Pedestrian linkage<br>Movement patterns<br>Spatial connectivity | Circulation flows, pedestrian networks, street linkages | Gehl (2010); Lefebvre (1991); von Meiss (1990) |
| Functionality | Daily usage patterns<br>Multipurpose use<br>Work-home interface | Sitting edges, activity spill over zones, flexible frontage use | Gehl (2010); Boettger (2014); Bourdieu (1977) |

| Parameter | Sub parameters | Design parameters | Author |
|---|---|---|---|
| Territoriality | Personal boundaries<br>Collective boundaries | Plant, furniture placement of frontage | Boettger (2014); Bourdieu (1977) |

## 2.2 THEORETICAL REFERENCES ON THRESHOLD CHARACTER OF HOUSES

Ashihara (1983) extends this argument to the urban scale, suggesting that townscape continuity depends on the articulation of edges and the treatment of semi-public interfaces. The street façade is not merely a vertical boundary but a layered surface that defines the character of urban space. According to Ashihara, the visual continuity of street fronts is often defined by how buildings articulate their edges through verandas, porches, steps, and other transitional elements. These features create a gradual transition between private interiors and public streets, enhancing both spatial coherence and human engagement with the urban environment. Similarly, Rapoport (1982) emphasizes that built environments communicate cultural values through their spatial configuration, particularly at transitional zones. Within configurational theory, Hillier and Hanson (1984) propose that spatial structure influences movement patterns and visibility fields. The interface between dwelling and street becomes critical in determining degrees of spatial integration. Later developments in space syntax theory reinforce the importance of visibility and permeability in shaping spatial systems (Hillier, 1996). In residential contexts, Newman's (1972) defensible space theory suggests that boundary articulation affects territorial control and environmental perception. Although primarily focused on crime prevention, the theory highlights how physical edge conditions shape spatial behaviour. According to Altman and Chemers (1980), territorial behaviour in residential environments is often expressed through physical elements such as fences, steps, and transitional platforms that signal ownership. Gehl (1987) similarly underscores the role of façade articulation and edge activation in sustaining public life. Climate also significantly influences the design and character of threshold spaces. In tropical environments, verandas, shaded platforms, and covered entrances provide protection from sun and rain while simultaneously creating comfortable spaces for outdoor activities. In South Asian housing contexts, Turner (1976) and Bhatt (1994) demonstrate that incremental housing growth frequently modifies street-front conditions. As dwellings expand and with increasing motorization, thresholds are enclosed, extended, or redefined, altering the morphological continuity of the street edge, growing preferences in inward-oriented life, privatized houses reduce visibility and casual contact (Gulati, 2020). Through this literature review, it identifies a set of parameters like climate modifiers, human scale, material and edge treatment, and permeability to identify threshold character in settlements.

*Table 2: Threshold determine parameters*

| Parameter | Sub parameters | Design parameters | Author |
|---|---|---|---|
| Climatic modifiers | Canopies<br>Verandas<br>Overhangs | Shaded edges, transitional comfort zones | Gehl (2010); Boettger (2014) |
| Human scale | Body-based proportions<br>Eye-level feature | Comfortable distance, micro-scale frontage proportions | Gehl (2010); Von Meiss (1990) |

| Parameter | Sub parameters | Design parameters | Author |
|---|---|---|---|
| | Street width to height ratio | | |
| Material and edge treatment | Wall height,<br>Gate height<br>Plinths and steps | Porous boundaries, semi-transparent edges, tactile material | Von Meiss (1990); Boettger (2014) |
| Permeability | Visual permeability<br>Physical access points | Transparent edges, gate openness, through-movement paths | Gehl (2010); Boettger (2014); Bourdieu (1977) |

As in Table 1 and 2, these set of parameters align with Tables 3 and 4 of methodology and Table 5 of case study analysis.

# 3. METHODOLOGY

## 3.1 IDENTIFICATION AND CLASSIFICATION OF LOCATION IDENTIFIED PARAMETERS

This study adopts a qualitative–quantitative architectural documentation approach to analyse street-front threshold spaces in Egoda Uyana. Field surveys were conducted to document spatial dimensions, boundary treatments, enclosure types, material articulation, and climatic modifiers. Measured drawings, sectional sketches, and photographic mapping were used to ensure accurate spatial recording. The analytical framework categorizes parameters into two primary groups: location identified parameters and threshold determined parameters. Location identified parameters include accessibility and connectivity, functionality, territoriality. These parameters define the spatial structure of the threshold as a volumetric entity. Threshold determine parameters include climatic modifiers, human scale, material and edge treatment, and permeability. These elements determine the permeability and environmental performance of the threshold. Each documented threshold was coded according to these parameters and grouped into typological categories reflecting degrees of openness and enclosure. Comparative analysis across cases enabled the identification of recurring patterns and transformation trends. By isolating physical variables from social and behavioural data, the methodology ensures analytical clarity and strengthens the architectural focus of the study.

*Table 3: Methodology for location identified parameters data collection and data analysis*

| Parameter | Data collection method | Data analysis method | Intended result |
|---|---|---|---|
| Accessibility and connectivity | Mapping, sketching, photographic study | Comparative analysis throughout the day | Find frequently active spaces and the connectivity pattern |
| Functionality | Activity mapping, lime-lapse photography | Time-activity mapping | Determine the primary functions of the threshold spaces |
| Territoriality | Observing shared zones, territorial signs | Territorial pattern mapping | Identify collective ownership of the place |

*Table 4: Methodology for Threshold determine parameters data collection and data analysis*

| Parameter | Data collection method | Data analysis method | Intended result |
|---|---|---|---|
| Climatic modifiers | Sun-path observation | Microclimate performance | Understand how shading support outdoor use |
| Human scale | Measuring street-building proportions, sketching | Human scale analysis | Evaluate comfort and engagement potential |
| Material and edge treatment | Closed-up photography, measured drawings | Edge typology analysis | Identify threshold character and openness |
| Permeability | Boundary documentation, photographic study for visibility | Permeability mapping and edge treatment | Identify visually opened and closed frontage |

Through morphological study, it selected different locations within the settlement and study how the location of threshold can affect the architectural character of that space.

## 3.2 CASE STUDY SELECTION AND JUSTIFICATION

Egoda Uyana represents a typical lower–middle-income suburban settlement characterized by plot-based housing, gradual extensions, and adaptive façade modifications, and the grid patterns of the road network create various nodes and linear spatial arrangements within the neighbourhood. The original housing units at the coastal edge typically included modest setbacks that generated semi-open transitional areas between the dwelling and the street and the common plot sizes such as 10, 12, 15, 18 perches. Over time, several transformation processes have reshaped these street-facing fronts. Roof extensions have been added to provide climatic protection from heavy monsoon rainfall and tropical sun exposure. Boundary walls have been raised to enhance privacy and security. Metal grills and gates have been installed to regulate permeability while maintaining visibility. In certain cases, threshold spaces have been fully absorbed into enclosed interior rooms. These transformations produce a morphological spectrum ranging from open veranda-based thresholds to fully enclosed street façades. The progressive enclosure of thresholds reflects broader socio-economic and urbanization dynamics. To capture these dynamics, the Egoda Uyana coastal edge old settlement area was selected. According to street hierarchy, for the case studies only suburban residential streets with the width of 20’ were selected for the study. No major or large streets containing commercial or mixed-use characters were observed.

# 4. CASE STUDY ANALYSIS OF IMPACT OF LOCATION ON THRESHOLD CHARACTER

## 4.1 LOCATION IDENTIFICATION ANALYSIS

The location identification analysis of street-front threshold spaces in Egoda Uyana reveals a dynamic spectrum of spatial configurations shaped by incremental transformation and plot-based development logic. Threshold morphology is primarily defined by accessibility and connectivity, functionality, frontage continuity, alignment, and volumetric layering between the street edge and interior living spaces.

*Figure 1: Selection of nodes*

Accessibility and connectivity emerged as defining morphological variables. Documented thresholds ranged from minimal recessed steps of approximately 0.5 meters to extended semi-open verandas exceeding 3 meters in depth. Increased depth created perceptible spatial gradation between the street and interior, reinforcing the transitional logic emphasized in architectural theory (Alexander et al., 1977). Shallow thresholds, by contrast, produced abrupt spatial transitions, compressing the interface into a thin boundary rather than a layered zone. Width-to-depth proportions also influenced spatial perception. Thresholds with balanced proportions generated usable transitional areas capable of accommodating movement, pause, and climatic buffering. Narrow yet deep thresholds tended to function as linear corridors, while wide but shallow thresholds operated as open platforms directly exposed to the street. These morphological distinctions significantly affected the continuity of the street edge. Frontage continuity was another critical morphological attribute. Where adjacent dwellings maintained similar setback distances and semi-open interfaces, a coherent street rhythm emerged. This continuity aligns with Ashihara's (1983) notion of townscape unity, where façade alignment contributes to spatial harmony. However, where enclosure heights and setbacks varied significantly, the street edge became fragmented, disrupting visual rhythm and volumetric cohesion. The behaviour of threshold morphology can be changed according to the location of the threshold, and it affects the architectural character of that certain space, such as a house in a linear street arrangement, a node at a two-road intersection, and a node at a four-road intersection. Alignment patterns further influenced morphological performance. Linear alignment along the street strengthened configurational integration, whereas staggered or irregular building lines produced discontinuity. Within configurational theory, such variations influence spatial connectivity and visual fields (Hillier, 1996; Hillier & Hanson, 1984). Although this study

isolates physical parameters, the morphological variations observed suggest implications for spatial integration and continuity at the settlement scale.

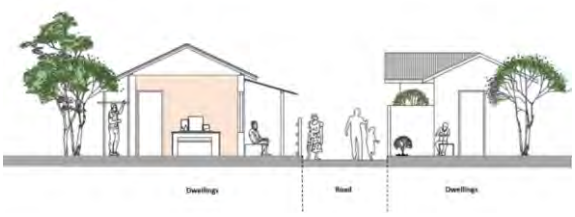



*Figure 2: Section of linear arrangement*

*Table 5: Relation of architecture character and the location of the threshold*

| Location determine parameter | Spatial location of threshold | Architectural character |
|---|---|---|
| Accessibility and connectivity | Linear street arrangement | Maintain direct access to the street with minimal transition depth. The architectural character tends to be open or semi-open, emphasizing continuity between domestic frontage and pedestrian movement along the street |
| | Node at two-road intersection | Increased connectivity encourages more articulated thresholds with wider openings and greater spatial visibility. Architectural character becomes more interactive and visually permeable due to multidirectional movement. |
| | Node at four-road intersection | Architectural character tends to incorporate extended verandas, wider entrances, or semi-public edge conditions responding to higher movement intensity. |
| Functionality | Linear street arrangement | Support domestic transitional functions such as entry, sitting, and climatic buffering. The architectural character remains modest and functionally oriented toward household activities. |
| | Node at two-road intersection | Support informal social interaction or small household-based activities. Architectural character becomes more active and outward-oriented. |
| | Node at four-road intersection | Accommodate extended activities such as informal commerce or gathering due to greater exposure. Architectural character becomes spatially expanded and multifunctional. |
| Frontage continuity | Linear street arrangement | Consistent building setbacks and semi-open thresholds generate rhythmic frontage continuity, producing a coherent street edge. |
| | Node at two-road intersection | Slight variations in setbacks and façade articulation occur to respond to corner visibility, producing a more dynamic frontage condition. |
| | Node at four-road intersection | Frontage continuity becomes visually fragmented due to corner articulation and multidirectional exposure, creating a more prominent architectural expression. |

| Location determine parameter | Spatial location of threshold | Architectural character |
|---|---|---|
| Alignment | Linear street arrangement | Buildings tend to follow a uniform street alignment, reinforcing spatial order and continuous threshold rhythm along the street edge. |
| | Node at two-road intersection | Corner plots frequently introduce angled or dual alignments responding to intersecting street directions, producing more complex façade compositions. |
| | Node at four-road intersection | Alignment variations become more pronounced as buildings orient toward multiple directions, resulting in highly articulated threshold configurations. |

Collectively, these morphological findings demonstrate that threshold spaces are not incidental architectural leftovers but structured volumetric entities whose dimensional properties significantly shape street character according to their specific locations.

## 4.2 THRESHOLD CHARACTER IDENTIFICATION ANALYSIS

Beyond volumetric morphology, the architectural elements composing threshold spaces determine degrees of permeability, enclosure, environmental performance, and material articulation.

### 4.2.1 Boundary Articulation and Permeability

Boundary treatment emerged as a central determinant of physical threshold character. Open thresholds lacked vertical barriers, enabling uninterrupted visual and physical continuity between dwelling and street. Semi-open thresholds incorporated low parapet walls, columns, railings, reused steel mesh, or timber slats that defined territory while preserving partial visibility. Enclosed thresholds utilized high masonry walls or solid gates that fully obstructed visual permeability. Low boundary heights, typically between 0.6 and 1.0 meters, maintained spatial dialogue with the street while subtly demarcating private territory. This condition reflects Newman's (1972) concept of territorial definition without complete exclusion. Conversely, boundary heights exceeding 1.5 meters created rigid separation and disrupted transitional layering. Material permeability further refined these conditions. Metal grills, perforated concrete blocks, and timber slats allowed filtered visibility, maintaining connection while providing enclosure. Solid masonry walls eliminated visual exchange entirely, converting the threshold into a defensive barrier rather than a mediating interface. These findings reinforce the theoretical argument that physical permeability is architecturally constructed rather than socially incidental. The degree of openness or enclosure is materially determined through edge articulation.

### 4.2.2 Roof Projection and Climatic Modulation

In tropical contexts such as Sri Lanka, roof projection functions as a critical climatic modifier. Extended overhangs exceeding 1.2 meters provided shading from intense solar radiation and protection from monsoon rainfall. This climatic buffering reinforced the threshold's role as an intermediate environmental zone. Where roof projections were minimal or absent, threshold usability was reduced due to exposure. This demonstrates that climatic performance is intrinsically tied to architectural configuration. Traditional tropical verandas historically integrated shading as a fundamental design principle (Rapoport, 1982). However, contemporary modifications often reduce roof projection in favour of vertical enclosure. The analysis indicates that climatic adaptability remains a

defining physical attribute of functional thresholds. Architectural interventions that neglect shading compromise the environmental logic of transitional space.

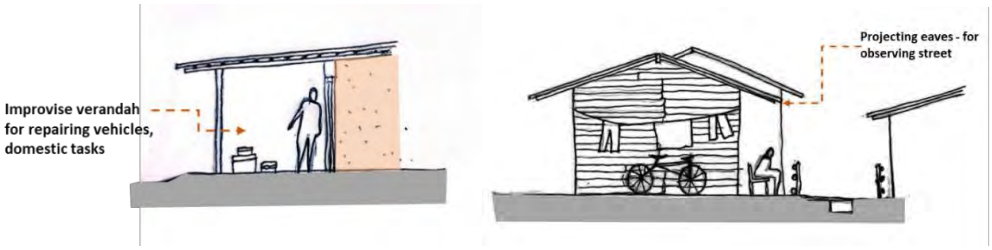



*Figure 3: Sections of different roof projections*

### 4.2.3 Plinth height and Level Differentiation

Level differences between the street and threshold space introduce subtle territorial demarcation without eliminating visibility. Raised plinths between 0.3 and 0.6 meters created a spatial cue indicating semi-private status while maintaining visual openness. Excessive elevation, however, increased separation and reduced accessibility. This vertical articulation contributes to the layered hierarchy of transitional space. Rather than forming abrupt vertical barriers, modest level differentiation reinforces gradation between realms.

### 4.2.4 Material Expression and Surface Treatment

Material selection significantly influenced the perceptual quality of thresholds. Lightweight and permeable materials such as grills and timber slats, maintained openness, whereas reinforced concrete block walls emphasized solidity and permanence. Incremental housing transformations often replaced temporary or semi-permeable elements with permanent masonry structures, signalling a shift toward rigid enclosure. Bhatt (1994) notes that incremental housing frequently moves toward material consolidation over time. The Egoda Uyana case confirms this trajectory, as early semi-open conditions are progressively replaced by permanent enclosures.

# 5. FINDINGS OF IMPACT OF LOCATION ON THRESHOLD CHARACTER

## 5.1 TYPOLOGICAL SYNTHESIS OF THRESHOLD CONFIGURATION

Based on the combined location identified analysis and threshold character analysis, four primary threshold typologies were identified: open, semi-open, semi-enclosed, and enclosed. Open thresholds maintain direct spatial continuity with the street, characterized by minimal vertical boundaries and extended roof projection. Semi-open thresholds introduce partial enclosure through low walls or columns while preserving permeability. Semi-enclosed thresholds incorporate grills or screens that regulate visibility. Enclosed thresholds utilize solid walls and gates that eliminate transitional layering. These typologies represent a gradient rather than fixed categories. Incremental transformation frequently shifts thresholds along this continuum. The typological synthesis reveals that enclosure is not binary but progressive. This gradient supports Boettger's (2014) assertion that thresholds operate as transitional sequences rather than static boundaries. The transformation from open to enclose reflects changing priorities in privacy, security, and spatial control.

## 5.2 TRANSFORMATION LOGIC AND URBANIZATION DYNAMICS

The progressive enclosure observed in Egoda Uyana reflects broader socio-spatial transformations associated with suburban densification. Increased vehicular ownership, economic activities at the household level, and heightened security concerns encourage rigid boundary construction. Turner (1976) argues that design guidelines evolve according to resident priorities and resource availability. In Egoda Uyana, these priorities increasingly favour privacy and territorial control over permeability. However, this transformation alters the morphological continuity of the street. While enclosure enhances individual control, it diminishes spatial layering and frontage rhythm. The street shifts from a sequence of transitional interfaces to a corridor lined with defensive walls. This morphological shift redefines the architectural character of the settlement. Importantly, the study demonstrates that such transformations are often incremental and reversible. Small design decisions such as boundary height adjustment or grill replacement can significantly recalibrate permeability without requiring structural demolition.

## 5.3 IMPLICATIONS FOR HOUSING UPGRADING AND SUBURBAN DESIGN

The physical parameter framework developed in this study offers practical implications for better house threshold designs in tropical suburban contexts. Rather than eliminating threshold spaces during densification, planners and architects can preserve transitional depth through minimum setback guidelines and semi-permeable boundary standards. Encouraging partial openness, moderate plinth height, and adequate roof projection can maintain climatic buffering while accommodating privacy needs. Urban design regulations that limit excessive boundary height may preserve frontage continuity and townscape coherence. By repositioning threshold spaces as measurable architectural infrastructures, housing interventions can balance security and spatial integration. The framework provides an analytical basis for evaluating existing conditions and guiding incremental modifications.

*Table 6: Performance indicators vs. incremental design modifications*

| Performance indicator | Diagnosed physical limitations | Design response strategy |
|---|---|---|
| Accessibility and connectivity | Disconnection from the street due to excessive setbacks, high boundary walls, and misaligned entrances | Maintain direct street linkage, orient entrances toward pedestrian flow; strengthen thresholds near nodes and junctions |
| Functionality | Insufficient spatial depth or enclosure reducing transitional usability | Provide minimum usable depth; retain semi-open platforms; avoid full enclosure of transitional zones |
| Territoriality | Rigid solid boundaries creating defensive edges and spatial segregation | Introduce layered edges; replace opaque walls with low or semi-permeable boundaries; use plinth differentiation instead of vertical barriers |
| Climatic modulation | Inadequate shading and rain protection limiting threshold usability in tropical conditions | Ensure adequate roof overhang; integrate passive shading devices; maintain cross-ventilated semi-open conditions |

| Performance indicator | Diagnosed physical limitations | Design response strategy |
|---|---|---|
| Human scale proportion | Over scaled façade and boundary heights reducing pedestrian comfort | Maintain eye-level boundary articulation; design proportionate frontage elements; avoid monolithic street walls |
| Material and edge treatment | Heavy masonry enclosure replacing permeable materials | Employ perforated blocks, grills, and layered materials; articulate edges through columns and framed transitions |
| Permeability | Full-height opaque gates reducing visibility and passive surveillance | Preserve eye-level visual continuity; apply layered transparency; limit fully opaque enclosures |

# 6. CONCLUSIONS

This study establishes a structured location identification and threshold character identification framework for analysing street-front threshold spaces in lower–middle-income suburban settlements. By isolating physical parameters from social variables, the research demonstrates that threshold spaces function as measurable architectural systems defined by accessibility and connectivity, functionality, territoriality, permeability, climatic modulation, and material expression. The present study findings reveal that open and semi-open thresholds sustain transitional layering and environmental buffering at linear housing arrangement and nodes of two roads intersections, while progressive enclosure transforms thresholds into rigid defensive edges that disrupt frontage continuity. In contrast, dwellings located at node of four roads intersections often develop more articulated threshold forms that respond to increased connectivity and multidirectional visibility. These locations tend to generate deeper transitional zones, wider entrances, and more expressive architectural elements. Threshold typologies are not static forms but dynamic configurations capable of incremental transformation. These transformations reveal that small-scale architectural modifications such as boundary height adjustments, material replacement, and shading extension significantly recalibrate the physical performance of the threshold without requiring comprehensive redevelopment. The structured framework of threshold performance indicators translates empirical findings into applicable design strategies. By synthesizing observed limitations and corresponding design responses within a compact analytical model, the study bridges descriptive morphological analysis in each location and operational architectural guidance. The table of proposed design decisions demonstrates that maintaining minimum transitional depth, ensuring eye-level permeability, articulating layered edges, and integrating climate-responsive shading are critical to preserving threshold functionality in house fronts, nodes or junctions in suburban upgrading contexts. Importantly, the framework does not advocate uniform design prescriptions but establishes adaptable principles grounded in measurable spatial parameters. From a theoretical standpoint, the research contributes to architectural discourse by repositioning threshold spaces as measurable morphological infrastructures rather than purely symbolic or social constructs. Classical architectural theory emphasizes transition, gradation, and spatial layering between domains (Alexander et al., 1977; Ashihara, 1983). Through field-based morphological analysis, this study found that these theoretical principles become increasingly vulnerable within rapidly urbanizing lower-middle-income

settlements and that can be systematically evaluated across different settlement locations. The findings also reinforce configurational perspectives that emphasize the relationship between spatial structure and architectural articulation (Hillier, 1996; Hillier & Hanson, 1984), demonstrating that the location of a dwelling within the street network significantly influences the physical expression of its threshold interface. From a practical perspective, the research offers implications for housing upgrading policies in rapidly urbanizing suburban environments. In lower–middle-income settlements where incremental enclosure is common, preserving threshold depth, moderating boundary height, and encouraging semi-permeable edge treatments can sustain morphological continuity while accommodating contemporary needs for privacy and security. The performance-based framework provides planners and architects with a tool for evaluating existing conditions and guiding small-scale interventions without disrupting the broader street morphology. Although the study is grounded in a specific Sri Lankan suburban context, the methodological framework is transferable to comparable tropical settlements experiencing incremental housing transformation. Future research may extend this analysis by integrating socio-behavioural data, longitudinal transformation studies, or comparative cross-settlement investigations to further validate and refine the threshold performance model. In conclusion, this research redefines street-front threshold spaces as critical architectural infrastructures within suburban morphology. By establishing a measurable, performance-based evaluation system and linking it to design decision strategies, the study contributes both conceptual clarity and applied relevance to the international discourse on transitional architecture in incremental housing environments.

## 7. REFERENCES

Alexander, C., Ishikawa, S., Silverstein, M., Jacobson, M., Fiksdahl-King, I., & Angel, S. (1977). *A pattern language: towns, buildings, construction.* Oxford University Press.

Altman, I., & Chemers, M. M. (1980). *Culture and environment.* Cambridge University Press.

Ashihara, Y. (1983). *The aesthetic townscape*. MIT Press.

Bhatt, V. (1994). *How the other half builds.* McGill University Minimum Cost Housing Group.

Boettger, T. (2014). *Threshold spaces: Transitions in architecture: Analysis and design tools.* Birkhäuser.

Bourdieu, P. (1977). *Outline of a theory of practice*. Cambridge University Press.

Gehl, J. (1987). *Life between buildings: Using public space*. Van Nostrand Reinhold.

Gehl, J. (2010). *Cities for people*. Island Press.

Gulati, R. (2020). Neighborhood spaces in residential environments: Lessons for contemporary Indian context. *Frontiers of Architectural Research, 9*(1), 20–33. https://doi.org/10.1016/j.foar.2019.10.002.

Gunathillaka, D., & Coorey, S. B. A. (2014). Relevance of threshold spaces in low-income communities of Colombo for sustaining social ties. In R. Dayaratne & J. Wijesundara (Eds.), *Proceedings of the International Conference on Cities, People and Places (ICCPP) 2014* (pp. 266–280). Department of Architecture, University of Moratuwa. http://dl.lib.uom.lk/handle/123/22978

Hillier, B. (1996). *Space is the machine: A configurational theory of architecture*. Cambridge University Press.

Hillier, B., & Hanson, J. (1984). *The social logic of space*. Cambridge University Press.

Lefebvre, H. (1991). *The production of space (D. Nicholson-Smith, Trans.).* Blackwell.

Lynch, K. (1960). *The image of the city*. MIT Press

Newman, O. (1972). *Defensible space: Crime prevention through urban design*. Macmillan.

Prasetiyo, A. Y., & Fuad, A. H. (2021). Crossing the threshold: Understanding spatial patterns formed by threshold space in urban contexts. *IOP Conference Series Earth and Environmental Science, 673*(1), 012037. https://doi.org/10.1088/1755-1315/673/1/012037

Rapoport, A. (1982). *The meaning of the built environment: A nonverbal communication approach*. Sage Publications.

Turner, J. F. C. (1976). *Housing by people: Towards autonomy in building environments*. Marion Boyars.

Tzortzi, J. N., & Saxena, I. (2024). Threshold spaces: The transitional spaces between outside and inside in traditional Indian dwellings. *Heritage, 7*(12), 6683–6711. https://doi.org/10.3390/heritage7120309

von Meiss, P. (1990). *Elements of architecture: from form to place.* Routledge.

Wijayarathne, P.N.S. and Hirudini, S.M., 2026. The impact of material expression at entrance thresholds on invitation to access: A comparative study of shopping malls in Colombo, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1707-1720. DOI: https://doi.org/10.31705/WCS.2026.124. Available from: https://ciobwcs.com/papers/

# THE IMPACT OF MATERIAL EXPRESSION AT ENTRANCE THRESHOLDS ON INVITATION TO ACCESS: A COMPARATIVE STUDY OF SHOPPING MALLS IN COLOMBO, SRI LANKA

**P.N.S. Wijayarathne[1] and S.M. Hirudini[2]**

## *ABSTRACT*

*Entrance thresholds in contemporary shopping malls function as critical interfaces between urban public space and privately managed interiors. Previous studies have examined shopping malls in relation to circulation, branding, and commercial performance. But limited research has focused on how material expression at entrance thresholds influences perceived invitation to access. This study investigates the impact of material expression at entrance threshold on invitation to access in two contemporary shopping malls in Colombo, Sri Lanka: Mall A and Mall B. Two ground floor pedestrian entrances from each case study were analysed using a comparative case study approach. Material expression variables, including façade transparency, threshold framing, material contrast, and volumetric presence were documented through structured architectural observation. Spatial visibility was examined using Visibility Graph Analysis in DepthmapX to assess visual integration and connectivity. Invitation to access was evaluated through perception-based surveys capturing legibility, spatial clarity, and social openness. The findings reveal a consistent relationship between strong material expression, higher spatial integration, and stronger invitation profiles. Entrances characterised by transparent glazing, clear framing, and visible interior volume demonstrate higher visual prominence and perceived openness. In contrast, entrances with reduced material differentiation exhibit lower integration values and weaker invitation perception. The study positions material expression as a spatial mediator that shapes both visibility structure and perceived accessibility at the building threshold. These findings contribute to architectural understanding of threshold design within dense urban retail environments.*

***Keywords:*** *Entrance Threshold Architecture; Invitation to Access; Material Expression; Shopping Malls in Colombo, Spatial Visibility Analysis; Sri Lanka.*

## 1. INTRODUCTION

Shopping malls have become important architectural and urban elements in rapidly developing cities. In Colombo, Sri Lanka, large-scale retail complexes are more than commercial destinations; they function as key urban nodes within the city's dense and evolving fabric. Malls are privately owned but publicly accessible, placing them between

[1] Undergraduate, Architecture Department, University of Moratuwa, nathashaw99@gmail.com
[2] Senior Lecturer, Architecture Department, University of Moratuwa, mihirih@uom.lk

commercial control and urban openness. In this condition, entrance thresholds become particularly important because they shape how people move from exterior public space into interior retail environments. Entrance thresholds are more than simple access points. They structure movement, frame visibility, and define the boundary between the city and the building (Hillier & Hanson, 1984; Rapoport, 1982). Architectural decisions at the threshold influence how entrances are perceived from the outside. Transparency, framing, material contrast, and visible interior volume help people recognize an entrance and shape first impressions (Bitner, 1992; Pallasmaa, 2005). Research on shopping malls has widely examined circulation, commercial performance, branding, and interior spatial organization (Coleman, 2006). Existing studies in urban design and Space syntax and urban design studies have also examined spatial integration, visibility, and pedestrian movement in built environments (Hillier, 1996; Penn, 2003). Environmental psychology and wayfinding research show that spatial layout, visibility, and environmental cues influence perception, orientation, and approach behaviour in commercial spaces (Arthur & Passini, 1992; Donovan & Rossiter, 1982; Mehrabian & Russell, 1974). However, entrance thresholds are often treated mainly as façade elements or functional access points. They are less frequently examined as layered transitional zones shaped by material expression.

Although material treatment is central to architectural design, few empirical studies isolate material expression at entrance thresholds as a measurable factor influencing perceived accessibility. In rapidly urbanizing South Asian countries such as Sri Lanka, comparative spatial analysis of entrance threshold expression remains limited. This study addresses this gap by examining how material expression operates as a spatial mediator at the building edge. By focusing on material expression as a primary architectural variable, the research isolates façade transparency, threshold framing, material differentiation, and volumetric presence to examine their relationship with spatial visibility and perceived invitation to access. Based on the identified research gap, this study focuses on material expression at entrance thresholds and its relationship with perceived invitation to access in contemporary shopping malls in Colombo, Sri Lanka. The study specifically examines ground-floor pedestrian entrances and evaluates how façade transparency, threshold framing, material contrast, and visible interior volume influence spatial visibility and perceived openness within urban retail environments.

## 1.1 AIM AND OBJECTIVES

The aim of this study is to examine the impact of material expression at entrance thresholds on invitation to access in contemporary shopping malls in Colombo, Sri Lanka. To achieve this aim, the study addresses the following objectives:

- To identify key material expression characteristics at shopping mall entrance thresholds, including transparency, threshold framing, material contrast, and volumetric presence.
- To analyse spatial visibility conditions at entrance thresholds using Visibility Graph Analysis (VGA) in DepthmapX.
- To evaluate perceived invitation to access through perception-based surveys measuring openness, spatial clarity, and visual continuity.

### 1.2 SCOPE AND LIMITATIONS

This study focuses exclusively on material expression at selected ground-floor pedestrian entrance thresholds in two contemporary shopping malls in Colombo, Sri Lanka: Mall A and Mall B. Upper-level, basement, vehicular, service, and restricted-access entrances are excluded to maintain spatial consistency across cases. The analysis concentrates on architectural and spatial characteristics of entrance thresholds, including façade transparency, framing, material contrast, and volumetric presence. While spatial visibility metrics are incorporated to support architectural interpretation, the study does not examine retail performance, economic outcomes, or long-term behavioural patterns. The findings are based on two case studies and are therefore limited to comparable large-scale urban retail environments.

### 1.3 METHODOLOGICAL OVERVIEW

This study adopts a comparative case study approach focusing on four ground-floor pedestrian entrances across two shopping malls in Colombo, Sri Lanka. Material expression variables were documented through structured architectural observation. Spatial visibility was examined using Visibility Graph Analysis in DepthmapX to assess integration and connectivity within defined threshold boundaries. Invitation to access was evaluated through perception-based surveys capturing openness, spatial clarity, and visual continuity. Detailed methodological procedures are presented in section 3.

## 2. LITERATURE REVIEW

Entrance thresholds are important architectural zones where buildings meet the city. In shopping malls, these spaces act as controlled edges between public urban life and privately managed commercial interiors. Although malls are privately owned, they function as publicly accessible environments. Because of this, entrance design influences how openness, access, and spatial hierarchy are communicated. Previous research has examined shopping malls in relation to circulation systems, commercial performance, and spatial integration within retail environments (Coleman, 2006; Hillier, 1996; Penn, 2003). Research in environmental psychology has also explored how spatial layout, visibility, and environmental cues influence perception and movement behaviour in commercial settings (Arthur & Passini, 1992; Bitner, 1992; Donovan & Rossiter, 1982). However, limited attention has been given to material expression at entrance thresholds as a distinct architectural condition. Material qualities such as transparency, façade permeability, surface expression, and interior visibility influence how entrances are perceived and shape first impressions before entry occurs (Benedikt, 1979; Pallasmaa, 2005). Although studies have separately examined retail environments, spatial visibility, and environmental perception, limited research has specifically examined how material expression at shopping mall entrance thresholds influences invitation to access. Therefore, this review connects threshold theory, environmental perception, and spatial visibility studies to develop a focused framework for examining how material expression shapes invitation to access in contemporary shopping malls.

### 2.1 ENTRANCE THRESHOLD ARCHITECTURE AS A SPATIAL INTERFACE

An entrance threshold is the transitional zone between exterior public space and the interior of a building. Rather than functioning as a single doorway element, it includes the exterior approach, façade expression, entry line, and immediate interior landing zone.

Architectural theory describes thresholds as layered spatial conditions that structure movement, visibility, and boundary definition between different spatial domains (Hillier & Hanson, 1984; Rapoport, 1982). In shopping malls, where publicly accessible interiors are privately managed, entrance thresholds operate as critical architectural interfaces between urban public space and controlled commercial environments. Within these interfaces, material expression plays an important role in shaping how entrances are recognized and interpreted. Transparency, façade articulation, framing elements, and visible interior volume influence how clearly an entrance is distinguished from the surrounding façade and how effectively it communicates accessibility. Material differentiation can strengthen spatial hierarchy and reinforce the recognizability of entry points within large-scale retail environments. Architectural literature further suggests that materials communicate meaning through light, texture, depth, and visual continuity (Pallasmaa, 2005). Similarly, framing elements and symbolic architectural expression help define thresholds as points of transition between spatial conditions (Eco, 1986; Rapoport, 1982).

Research on architectural perception also demonstrates that glazing proportion, façade permeability, and visible interior depth influence how buildings communicate openness and spatial accessibility (Benedikt, 1979; Pallasmaa, 2005). In commercial environments, clearly articulated entrances improve recognizability and support spatial orientation within complex retail developments (Coleman, 2006). Recent research on shopping Centre façades further indicates that façade attributes influence public preference and the perceived quality of commercial buildings (Khomeiri et al., 2025). And Recent urban interface research also highlights that ground-floor façade permeability can influence pedestrian activity and the experience of public space (Abdelmonem, 2022). Together, these studies indicate that material expression influences both perceptual interpretation and spatial recognition at architectural thresholds. However, while previous studies have examined threshold conditions, spatial visibility, and retail perception separately, limited research has specifically examined how material expression at shopping mall entrance thresholds shapes invitation to access. Based on this literature, material expression at entrance thresholds can be examined through the following architectural dimensions:

*Table 1: Material expression dimensions at entrance threshold architecture by author*

| Material Dimension | Explanation | Key Sources |
|---|---|---|
| Transparency and Visual Permeability | Degree to which interior space is visible from exterior | Benedikt (1979); Bitner (1992) |
| Surface Expression and Framing | Architectural elements that define and emphasise the entry line | Eco (1986); Rapoport (1982) |
| Material Contrast | Distinction between entrance zone and surrounding façade | Rapoport (1982) |
| Volumetric Presence | Visibility of interior height and spatial depth at the threshold | Benedikt (1979); Hillier & Hanson (1984) |
| Light and Reflectivity | Role of lighting and surface quality in enhancing recognition | Pallasmaa (2005) |

## 2.2 MATERIAL EXPRESSION AND PERCEIVED OPENNESS

Material expression at entrance thresholds influences how users interpret openness and accessibility before entering a building. Environmental psychology explains this relationship through the Stimulus-Organism-Response (S-O-R) framework, where physical environmental conditions act as stimuli that shape perceptual and behavioural responses (Mehrabian & Russell, 1974). Empirical research in retail environments further demonstrates that environmental cues at entrances influence emotional response, spatial interpretation, and approach behaviour (Bitner, 1992; Donovan & Rossiter, 1982). Research on wayfinding and spatial cognition also suggests that transparency and visible interior activity reduce uncertainty and increase perceived accessibility at entry points (Arthur & Passini, 1992). Within this context, material expression operates as the primary architectural stimulus at the building edge. Transparency and interior visibility reduce uncertainty during pedestrian approach by allowing users to visually understand interior depth and circulation before entry occurs (Arthur & Passini, 1992; Benedikt, 1979). When entrances provide clear visual continuity between exterior and interior spaces, the cognitive effort required at the point of entry is reduced. Similarly, framing elements and material contrast help users recognize entrances more clearly and interpret access conditions.

Prospect-refuge theory further supports this relationship by suggesting that people prefer environments balancing visibility with a sense of protection (Appleton, 1975). At entrance thresholds, this balance can be achieved through framed glazing, recessed entries, or sheltered canopies, which allow visual access while maintaining environmental comfort. Research on commercial environments also indicates that lighting quality, material transparency, and façade expression influence emotional response and behavioural expectations within retail settings (Bitner, 1992; Donovan & Rossiter, 1982). Together, these studies suggest that material expression influences both perceptual interpretation and behavioural response at architectural thresholds. Recent experimental research also shows that entrance transparency and door-opening conditions influence perceived hospitality, mental ease of access, and invitation (Pijls et al., 2023). In this study, perceived openness is examined through the concept of invitation to access. This concept refers to how clearly and comfortably an entrance communicates openness, accessibility, and permission to enter. Although previous studies have examined environmental perception, retail behaviour, and spatial visibility separately, limited research has specifically examined how material expression at shopping mall entrance thresholds shapes invitation to access within contemporary urban retail environments.

## 2.3 INVITATION TO ACCESS AS A PERCEPTUAL CONSTRUCT

Invitation to access refers to the extent to which an entrance is perceived as open, understandable, and socially acceptable to enter. It is a perceptual interpretation that occurs during approach, before users physically cross the threshold. Unlike functional accessibility, which focuses primarily on physical entry conditions, invitation to access concerns how architectural cues communicate openness, inclusion, and perceived permission to enter. Environmental psychology suggests that physical environments influence emotional and cognitive responses that guide approach behaviour (Mehrabian & Russell, 1974). In retail environments, clarity, visibility, and environmental comfort are associated with stronger approach tendencies and positive behavioural responses (Bitner, 1992; Donovan & Rossiter, 1982). At entrance thresholds, these perceptual

responses are shaped by material expression, visual accessibility, and boundary definition. Publicness theory further explains that perceptions of openness are influenced by visible regulation and spatial signalling within publicly accessible environments. Even when entrances are physically accessible, architectural cues such as opaque façades, recessed entries, or strong visual barriers may reduce the perceived openness of the threshold.

In contrast, transparent glazing, visible interior activity, and clearly framed entrances communicate accessibility and strengthen perceived openness. Wayfinding research also demonstrates that clarity at decision points reduces cognitive effort and increases confidence during movement (Arthur & Passini, 1992). When entrances are materially and visually legible, users require less interpretation before deciding to enter. Together, these studies suggest that invitation to access is shaped not only by physical accessibility, but also by how architectural expression communicates openness and spatial clarity at the building edge. In this study, invitation to access is interpreted through four perceptual indicators: openness, spatial clarity, comfort, and visual continuity. Openness refers to the perceived public accessibility of the entrance. Spatial clarity refers to how easily users understand the direction and location of entry. Comfort refers to the environmental and psychological ease experienced during approach and entry. Visual continuity refers to the perceived connection between exterior and interior spaces. Together, these indicators provide a framework for evaluating how material expression influences perceived invitation at shopping mall entrance thresholds.

## 2.4 CONCEPTUAL FRAMEWORK

This study adopts a focused conceptual framework to examine how material expression at entrance thresholds influences perceived invitation to access. Material expression is treated as the primary architectural stimulus, while invitation to access is treated as the perceptual response. This framing builds on environmental psychology, architectural perception, and retail threshold studies, which collectively suggest that physical design cues shape how users interpret access, openness, and spatial clarity (Bitner, 1992; Mehrabian & Russell, 1974; Pallasmaa, 2005). Within this framework, façade transparency, material contrast, lighting treatment, threshold framing, and visible interior volume are understood as material cues that influence visual preview, spatial continuity, and symbolic signalling at the building edge. Users interpret these cues in terms of openness, clarity, inclusivity, and perceived permission to enter. Rather than examining entrance threshold architecture as a broad set of variables, this study isolates material expression to evaluate its specific influence on invitation to access in contemporary shopping malls. This framework therefore links three bodies of literature: entrance threshold theory, material expression and perception, and spatial visibility. It responds to the identified gap by examining how material expression at shopping mall thresholds operates as a spatial mediator between architectural form and perceived invitation.

*Table 2: Analytical structure of the study by author*

| Component | Focus | Key Indicators |
|---|---|---|
| Architectural Stimulus | Material Expression at Entrance Threshold | Transparency, façade expression, material contrast, lighting, volumetric visibility |

| Component | Focus | Key Indicators |
|---|---|---|
| Perceptual Response | Invitation to Access | Perceived openness, clarity of entry, inclusivity, permission to enter |
| Relationship Tested | Impact Analysis | How material expression influences perceived invitation |

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN

This study adopts a comparative case study approach to examine how material expression at entrance thresholds influences invitation to access in contemporary shopping malls in Colombo, Sri Lanka. The research focuses on four ground-floor pedestrian entrances across two shopping malls, referred to as Mall A and Mall B to maintain anonymity in data collection and reporting. The analyzed entrances are identified as Entrance 1 and Entrance 2 within each case study. Material expression is treated as the primary architectural variable, with transparency, façade articulation, material contrast, lighting treatment, and visible interior volume examined as key spatial stimuli at the threshold. These material conditions are analyzed in relation to how users perceive openness, spatial clarity, comfort, and visual continuity during approach and entry. The research design integrates three methodological components: architectural documentation, perception-based survey responses, and spatial visibility analysis using DepthmapX. This mixed-method structure enables both spatial and perceptual evaluation within a consistent analytical framework.

## 3.2 CASE STUDY SELECTION

Two contemporary shopping malls in Colombo, Sri Lanka were selected and anonymized as Mall A and Mall B. Within each mall, two public ground-floor pedestrian entrances were analyzed.

*Figure 1: Ground floor plan layout of mall A and Ground floor plan layout of Mall B (Source: Author)*

The entrances were selected using purposive sampling because they offered comparable public access conditions while showing clear variation in material expression and threshold configuration. Only ground-floor pedestrian entrances connected to surrounding public or semi-public approach spaces were included. Upper-level,

basement, vehicular, service, and restricted-access entrances were excluded to maintain spatial consistency. The selected entrances were comparable because each functioned as a publicly accessible mall entrance within a large-scale retail environment. However, they differed in entrance hierarchy, façade transparency, threshold framing, interior visibility, surrounding activity, security presence, and urban exposure. These differences allowed the study to examine how variations in material expression influence perceived invitation to access across comparable entrance conditions.

*Table 3: Summary of case study entrances by Author*

| Mall | Entrance | Role | Approach Condition | Key Material/Spatial Variation |
|---|---|---|---|---|
| Mall A | Entrance 1 | Primary | Plaza-facing, axial approach | High transparency, strong framing, visible interior volume |
| Mall A | Entrance 2 | Secondary | Recessed roadside approach | Lower material contrast, limited interior preview, stronger control presence |
| Mall B | Entrance 1 | Primary | Forecourt-facing approach | High transparency, canopy emphasis, visible interior volume |
| Mall B | Entrance 2 | Secondary | Courtyard-based approach | Moderate transparency, softer framing, localised visibility |

## 3.3 DELIMITATION OF ENTRANCE THRESHOLD BOUNDARY

For analytical consistency, the entrance threshold boundary was operationally defined as the transitional zone extending from the immediate exterior approach to the first interior landing space. This boundary included three spatial layers:

- Exterior approach zone (early visual recognition area)
- Façade and doorway line (formal entry plane)
- Interior landing zone (completion of transition)

This definition ensured that material expression was assessed within a clearly bounded spatial field across all case studies. The same threshold depth was modelled and analysed in each entrance to maintain comparability.

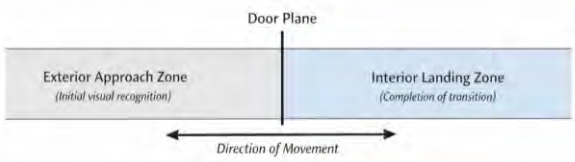



*Figure 2: Diagrammatic representation of entrance threshold boundary (source: author)*

## 3.4 DATA COLLECTION AND ANALYSIS

Data collection integrated architectural documentation, perception-based evaluation, and spatial visibility analysis. Each component was applied consistently across all four entrances.

### 3.4.1 Architectural Material Documentation

Structured on-site observation recorded material expression variables within the defined threshold boundary: transparency, material contrast, threshold framing, lighting treatment, volumetric presence, and façade depth expression. These variables captured glazing and interior preview, façade differentiation, framing devices, entry lighting, visible interior height and depth, and recessed or projected threshold conditions. Photographs and annotated sketches supported comparison across the four entrances.

- Transparency- Extent of glazing and interior visual preview
- Material Contrast- Degree of differentiation from adjacent façade elements
- Threshold Framing-Presence of canopy, structural emphasis, or framing devices
- Lighting Treatment-Natural and artificial lighting conditions at entry
- Volumetric Presence- Visibility of interior height and spatial depth
- Façade Depth Expression- Recessed or projected threshold condition

### 3.4.2 Perception-Based Survey

Short intercept interviews were conducted immediately after participants crossed the entrance threshold to capture first impressions of invitation to access. Respondents were selected using random intercept sampling, where every available adult pedestrian exiting the threshold zone during the survey period was approached when practical. Thirty participants were surveyed at each entrance, resulting in 120 total responses. Surveys were conducted during regular daytime operating hours across both weekday and weekend periods to reduce bias from a single time condition. The survey items were developed from the invitation to access indicators identified in the literature review and conceptual framework. These indicators were openness, spatial clarity, comfort, and visual continuity. Responses were recorded using a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), and were aggregated to produce mean scores for comparative analysis.

- Openness- perceived public accessibility
- Spatial clarity- ease of understanding the entry direction
- Comfort- environmental and psychological case
- Visual continuity- perceived connection between exterior and interior

### 3.4.3 Spatial Visibility Analysis

Visibility Graph Analysis (VGA) was conducted using DepthmapX (Turner, 2004). Simplified ground-floor plans were modelled within the defined threshold boundary to evaluate spatial visibility conditions. Two spatial metrics were extracted: visual integration (Rn), which indicates the degree of spatial prominence within the visibility network, and visual connectivity, which represents the number of directly visible spatial connections from a given point.

### 3.4.4 Analytical Strategy

Comparative analysis was conducted at two levels: Within-case comparison between primary and secondary entrances in each mall and Cross-case comparison between Mall A and Mall B. Material expression variables were interpreted alongside spatial visibility metrics and perception scores to evaluate relationships between façade expression and invitation to access.

# 4. RESULTS

This section presents the comparative findings across four selected entrances. Results are structured in three stages: material expression analysis, spatial visibility metrics, and invitation to access evaluation.

## 4.1 MATERIAL EXPRESSION PROFILES

*Table 4: Material Expression Profiles by Author*

| Entrance | Transparency | Threshold Framing | Material Contrast | Volumetric Presence |
|---|---|---|---|---|
| Mall A Entrance 1 | High - full-height glazing, clear interior preview | Strong canopy and symmetrical expression | High - Extensive use of transparent materials and minimal structural obstruction | Double-height atrium visible from exterior |
| Mall A Entrance 2 | Moderate-Low - blended façade, limited preview | Weak framing integrated with retail frontage | Low - minimal differentiation | Compressed interior not visible until entry |
| Mall B Entrance 1 | High - transparent glazing with visible interior volume | Strong canopy and façade emphasis | High - coherent material hierarchy | Double-height lobby visible |
| Mall B Entrance 2 | Moderate - partial transparency | Subtle architectural emphasis | Moderate - softer expression | Moderate interior volume |

*Figure 3: Material expression profile of Mall A- Entrance 1 (Source: Author)*

*Figure 4: Material expression profile of Mall A- Entrance 2 (Source: Author)*

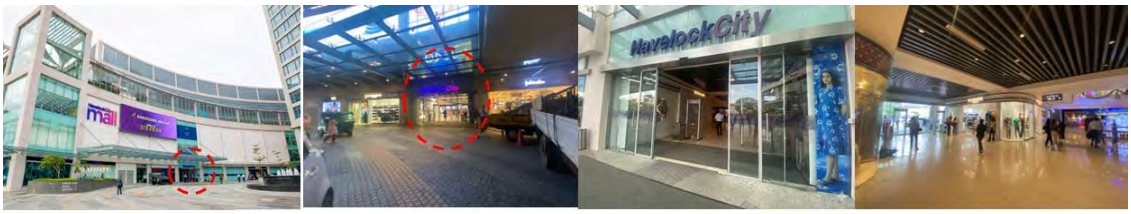



*Figure 5: Material expression profile of Mall B- Entrance 1 (Source: Author)*

*Figure 6: Material expression profile of Mall B-Entrance 2 (Source: Author)*

The comparison reveals clear differences in material articulation across the four entrances. Primary entrances in both malls demonstrate stronger transparency, clearer threshold framing, and greater visible interior volume, while secondary entrances exhibit weaker façade differentiation and more limited interior preview. These variations establish differing conditions of spatial prominence and perceived accessibility prior to entry.

## 4.2 SPATIAL VISIBILITY RESULTS

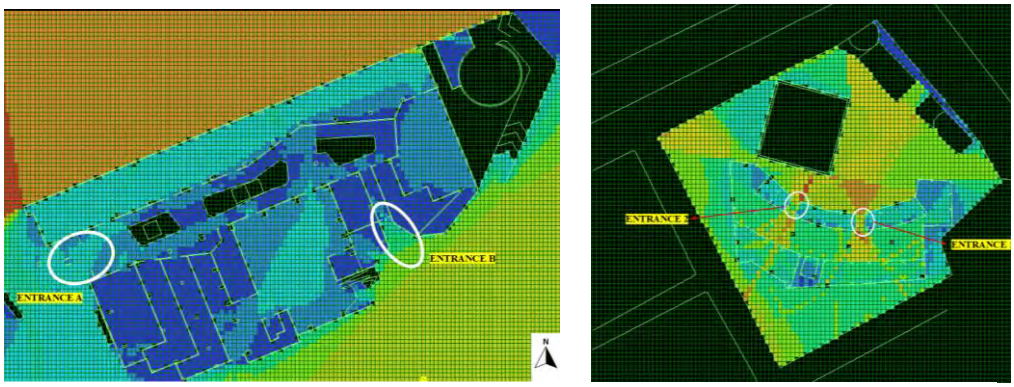



*Figure 7: Visibility Connectivity map of CCC both entrances and HCM both entrances (Source: DepthmapX)*

Visibility Graph Analysis (VGA) showed clear differences in integration and connectivity across the four entrances. Mall A-Entrance 1 and Mall B-Entrance 1 recorded the highest visual integration values, indicating stronger visibility links between exterior approach areas and interior circulation spaces. Mall A-Entrance 2 recorded the lowest integration due to its recessed threshold condition and limited interior visibility, while Mall B-Entrance 2 showed moderate integration within its courtyard setting. Connectivity followed a similar pattern: transparent entrances with open forecourt conditions produced stronger local visual connections, while recessed entrances with limited façade permeability showed lower connectivity. Overall, entrances with stronger material articulation and visible interior volume demonstrated higher spatial visibility and integration.

*Table 5: DepthmapX Visibility Metrics by Author*

| Entrance | Integration (Rn) | Connectivity | Visibility Profile |
|---|---|---|---|
| Mall A-Entrance 1 | 1.65-1.90 | 120-160 | Highly integrated |
| Mall A-Entrance 2 | 0.85-1.05 | 40-60 | Visually constrained |
| Mall B-Entrance 1 | 1.45-1.75 | 95-140 | Well-connected |
| Mall B-Entrance 2 | 1.10-1.30 | 75-95 | Locally embedded |

### 4.3 INVITATION TO ACCESS RESULTS

Primary entrances demonstrated stronger invitation profiles than secondary entrances. Mall A-Entrance 1 and Mall B-Entrance 1 recorded the highest overall scores, particularly for openness, spatial clarity, and visual continuity. Mall A-Entrance 2 recorded the lowest scores, corresponding with reduced façade expression, limited interior preview, and weaker spatial integration, while Mall B-Entrance 2 showed moderate–high invitation levels within its courtyard-based setting. Across both malls, entrances with higher transparency, stronger material contrast, and visible interior volume showed clearer alignment between material articulation, spatial integration, and invitation to access. The survey was designed as a focused comparative perception tool; therefore, the analysis relied on descriptive comparison of mean scores derived from 120 respondents, with 30 respondents surveyed at each entrance. (**Note.** Mean scores were interpreted as follows: 1.0–2.0 = Low; 2.1–3.0 = Moderate; 3.1–4.0 = Moderate–High; 4.1–5.0 = High.)

*Table 6: Invitation to access mean scores*

| IA Dimension | Mall A - Entrance 1 | Mall A - Entrance 2 | Mall B - Entrance 1 | Mall B - Entrance 2 |
|---|---|---|---|---|
| Openness | 4.4 | 3.1 | 4.5 | 3.8 |
| Spatial Clarity | 4.3 | 3.0 | 4.4 | 3.7 |
| Comfort | 4.1 | 3.2 | 4.2 | 3.9 |
| Visual Continuity | 4.2 | 3.1 | 4.3 | 3.8 |
| Overall Mean | 4.25 | 3.10 | 4.35 | 3.80 |
| Interpretation | High | Moderate-High | High | Moderate-High |

## 5. DISCUSSION

The findings indicate that material expression at entrance thresholds is associated with both spatial prominence and perceived invitation to access. Entrances with higher transparency, clear framing, and visible interior volume demonstrated stronger spatial integration and clearer invitation patterns. This aligns with architectural perception and wayfinding literature, which suggests that visual continuity and legibility reduce uncertainty during movement through built environments (Arthur & Passini, 1992; Benedikt, 1979). Transparent glazing allows pedestrians to preview interior activity

before entry, while threshold framing and material contrast distinguish the entrance from surrounding retail frontage. The relationship between façade transparency and spatial visibility also aligns with space syntax studies, where visually integrated spaces are associated with stronger spatial prominence and movement potential (Hillier, 1996; Penn, 2003). Perception results followed a similar pattern, with visually continuous entrances receiving higher ratings for openness and legibility. These findings also support servicescape research, which shows that environmental cues shape emotional response and approach behaviour in commercial environments (Bitner, 1992; Donovan & Rossiter, 1982). The present study extends these arguments by showing how material expression at shopping mall entrance thresholds contributes to perceived invitation before entry occurs. The analysis further reveals a clear distinction between primary and secondary entrances. Primary entrances demonstrated stronger material articulation, higher spatial integration values, and stronger invitation profiles, while secondary entrances showed weaker façade emphasis and lower integration levels. This suggests that entrance hierarchy is partly constructed through material expression. Elements such as transparency, threshold framing, and visible interior volume reinforce the prominence of primary entrances within the urban interface, whereas secondary entrances remain functionally accessible but less visually emphasized. This finding is consistent with retail design literature, which suggests that clearly articulated entrances support recognizability and orientation within large-scale commercial environments (Coleman, 2006). However, the relationship identified in this study should be interpreted as correlational and perceptual rather than strictly causal. Although material expression showed a strong association with invitation to access, other spatial and environmental factors may also influence how pedestrians interpret entrances. These include entrance location, pedestrian flow, signage visibility, lighting intensity, entrance width, surrounding retail activity, and security presence. While this study focused on material expression as the primary architectural variable, other factors within the wider threshold condition may also contribute to perceived openness and accessibility. The findings suggest that material expression should be treated as an important component of entrance threshold design, not merely as an aesthetic treatment. Design strategies that may support stronger invitation include high façade transparency for interior preview, clear threshold framing through canopies or structural articulation, and alignment with visible interior circulation or double-height spaces. Conversely, deeply recessed entrances or those visually blended with surrounding façade elements may weaken entrance recognition and perceived accessibility, especially in dense urban retail contexts such as Colombo, Sri Lanka.

## 6. CONCLUSIONS

This study examined how material expression at entrance thresholds relates to invitation to access by combining architectural observation, spatial visibility analysis, and perception-based evaluation. The research investigated the relationship between material articulation, spatial prominence, and perceived openness at the building edge. The findings show a consistent association between higher transparency, clear threshold framing, visible interior volume, and stronger invitation profiles. Entrances with greater visual continuity between exterior and interior spaces recorded higher spatial integration and stronger perceptions of openness and legibility. In contrast, recessed entrances with limited material differentiation and reduced interior visibility showed weaker spatial prominence and lower invitation scores. The study highlights material expression as an important architectural component of entrance threshold design rather than a purely

aesthetic treatment. Transparent glazing, visible interior preview, and clearly articulated threshold framing may support stronger perceived accessibility and spatial recognition during pedestrian approach. Overall, the study contributes a comparative perspective on the relationship between material expression, spatial visibility, and invitation to access within contemporary urban retail architecture.

# 7. REFERENCES

Abdelmonem, M. G. (2022). Fear in disguise: Defensive architecture and façade permeability in shaping the urban experience of Belfast's public spaces. *Architectural Research Quarterly, 26*(2), 148–160. https://doi.org/10.1017/S1359135522000392

Appleton, J. (1975). *The experience of landscape*. Wiley.

Arthur, P., & Passini, R. (1992). *Wayfinding: People, signs, and architecture*. McGraw-Hill.

Benedikt, M. L. (1979). To take hold of space: Isovists and isovist fields. *Environment and Planning B: Planning and Design, 6*(1), 47–65. https://doi.org/10.1068/b060047

Bitner, M. J. (1992). Servicescapes: The impact of physical surroundings on customers and employees. *Journal of Marketing, 56*(2), 57–71. https://doi.org/10.1177/002224299205600205

Coleman, P. (2006). *Shopping environments: Evolution, planning and design*. Architectural Press. https://doi.org/10.4324/9780080480909

Donovan, R. J., & Rossiter, J. R. (1982). Store atmosphere: An environmental psychology approach. *Journal of Retailing, 58*(1), 34–57.

Eco, U. (1986). Function and sign: The semiotics of architecture. In *Travels in hyperreality* (W. Weaver, Trans., pp. 181–202). Harcourt Brace Jovanovich.

Hillier, B. (1996). *Space is the machine: A configurational theory of architecture*. Cambridge University Press. https://discovery.ucl.ac.uk/id/eprint/3848/

Hillier, B., & Hanson, J. (1984). *The social logic of space*. Cambridge University Press.

Khomeiri, F., Pazhouhanfar, M., & Stoltz, J. (2025). The impact of architectural facade attributes on shopping center choice: A discrete choice modeling approach. *Buildings, 15*(17), Article 3161. https://doi.org/10.3390/buildings15173161

Mehrabian, A., & Russell, J. A. (1974). *An approach to environmental psychology*. MIT Press.

Pallasmaa, J. (2005). *The eyes of the skin: Architecture and the senses* (2nd ed.). Wiley.

Penn, A. (2003). Space syntax and spatial cognition: Or why the axial line? *Environment and Behavior, 35*(1), 30–65. https://doi.org/10.1177/0013916502238864

Pijls, R., Groen, B. H., Galetzka, M., & Pruyn, A. T. H. (2023). Come in please: A virtual reality study on entrance design factors influencing the experience of hospitality. *Journal of Environmental Psychology, 91*, Article 102137. https://doi.org/10.1016/j.jenvp.2023.102137

Rapoport, A. (1982). *The meaning of the built environment: A nonverbal communication approach*. Sage.

Turner, A. (2004). *DepthmapX 4: A researcher's handbook*. University College London.

Dissanayake, Y.R. and Hirudini, S.M., 2026. The influence of visibility on personal space creation in urban public spaces: A case study of the Arcade at Independence Square. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1721-1734. DOI: https://doi.org/10.31705/WCS.2026.125. Available from: https://ciobwcs.com/papers/

# THE INFLUENCE OF VISIBILITY ON PERSONAL SPACE CREATION IN URBAN PUBLIC SPACES: A CASE STUDY OF THE ARCADE AT INDEPENDENCE SQUARE

**Y.R. Dissanayake[1] and S.M. Hirudini[2]**

## *ABSTRACT*

*Urban open public spaces play an important role in supporting social interaction, recreation, and psychological well-being within dense urban environments. While much of the existing literature emphasizes the role of public spaces in encouraging social interaction and ensuring safety through visibility, relatively limited attention has been given to how visibility can also support personal space creation in urban public spaces. The research focuses on the Independence Square Monument in Colombo as a case study. A mixed-method approach was adopted, combining spatial analysis and behavioural observation. For the spatial analysis, two parameters were used to examine visibility: overall visibility and point visibility. Under behavioural analysis, users' spatial choices were examined using two parameters: proximity and movement patterns. Visibility conditions were analysed using Visibility Graph Analysis (VGA) and point isovist mapping through DepthMapX software, while user spatial behaviour was documented through observations and photographic documentation. The findings indicate that users tend to select locations where visibility can be partially controlled, allowing them to balance exposure to the public environment while maintaining personal space. The study concludes that managing visibility through architectural and landscape elements such as columns, edges, and shaded zones can enhance privacy in urban public spaces without compromising safety or social interaction.*

***Keywords:*** *Arcade Independence Square; Privacy; Urban Open Public Spaces; User Behaviour; Visibility.*

## 1. INTRODUCTION

In contemporary society, people's lives are often shaped by demanding schedules and repetitive daily routines. For many, each day follows a predictable pattern of commuting from home to work and back again. Homes and workplaces are mostly designed to meet functional needs, leaving little room for relaxation or leisure (Maslow, 1970). Consequently, the need for accessible open spaces in urban settings has become increasingly significant.

Urban open public spaces provide opportunities for relaxation, social interaction, and temporary escape from daily pressures. However, the way people use these spaces is not random. Users often select specific locations within a space based on environmental and

[1] Undergraduate, Department of Architecture, University of Moratwa, Sri Lanka.
[2] Senior Lecturer, Department of Architecture, University of Moratwa, Sri Lanka.

spatial conditions that allow them to feel comfortable while maintaining an appropriate level of personal space.

Much of the existing literature on public spaces emphasizes their role in promoting social interaction and community life. Within these discussions, visibility is often considered primarily as a factor that enhances safety. However, an equally important dimension of public life is the human need for privacy. Most foundational studies on public space behaviour were conducted during the 20th century, when social life was largely shaped by face-to-face interactions and limited technological influence. In contrast, the 21st century has introduced significant changes in the ways people experience and value public spaces. With the rapid growth of digital devices, social media, and virtual networks, individuals increasingly seek moments of personal reflection, temporary withdrawal, and calm within urban environments. In this context, managed visibility becomes an important spatial condition, enabling users to balance exposure to the public realm while maintaining a sense of personal space and privacy.

### 1.1 AIM AND OBJECTIVES

The main aim of this study is to examine visibility levels in different spatial conditions and identify the personal space adopted by users in Sri Lankan urban open public spaces, to understand how effectively existing public space designs support the maintenance of personal space while maintaining balanced social interaction.

To achieve this aim, the research is guided by the following objectives:

- To identify the current visibility level of urban public spaces that influence users' personal space.
- To understand users' spatial choices in urban public spaces, particularly how they maintain personal space.
- To derive recommendations for creating effective open public spaces that balance personal space creation, safety, and social interaction within the Sri Lankan urban context.

### 1.2 SCOPE AND LIMITATIONS

The scope of this study is to analyse how visibility within the built environment influences the creation of personal space in urban public spaces.

The study is limited to a single case study, which may restrict the generalizability of its findings to other contexts. Technological or digital aspects of privacy, such as CCTV or electronic sensors, were not examined in this research. The user behaviour across different seasons or during large public events is also beyond the scope of this research. Emotional states or individual health-related factors are not considered within the boundaries of this research.

## 2. LITERATURE REVIEW

### 2.1 PRIVACY AS A DYNAMIC PROCESS

Privacy is a complex concept that has been defined in multiple ways, ranging from legal to normative interpretations, each revealing different dimensions of the concept. Its theoretical foundations draw from philosophical, legal, and sociological perspectives. These different approaches emerge from fundamental differences in how privacy is

understood across cultures. For example, most European legislation treats privacy as a fundamental human right that must be protected (Solove, 2008), whereas in American contexts, privacy is often considered a commodity that can be traded and negotiated against other benefits and risks (Solove, 2008).

A major contribution to the understanding of privacy was made by Alan F. Westin, who explored the philosophical, sociological, and legal aspects of privacy in modern society. Westin argued that privacy should not be understood as a static "right to be left alone," but rather as a dynamic process of boundary regulation through which individuals manage their level of interaction with others (Westin, 1967).

According to Westin, individuals constantly move between four states of privacy:

- Solitude – being alone and free from observation
- Intimacy – privacy shared within close relationships
- Anonymity – being present in public without being personally identified
- Reserve – the psychological barrier individuals maintain to control personal information

These shifting states illustrate that privacy in everyday life is actively managed rather than fixed. Individuals constantly regulate their exposure to others in order to maintain control over their personal space and social interactions. Visibility is understood as the spatial condition that determines how much a user can see and be seen within the public space.

## 2.2 THE INDIVIDUAL DIMENSION OF PRIVACY

In public environments, the experience of privacy is closely connected to visibility and spatial perception. The way individuals position themselves in relation to others is often influenced by how visible or exposed they feel within a given environment.

The study of human spatial behaviour was significantly advanced by Edward T. Hall's Proxemics Theory, which examines how people regulate interpersonal distance to maintain comfortable levels of interaction (Hall, 1966).

*Table 1: Hall identified four primary zones of interpersonal distance*

| Zone | Distance | Description |
|---|---|---|
| Intimate Distance | 0–18 inches | Reserved for close emotional relationships such as partners and family. Uninvited entry into this zone is perceived as highly intrusive. |
| Personal Distance | 1.5–4 feet | Used in casual interactions with friends and relatives, allowing comfortable conversation while maintaining personal boundaries. |
| Social Distance | 4–12 feet | Maintained during formal or casual social interactions with acquaintances, colleagues, or strangers. |
| Public Distance | 12+ feet | Used in public settings such as lectures, performances, or observation, where interaction becomes more formal and impersonal. |

These spatial zones demonstrate how individuals naturally regulate distance to maintain psychological comfort (Altman, 1975). These conditions of comfort then shape observable user behaviour and spatial choices, such as where they sit, how far they remain

from others, whether they occupy edge zones, and how they position themselves within the space.

## 2.3 PRIVACY OF INTIMATE GROUPS IN PUBLIC ENVIRONMENTS

Privacy is not limited to individuals alone. It also extends to intimate pairs and small social groups, such as couples, families, and close friends. These groups operate as collective social units whose members share emotional and behavioural boundaries.

The sociologist Erving Goffman provides an important theoretical perspective through his concept of civil inattention, which explains how people acknowledge the presence of others in public while avoiding intrusive engagement. It provides a foundation for understanding how interactions surrounding these groups unfold in public environments. Outsiders acknowledge the presence of others, including intimate groups, while avoiding intrusive engagement (Goffman, 1963).

- Focused interaction - individuals are jointly engaged in a shared activity, conversation, or task. Within intimate pairs or groups, this type of interaction strengthens internal cohesion and reinforces shared boundaries.
- Unfocused interaction - individuals are merely in one another's presence without active engagement. In public settings, intimate groups often engage primarily in focused interaction among themselves while maintaining unfocused interaction with surrounding strangers.

Mutual civil inattention allows strangers to avoid intruding upon the internal dynamics of a group while still acknowledging their presence in socially appropriate ways.

## 2.4 VISIBILITY AND PRIVACY IN URBAN PUBLIC SPACES

In compact residential environments, particularly among apartment dwellers, leisure time is frequently spent in outdoor public spaces such as parks. Therefore, these spaces play a critical role in supporting both social interaction and psychological well-being. Research highlights that urban parks contribute to emotional well-being, social connectedness, and the reduction of loneliness among urban residents (Cheung & Jim, 2019; Kim & Jin, 2018). At the same time, users often seek locations within parks that allow them to regulate their visibility and level of social exposure (Asadpour et al., 2022).

The concept of Defensible Space, introduced by Oscar Newman, provides insight into how spatial organization can support both security and privacy. Newman argued that environments function more effectively when they are structured through a clear hierarchy of spaces, ranging from public to semi-public to private. Although originally applied to residential environments, this concept can also be extended to public parks. Similar hierarchical spatial transitions, such as moving from a busy street to the central open area, and finally to more secluded peripheral "urban pockets," enable park users to select settings that match their desired level of privacy. These layered spatial conditions allow users to select environments that match their desired level of visibility, interaction, and privacy (Newman, 1972).

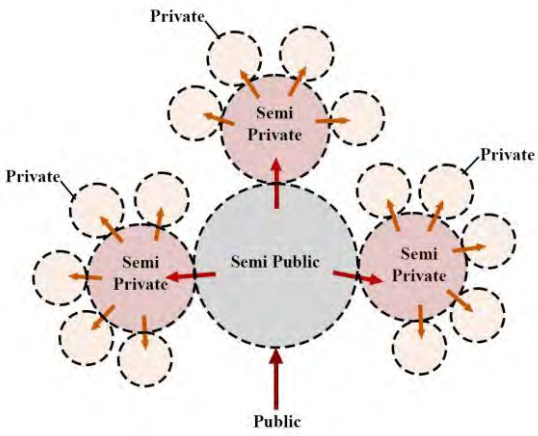



*Figure 1: Hierarchy/ gradient of space from public to semi-public to private (Source: Defensible Space; Crime Prevention Through Urban Design by Oscar Newman (Redrawn by authors))*

The literature review frames privacy in urban public spaces as a dynamic process of regulating exposure rather than achieving complete isolation. Within this process, visibility plays a significant role, as it shapes how users see others, how they are seen by others, and how comfortable they feel when occupying a particular space.

### 2.5 THEORETICAL FRAMEWORK

The theoretical framework of this study was arranged as follows. The framework is structured under two main aspects: the physical aspect and the social aspect.

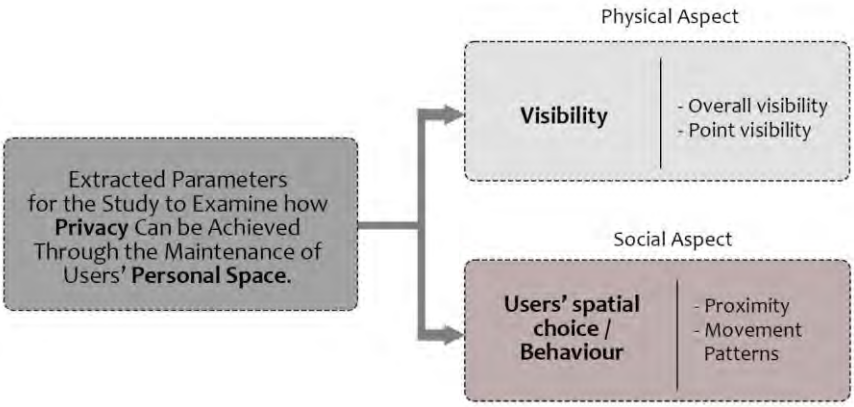



*Figure 2: Theoretical Framework for the Study (Source: By Author)*

## 3. METHODOLOGY

This study adopted a mixed-method approach combining spatial visibility analysis and behavioural observation. The methodology consisted of three main stages: first, analysing the visibility conditions of the selected nodes; second, recording user behaviour within the same spaces; and third, cross-analysing the two sets of parameters to identify the relationship between spatial visibility and users' creation of personal space.

*Table 2: Identified parameters, data collection methods, data types, and intended outcomes*

| | Parameter | Data Collection Methods | Data | Intended Outcome |
|---|---|---|---|---|
| Visibility | P1 - Overall Visibility | Space syntax mapping by the DepthMapX software | Visibility Graph Analysis (VGA) | Analyse the level of safety and segregation within the public spaces through visibility |
| | P2 - Point Visibility | Space syntax mapping by the DepthMapX software | Point Isovist map | |
| Users' spatial choice | P3 - Proximity | Observations Photographic documentation | Maintaining distance among groups and solo users | Understand the preferred physical distance between individuals or small groups |
| | P4 - Movement Patterns | Observations, Photographic, and video documentation | User movement types within the space | Understand whether dynamic or static movement patterns occur within the area |

User behaviour in public open spaces is influenced by spatial and environmental conditions; therefore, behavioural observations were compared with visibility conditions to understand how users selected, occupied, and moved through each node (Han et al., 2022). This cross-analysis helped identify whether users preferred highly visible central spaces, partially visible edge zones, or lower visibility shaded areas. It also allowed the study to examine whether static activities, such as sitting and intimate conversation, occurred more often in areas with controlled visibility, while dynamic activities, such as walking and passing through, occurred more often in highly visible areas.

Behavioural observations were conducted over three weekdays and one weekend day to capture both regular weekday use and weekend public-space use. On each observation day, data were collected during four time periods: morning from 9.00 a.m. to 12.00 noon, afternoon from 12.00 noon to 3.00 p.m., evening from 3.00 p.m. to 6.00 p.m., and night from 6.00 p.m. to 9.00 p.m. This allowed the study to observe variations in spatial use across different levels of activity, climate comfort, and user presence throughout the day.

Users were classified into main groups based on observable behaviour and group size. Individual users were recorded as single users occupying or moving through the space alone. Intimate groups were identified as pairs or small groups of 3–5 persons engaged in close social interaction. Large groups were defined as groups with more than 5 persons occupying or moving through the space together. These classifications helped compare how different user types responded to different visibility conditions. For this paper, the behavioural findings are presented as average observed patterns across the selected observation days and time periods, rather than as separate results for each time slot.

The number of users was not fixed and varied according to the time of day, day type, and level of activity within the site. Therefore, a fixed sample size was not predetermined. Instead, the study counted the selected observable user groups within each node during each observation period.

# 4. CASE STUDY

This case study examines a significant public space in Colombo, Sri Lanka, the Independence Square monument. The site is located within the Cinnamon Gardens area of Colombo 07, a zone known for its historical and prestigious urban character.

## 4.1 CASE STUDY SELECTION JUSTIFICATION

Independence Square was selected as the case study because it is a significant urban public space in Colombo that supports recreation, social interaction, pedestrian movement, and relaxation within a dense urban context. The site is used by different user groups, including individuals, intimate groups, local visitors, foreign visitors, and larger groups, making it suitable for observing personal space behaviour in a public setting.

## 4.2 NODE SELECTION

The spatial character of the case study area varies significantly across different parts of the site. The area consists of both built structures and landscape spaces, each offering different spatial conditions. Therefore, to improve the accuracy of the research, two distinct nodes were identified within the case study area for more detailed investigation.

- Node 1: Independence Memorial Hall

It represents a built architectural setting where visibility is shaped by columns, the elevated plinth, central open space, and peripheral edge zones. These elements create different degrees of exposure and enclosure, making the node suitable for examining how users respond to architectural control of visibility.

- Node 2: Independence Square Park

It represents a landscape-based public setting where visibility is influenced by tree canopies, shaded areas, pond ledges, pathways, and vegetated edges. This node allows the study to examine how softer landscape elements create controlled visibility and support personal space creation.

## 4.3 RESEARCH RESULTS

### 4.3.1 Visibility Parameters Analysis

**NODE 1**

**P1 – overall visibility**

The visibility of this node is analysed considering:

1. Visibility to the immediate neighbourhood
2. Visibility within the structure

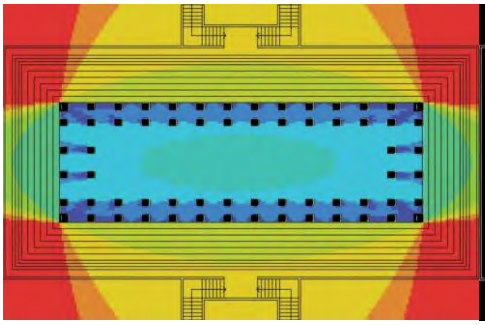


*Figure 3: Node 1 – VGA of exposure to exterior*

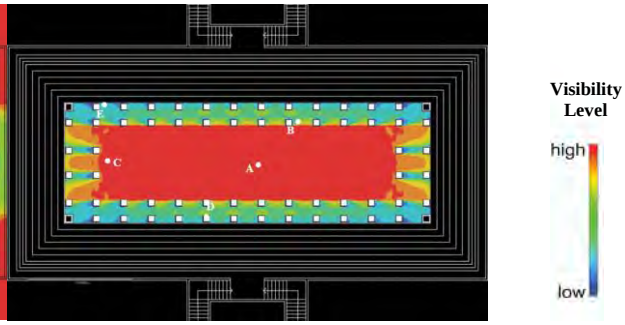



*Figure 4: Node 1 – VGA of the internal space*

According to the visibility graph in Figure 3, the peripheral edges of the structure are clearly visible from a distance. However, the central area of the hall is comparatively less visible from the immediate neighborhood due to the presence of large structural columns. The hall is situated on an elevated plinth, which significantly enhances its visibility from the surrounding urban context.

According to the visibility graph in Figure 4, the central area of the hall demonstrates the highest internal visibility, whereas the edge zones show comparatively lower visibility within the interior space. The column configuration and spatial layout of the hall primarily influence internal visibility.

**P2 – Point Visibility**

This approach enables an understanding of how visibility varies across space and its contribution to spatial perception and internal visual connectivity.

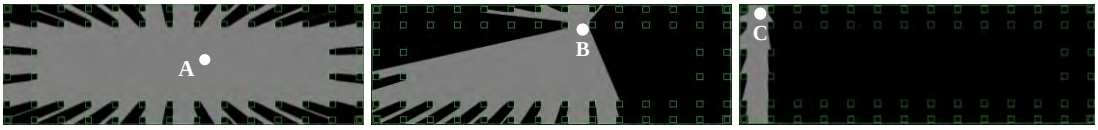



*Figure 5: Node 1 – Point Isovist maps of selected points*

Point A - Allows broader visual access across the interior.

Point B - Moderate level of visual access across the interior, compared to point A.

Point C - Visual access is low. There is very low outward visibility to other internal spaces from point C, and limited visibility directed toward point C from the surroundings.

**NODE 2**

**P1 – overall visibility**

On one side, the Independence Memorial Hall forms a visual barrier from Independence Avenue, while the remaining edges are largely enclosed by trees. Consequently, visual connections to the immediate vehicular road network are blocked.

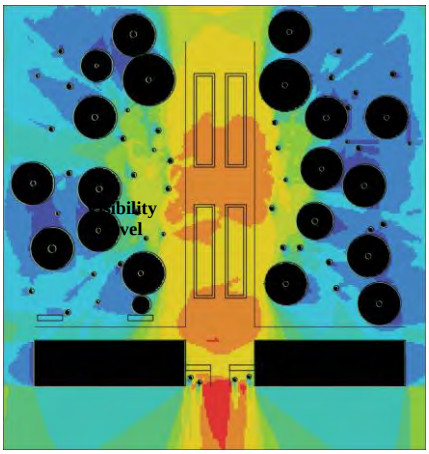


*Figure 6: Node 2 -VGA*

This area is surrounded by dense vegetation. At certain points, tree trunks are visible at eye level. However, in most locations, the tree canopy occurs at eye level, blocking direct sight. As a result, visibility toward the surrounding spaces is limited. According to the visibility graph, the open paved space within the node provides clear and unobstructed visual connections, confirming that although visibility to the surrounding areas is blocked, internal visibility within the node remains high.

**P2 – Point Visibility**

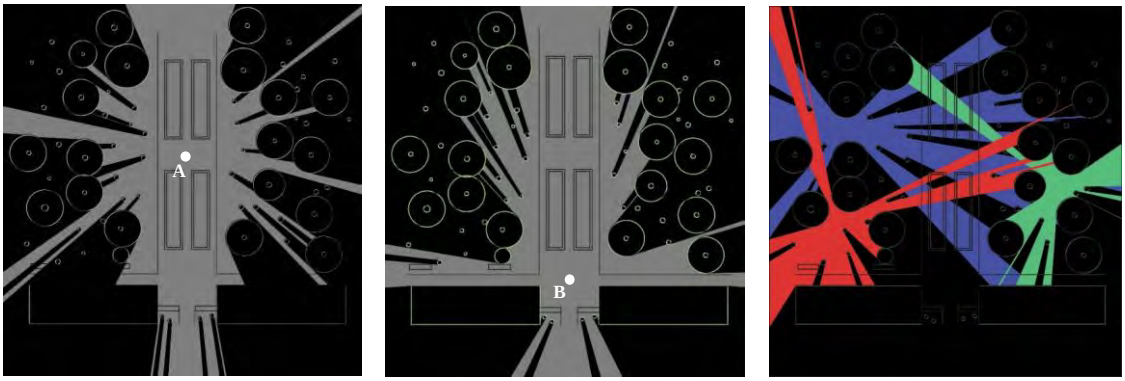



*Figure 7: Node 2 – Point Isovist maps of selected points*

Point A - Provides a straight visual connection from the Independence Memorial Hall to the Independence Walk.

Point B - Located at the intersection of two paths. Visibility is available in four directions, including the same direction as Point A and the perpendicular direction.

Comparatively less visual connectivity than point A and point B. Unpaved areas beneath the tree canopies, represented in blue, show comparatively limited visual connectivity.

### 4.3.2. Users' Spatial Choice Parameter Analysis

**NODE 1**

**P3 - Proximity**

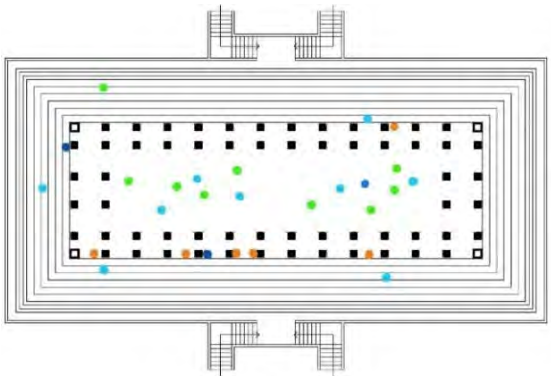


*Figure 8: Node 1 – Points where user groups mostly spend*

**P4 - Movement Patterns**

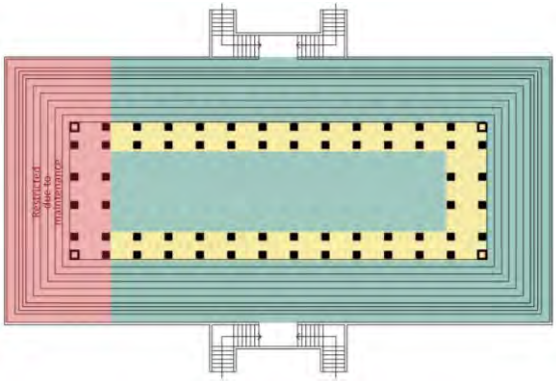



*Figure 9: Node 1 – Behaviour mapping*

- *Individuals*
- *Local Intimate groups*
- *Foreign Intimate groups*
- *Large groups*

*Preferred area of individuals and local intimate groups for static postures*

*Preferred area of large groups and foreign intimate groups for movements*

*Restricted area due to maintenance*

According to the collected data, individual users tend to occupy the peripheral areas of the hall. Similarly, local intimate groups are more likely to use the peripheral zones, often positioning themselves against the columns and leaning their backs on them. These users generally prefer the outer column ring rather than the inner ring. Large groups, however, do not remain seated for extended periods. They tend to spend most of their time in the central area of the space. Foreign intimate groups also show similar behaviour, preferring the central zone and remain for relatively short durations. When considering the time of day, no significant variation in spatial behaviour is observed. However, during the evening hours, the stepped areas are also used for seating, as the absence of direct sunlight improves thermal comfort and reduces discomfort.

## NODE 2

### P3 - Proximity

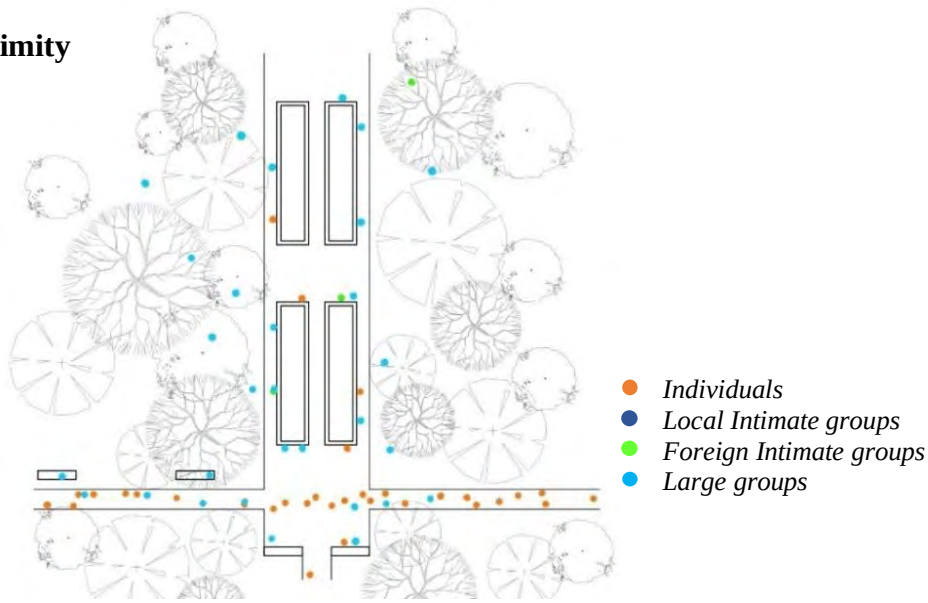



*Figure 10: Node 2 – Points where user groups mostly spend*

### P4 - Movement Patterns

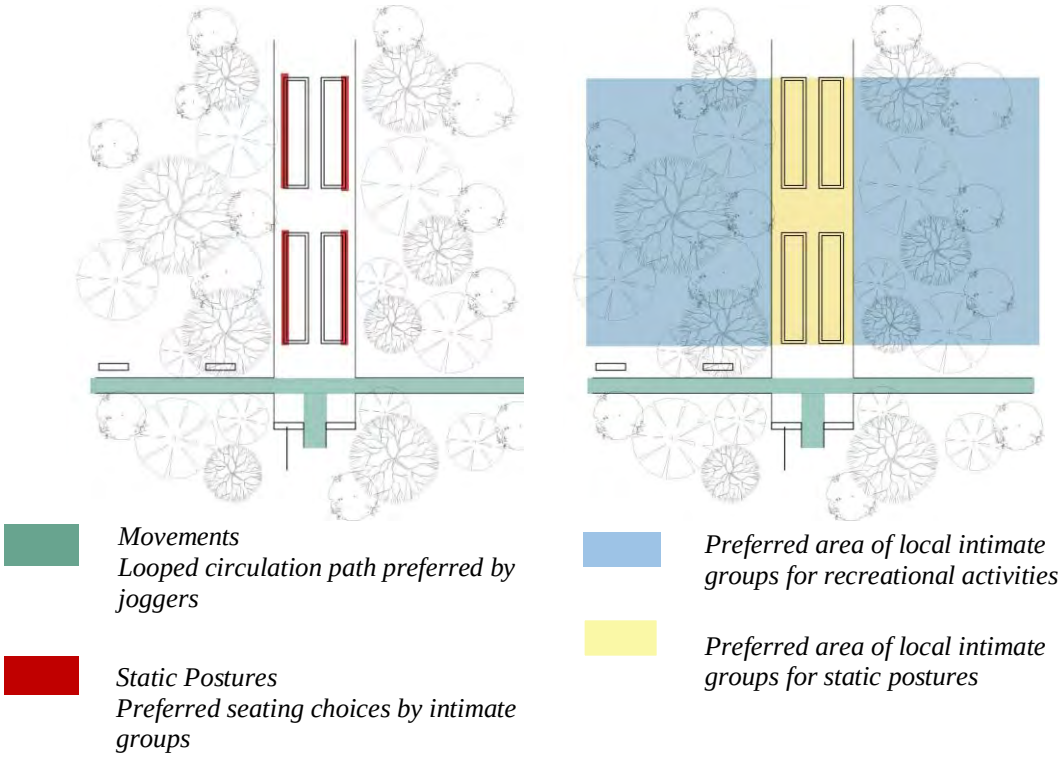



*Figure 11: Node 2 – Behaviour mapping*

According to the collected data, individual user movement is most prominent at the intersection of the two pedestrian paths along the Independence Walk. In contrast, the areas around the ponds show a higher occurrence of static activities, particularly seating. Users tend to select the pond ledges for sitting, with a clear preference for outward-facing

positions rather than inward-facing ones. The outermost pond ledges are used more frequently, as these areas are shaded and allow reduced interaction with nearby users, contributing to increased comfort and a sense of privacy.

In addition, the unpaved areas beneath the tree canopy are primarily used during the evening hours, when some intimate groups engage in activities such as playing and exercising. These shaded zones support group-based activities and provide an alternative spatial setting within the node.

## 4.4 FINAL DISCUSSION

Based on the analysis of the case study data, the following graphical summary illustrates the relationship between visibility levels and observed user behaviour.

According to the Visibility Graph Analysis data collected for each node,

*Table 3: Relationship between visibility levels and observed user behaviour.*

| Visibility Level | User Behaviour | State Type | State Intensity |
|---|---|---|---|
| High visibility | Walking, group activities, and short stays | Dynamic | |
| | | Static | |
| Medium visibility | Sitting, pausing, and casual interaction | Dynamic | |
| | | Static | |
| Controlled visibility | Resting, intimate conversation, and longer stays | Dynamic | |
| | | Static | |
| Low visibility | Perceived as unsafe or uncomfortable zones | | |

**NODE 1**

**Column configuration enhances internal visibility & experience**

The columns are the primary architectural-spatial mediator. Externally, they create a semi-permeable screen, making the hall partly visible while concealing its full activity.

Internally, they structure a hierarchy of space,

- The central void (high visibility): The column-free center offering panoramic views outward and being the most visually connected point inward. It is an active, social heart.
- The peripheral zones (Low Visibility): The spaces between and behind columns create niches of partial enclosure and privacy. This allows for smaller, intimate activities (resting, private conversation) within a major public hall.

**The elevated plinth establishes a realm of psychological privacy**

The raised platform visually separates the hall from the everyday flow of the city. This elevation creates a threshold of entry and supports the behaviour of small groups or individuals seeking a "spot of their own" without full isolation.

**NODE 2**

**Landscape character enhances visibility and experience**

This does not create private niches for individuals but establishes macro-scale privacy for the entire park collective. By severing visual ties to the enclosing roads and city, it generates a psychologically secluded realm.

The gradient of privacy

- High-exposure zone (paved pathways): For movement-based behaviour. Privacy is minimal, but the activity expects this.
- Medium-privacy zone (outer pond ledges): Users gain a degree of removal by positioning themselves at the edge, backed by water or vegetation, facing outward. They have a "territory" with a controlled view.
- Higher-privacy zone (shaded ground under trees): For social or focused group behaviour. The overhead canopy and tree trunks create a softer, more enveloping enclosure, allowing groups to feel separated.

This comparison confirms that personal space creation in urban public spaces depends not only on the level of visibility but also on how visibility is spatially structured. Architectural elements create more defined boundaries, while landscape elements create softer transitions.

### 4.5 RECOMMENDATIONS

The recommendations aim to strengthen existing spatial qualities to manage the visibility of space, allowing users to experience privacy within an open urban public setting.

**Node 1** – As a protected historical monument, major physical interventions are not appropriate. The existing architectural elements already help manage visibility and create varying degrees of visual exposure within the same setting. This node successfully demonstrates how architectural form alone can regulate visibility and achieve a sense of privacy within an open public setting.

**Node 2** – Privacy can be further enhanced by creating shaded edge zones that offer areas of reduced visibility. These shaded edges act as transitional zones between highly visible central areas and more secluded peripheral areas.

## 5. CONCLUSIONS

This study investigated the relationship between spatial visibility and the maintenance of privacy in urban open public spaces, using Independence Square in Colombo as a case study. While existing literature has predominantly emphasized visibility as a mechanism for safety and social interaction, this research demonstrates that visibility also functions as a critical mediator of privacy, a dimension increasingly relevant in contemporary urban life where individuals seek moments of withdrawal and personal reflection within public environments.

The research confirms that privacy in public spaces is not about complete visual obstruction but about providing users with choice and control over their visibility. Both architectural and landscape elements can successfully mediate this balance. For Node 1, the existing architectural form already demonstrates effective visibility regulation without requiring intervention. For Node 2, enhancing shaded edge zones as transitional spaces between high and low visibility areas would further support users' privacy needs.

These findings can inform design guidelines beyond the case study by highlighting the importance of controlled visibility. Architectural and landscape elements can be used to create partially enclosed spaces without producing unsafe hidden spaces. Such design strategies allow users to maintain personal space while remaining visually connected to the public environment.

Accordingly, urban public spaces should be planned with visibility gradients rather than uniform openness or complete enclosure. High-visibility areas can support movement, orientation, and public safety, while controlled-visibility areas can support sitting, resting, conversation, and longer occupation. This approach can help designers create public spaces that balance safety, social interaction, privacy, and user comfort in different urban contexts.

## REFERENCES

Altman, I. (1975). *The environment and social behavior: Privacy, personal space, territory, crowding.* Brooks/Cole Publishing Company.

Asadpour, H., Razmara, M., Heidari, A. A., & Taghipour, M. (2022). Privacy, patterns, and factors in urban open spaces: (Case study: Jannat Park in Shiraz City). *Megaron, 17*(2), 195–208. https://doi.org/10.14744/megaron.2022.98965

Cheung, P. K., & Jim, C. Y. (2019). Differential cooling effects of landscape parameters in humid-subtropical urban parks. *Landscape and Urban Planning, 192,* 103651. https://doi.org/10.1016/j.landurbplan.2019.103651

Goffman, E. (1963). *Behavior in public places: Notes on the social organization of gatherings*. Free Press of Glencoe.

Hall, E. T. (1966). *The hidden dimension*. Doubleday.

Han, S., Ye, Y., Song, Y., Yan, S., Shi, F., Zhang, Y., Liu, X., Du, H., & Song, D. (2022). A systematic review of objective factors influencing behavior in public open spaces. *Frontiers in Public Health, 10,* 898136. https://doi.org/10.3389/fpubh.2022.898136

Kim, D., & Jin, J. (2018). Does happiness data say urban parks are worth it? *Landscape and Urban Planning, 178,* 1–11. https://doi.org/10.1016/j.landurbplan.2018.05.010

Maslow, A. H. (1970). *Motivation and personality* (2nd ed.). Harper & Row.

Newman, O. (1972). *Defensible space: Crime prevention through urban design*. Macmillan.

Solove, D. J. (2008). *Understanding privacy*. Harvard University Press.

Westin, A. F. (1967). *Privacy and freedom.* Atheneum.

Pulasinghe, K.M., De silva, G.H.S.P., Vihindhuni, A.A.D.A.T. and Lokuge, A., 2026. The mind behind the machine: Mapping personality-based traits to entrepreneurial decision-making in construction SMES. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1735-1746. DOI: https://doi.org/10.31705/WCS.2026.126. Available from: https://ciobwcs.com/papers/

# THE MIND BEHIND THE MACHINE: MAPPING PERSONALITY-BASED TRAITS TO ENTREPRENEURIAL DECISION-MAKING IN CONSTRUCTION SMES.

**K.M. Pulasinghe[1], G.H.S.P. De Silva[2], A.A.D.A.T. Vihindhuni[3] and A. Lokuge[4]**

## *ABSTRACT*

*The management of entrepreneurial decisions is a factor of successful and sustainable entrepreneurial construction SMEs and is especially important in markets which are highly uncertain and competitive. But there are few studies that have studied the effect of personality-based traits on entrepreneurial decisions in construction SMEs. Therefor, this study investigates the influence of Big Five personality-based traits, (Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism), on entrepreneurial decision-making processes within Small and Medium Enterprises (SMEs) construction organisations in Sri Lanka. Following a comprehensive literature review, the data were collected from 45 managerial-level professionals in Sri Lankan construction SMEs by administrating a questionnaire survey assessing participants' Big Five personality profiles and entrepreneurial decision-making styles (creative thinking, information dependence, risk-taking, monitoring/evaluation, and decision framing). Data were analysed using descriptive statistics and Pearson's correlation coefficient. Key findings revealed that construction SME leaders exhibit high levels of Openness, Agreeableness, Extraversion and Conscientiousness, with comparatively lower Neuroticism. In decision-making, a strong reliance on information dependence and active monitoring was evident, with moderate engagement in creative thinking and risk-taking. Correlation analysis revealed that Conscientiousness demonstrated the strongest relationship with information dependence while Openness and Agreeableness showed moderate correlations with creative thinking. These findings confirm that specific personality configurations are prevalent among SME leaders and significantly shape their decision-making approaches. The insights offer valuable implications for developing targeted leadership training programmes and enhancing strategic planning in Sri Lankan construction SMEs.*

***Keywords:*** *Construction Industry; Entrepreneurial Decision-Making; Personality Traits; SME.*

## 1. INTRODUCTION

The construction industry claims an instrumental role in economic, environmental, and social sustainability, contributing significantly to the national infrastructure growth (Ali,

[1] Quantity Surveyor, Savinda Entreprises , Sri Lanka, manudileepulasinghe2001@gmail.com
[2] Senior Lecturer, Dept. of QS,SLIIT, Sri Lanka, Priyanwada.d@sliit.lk
[3] Student, Liverpool John Moores University, Sri Lanka, qs23890428@my.sliit.lk
[4] Academic Instructor, Dept. of QS,SLIIT, Sri Lanka, angel.o@sliit.lk

2021; Ardakani, 2013) with Small and Medium Enterprises (SMEs) making the primary influence. In the construction sector, SMEs account for the most business ventures in most regions (Mazzarol & Reboud, 2020). They are also recognised as key drivers of innovation, employment, and economic expansion (Stel et al., 2005; Bosma et al., 2018; Mazzarol & Reboud, 2020).

However, regardless of the context, these SMEs often operate in a resource-constrained, highly dynamic environment, making effective decision-making a critical factor for achieving competitive advantage. Therefore, in these organisations, where entrepreneurs often assume multiple leadership roles under high-pressure, uncertain conditions, understanding the internal drivers of decision-making has been treated as essential for their survival and success as decision making is widely recognised as a central and inseparable component of entrepreneurial activity.

The growing body of knowledge recognises decision-making as a core aspect of entrepreneurship, driving activities, goals, and performance outcomes (Ardakani, 2013). Ardakani and Avorgani (2021), say decision-making is the process by which entrepreneurs choose a course of action, and that is, based on internal judgement and external analysis, out of a number of possibilities, they select the way forward. It is defined as the process of selecting a specific solution (Easton, 1973), often characterised by complexity and sensitivity (Sidney et al., 2012). In the entrepreneurial context, decision-making is often high-stakes and time-sensitive, especially in dynamic environments such as SMEs in the construction sector.

There are various factors that influence decision-making. Among these factors, one that can significantly impact the success or failure of the entrepreneurial venture is the decision maker's personality traits. Personality is a defining characteristic that distinguishes individuals, encompassing personal qualities, emotional responses, and situational reactions (Matthews et al., 2003). Personality is often classified using "trait theories," which suggest that individual personalities are composed of broad dispositions. Among these theories, the Big Five model (OCEAN) categorises personality traits into five dimensions: *openness*, *conscientiousness*, *extraversion*, *agreeableness*, and *neuroticism* (McCrae & Costa, 1987).

Similar to the large-scale construction organisations, SMEs also face financial risks, project uncertainties, tight deadlines, and competing demands and therefore, the personality traits are the most important resource to fine tune the strategic decisions and increase business resilience and success. In this way, it is essential to comprehend how the individual characteristics of the personalities can affect decision-making in such situations because various traits can affect risk tolerance, ways of solving problems and coping with changing situations.

Despite the recognised importance of personality-based traits in entrepreneurship, there is limited evidence on their specific relationship with entrepreneurial decision-making in construction SMEs. Given the dynamic and uncertain nature of the construction industry, identifying the personality traits most beneficial to effective decision-making is critical for better leadership development in SMEs, strategic planning, and business performance. Furthermore, understanding the unique characteristics of individuals who create and manage these enterprises is crucial for supporting entrepreneurial activities and ensuring their success (Markman & Baron, 2003).

The significance of personality dimensions and entrepreneurial behaviours in the context of business in general has been explored in the previous studies, but there are very few empirical studies specially conducted on construction SMEs in developing countries like Sri Lanka. In addition, most studies have not investigated how the dimension of personality traits are related to each of the entrepreneurial decision making aspects such as creative thinking, dependence on information, risk taking, information monitoring and evaluation, and entrepreneurial decision framing Therefore, this research aims to explore the impact of personality-based traits on entrepreneurial decision-making processes in construction SMEs. The specific objectives are to: *(1)* review the different personality-based traits and their impacts on entrepreneurial decision-making processes in the construction industry; *(2)* examine the impact of each personality-based trait on the entrepreneurial decision-making processes in construction SMEs; and *(3)* establish a relationship between the impact of personality-based traits and entrepreneurial decision-making processes to improve the entrepreneurial success of construction SMEs.

# 2. LITERATURE REVIEW

## 2.1 ENTREPRENEURIAL DECISION-MAKING IN CONSTRUCTION SMES

Making the decisions involve choosing certain solution among possible alternatives (Easton, 1973, as cited in Ardakani and Avorgani, 2021). It is an essential element of professional and managerial work, which is often complex and sensitive as the issues at work are multifaceted (Sidney et al., 2012). Decision-making, as a cognitive phenomenon, is a complex process of collecting information, consulting, and assessing the possible results and uncertainties and concluding (Mooler et al., 2009).

In entrepreneurial contexts, this process becomes even more critical, as entrepreneurs must often make rapid and impactful decisions in high-pressure environments with limited resources. Decisions are widely recognised as a central and inseparable component of entrepreneurial activity, directly influencing the goals, direction, and performance of the business (Ardakani, 2013). Entrepreneurial decision making includes formulating sense of ambiguity, calculating risk and responding promptly to the arising chances or challenges characteristics that are very crucial in dynamic industries like construction.

Even decision making itself as a core entrepreneurial activity has been identified by many previous studies, but different factors have been identified for the influence on decision quality. Analytical reasoning, information availability and behaviours/personality are often emphasised by different researchers. This lacks consistency and this indicates the need for further study in specific industrial contexts, e.g., Construction SMEs.

## 2.2 THE BIG FIVE PERSONALITY TRAITS FRAMEWORK

The development of the Big Five personality traits was the result of research spanning several decades, with multiple studies contributing to the model. It is recognised as a robust framework for understanding personality structure (Goldberg, 1990; McCrae & John, 1992) and is instrumental in studying entrepreneurial behaviour. They are personality characteristics, both nature and nurtured, which provide useful information on individual behaviour and decision-making differences. This is because it has become one of the most elaborate and empirically evidenced theories of human personality.

These five traits represent basic dimensions of personality based on four key criteria: *temporal stability, cross-observer validity, cross-cultural presence*, and *biological foundations (*Costa & McCrae, 1992). Openness to Experience: this tendency is correlated with intellectual interest, creativeness, and readiness to be open to new concepts. Within the construction context, people who have a high level of openness are likely to adopt change and innovation (Lee and Foo, 2022)-conscientiousness: organised, disciplined and goal-oriented.

Within construction, this trait links with risk-averse behaviour and structured, well-planned approaches. *Extraversion:* describes energetic, sociable, and assertive individuals. Extraverted construction professionals are more likely to engage in risk-taking due to confidence and optimism. *Agreeableness*: Refers to being cooperative, empathetic, and compassionate.

Personality traits are more enduringly established traits which lead to behaviour in different situations. Entrepreneurial decision-making styles, on the other hand, have to do with the way people make business decisions. Personality qualities influence behavioural extractions, but decision-making styles are manifestations of the behavioural trends. It can thus be inferred those personals characteristics can be regarded as antecedents of entrepreneurial decision-making styles.

## 2.3 PERSONALITY TRAITS AND ENTREPRENEURIAL DECISION-MAKING

While personal factors influence the identification of problems or opportunities, choices are made in the decision-making process (Jones et al., 2018). Entrepreneurial decisions are unrestrained decisions or planned reactions concerning objects that affect an organisation's survival (Ardakani, 2013). Individuals engaging in entrepreneurial behaviour often exhibit specific personality traits, such as being opportunity-seeking, taking initiative, and making intuitive decisions (Jones et al., 2018). The author also identifies independence, locus of control, risk-taking, creativity, need for achievement, and self-confidence as determinants of entrepreneurial motivation (Jones et al., 2018).

Various personality traits are linked to entrepreneurial behaviour and decision-making, influencing everything from motivation and venture creation to opportunity recognition and firm performance. While specific studies show varied impacts depending on context and methodology, the consensus is that personality plays a crucial role in the entrepreneurial process (Zarnadze et al., 2022). In their study, Ardakani and Avorgani (2021) argued that decision-making is the core of entrepreneurial activities, which is reflected in entrepreneurs' behaviour. Furthermore, in their study of 65 entrepreneurs from SMEs in Iran, they found that access to and use of information had a statistically significant effect on decision-making. At the same time, risk-taking and creative thinking had no significant impact on decision-making in the Iranian context. Similarly, another study on the personality traits and risk attitudes among construction project practitioners in the Malaysian construction industry, Lee and Foo (2022), found that traits exist on a continuum and influence individuals' emotional and cognitive processing of risk. The authors also highlighted that extraversion and *neuroticism*, emotional instability, anxiety, and stress susceptibility involve strong affective elements, which align with emotional components of risk perception. Moreover, they highlighted that Individuals high in neuroticism are less likely to take risks, as they are more sensitive to potential negative outcomes.

There are limited studies that identify a relationship between personality characteristics mentioned and entrepreneurial decision making, but the results are varied. For instance, Ardakani and Avorgani (2021) reported that creative thinking and risk taking did not affect decision making while Lee and Foo (2022) noted that openness and risk attitude were crucial in the construction domain. The town and city results were contrasted, possibly suggesting that personality and decision-making are shaped by different contextual variables like industry characteristics and organisational size for towns compared to cities.

# 3. METHODOLOGY

## 3.1 RESEARCH DESIGN AND APPROACH

The author initiated the research with a comprehensive literature review of personality traits, their theoretical frameworks, and their influence on entrepreneurial decision-making in the construction industry referring to journal articles, books, conference papers, and other sources.

This research adopted a quantitative research design to investigate the influence of personality-based traits on entrepreneurial decision-making in construction SMEs. In light of literature findings, the author administered a questionnaire survey among managerial-level professionals in construction SMEs in Sri Lanka. These individuals include owners, directors, project managers, site managers, and other decision-makers actively involved in strategic and operational functions. The rationale for selecting this group is their direct engagement in entrepreneurial decision-making processes, which makes them highly relevant to the study's objectives. Out of the 65 questionnaires distributed, only 45 complete responses were received by the author and included in the analysis. The collected data were then analysed using descriptive statistical tools, such as weighted averages, percentage counts, means, etc., through 5-point Likert Scales and Pearson's correlation coefficient to examine relationships between variables.

The entrepreneurship and decision-making literature guided the selection of the entrepreneurial decision-making variables (creative thinking, information dependence, risk-taking, monitoring and evaluation, and decision framing) which are common variables used to measure entrepreneurial decision-making behaviour.

According to Kusmaryono et al. (2022), 90% of research uses Likert scales, which are recognised tools for measuring attitudes, concepts, and values. As shown in Table 1. The 5-point Likert scale enables the quantification of individual traits and decision-making styles. These Likert scales are based on two assumptions. These assumptions are the distance between "*strongly disagree/never*" and "*disagree/rarely"* is the same as the distance between "strongly agree/always" and "agree/often". Thereby, the distance between "*strongly disagree/never*" and "*disagree/rarely*" is five times less than the distance between "*strongly agree/always*" and "agree/often" respectively.

*Table 1: Likert scales*

| **Table 1a: Likert Scale for existence of Big Five personality traits** | | | **Table 1b: Likert Scale for decision making** | | |
|---|---|---|---|---|---|
| ***Value*** | ***Range*** | ***Scale*** | ***Value*** | ***Range*** | ***Scale*** |
| 1 | 1.00-1.08 | Strongly disagree | 1 | 1.00-1.08 | Never |

| Table 1a: Likert Scale for existence of Big Five personality traits | | | Table 1b: Likert Scale for decision making | | |
|---|---|---|---|---|---|
| ***Value*** | ***Range*** | ***Scale*** | ***Value*** | ***Range*** | ***Scale*** |
| 2 | 1.81-2.60 | Disagree | 2 | 1.81-2.60 | Rarely |
| 3 | 2.61-3.40 | Neutral | 3 | 2.61-3.40 | Occasionally |
| 4 | 3.41-4.20 | Agree | 4 | 3.41-4.20 | Often |
| 5 | 4.21-5.00 | Strongly agree | 5 | 4.21-5.00 | Always |

The interpretation scale for Pearson's correlation coefficient (r) was: $0 < r \leq 0.19$ = Very Low Correlation; $0.2 \leq r \leq 0.39$ = Low Correlation; $0.4 \leq r \leq 0.59$ = Moderate Correlation; $0.6 \leq r \leq 0.79$ = High Correlation; $0.8 \leq r \leq 1.0$ = Very High Correlation.

The sample size of 45 respondents was found to be satisfactory for exploratory analysis, but the results might not be entirely representative of the Sri Lankan construction SME population. Therefore, the results should be linked with the selected sample.

# 4. DATA ANALYSIS AND DISCUSSION

## 4.1 PARTICIPANT DEMOGRAPHICS

A total of 45 construction sector professionals of the Sri Lankan SMEs participated in filling in the questionnaire. The respondents were categorised into different positions such as directors, project and site managers, planning and operations managers, quantity surveyors, engineers (electrical, maintenance and systems) [PD3.1] and also architects. This diversity of participants achieved sufficient coverage of managerial and decision-making views of the industry. Majority of the respondents (60%) had 1 to 5 years' experience of managerial or entrepreneurial position, 21% had 6 to 10 years' experience. The SMEs reported were mainly of the 11-50 and 51-300 number of employee categories.

## 4.2 PERSONALITY-BASED TRAITS IN THE CONSTRUCTION CONTEXT

Table 2 presents the average scores for the Big Five personality traits among respondents.

*Table 1:Average scores for Big Five personality traits*

| Trait | Average Score |
|---|---|
| Openness to Experience | 4.36 |
| Conscientiousness | 4.34 |
| Extraversion | 4.36 |
| Agreeableness | 4.36 |
| Neuroticism | 3.20 |

Among all personality-based traits, openness to experience, extraversion and Agreeableness recorded the highest average score of 4.36, indicating that participants strongly agree that they tend to be creative, curious, and open to innovation, while also being cooperative, empathetic, and respectful toward others. The mentioned traits are especially useful and implemented and amused in the construction industry, where flexibility, cooperation, and problem-solving are needed. In the same way, participants established a strong agreement with an average of 4.34 that Conscientiousness came in second, and this implies that respondents tend to be always reliable, well organised and

goal oriented. Extraversion also scored relatively high with an average of 4.36, reflecting a strong tendency toward sociability, enthusiasm, and assertiveness.

The lowest average score was recorded in neuroticism with 3.20, which showed that the majority of the participants were at the neutral level which confirms that they possess emotional control and are not easily stressed and anxious. Low neuroticism is a good entrepreneurial and management characteristic especially in a demanding business such as construction since it helps to stay focused and more decisive in the face of uncertainty. The discussion demonstrates that the traits of the respondents are largely personality-based and able to influence successful entrepreneurial decision-making. This congruence supports the idea that these were the frequent attributes attributed to efficient entrepreneurial decision-making, especially in the construction SME industry, in line with the results presented by Salmony and Kanbach (2021).The findings align closely with prior research by Lee and Foo (2022), who examined the relationship between Big Five personality traits of pressure and risk attitudes in construction project practitioners in Malaysia. Their analysis has shown that openness to experience, conscientiousness and extraversion had a positive effect on risk-taking behaviour, but neuroticism had a negative effect on it. These patterns are consistent with the present study's results, which show that participants with higher scores in openness, conscientiousness, and extraversion demonstrated more confident and adaptive decision-making behaviours.

## 4.3 ENTREPRENEURIAL DECISION-MAKING STYLES

Table 3 presents the average scores for entrepreneurial decision-making qualities among respondents.

*Table 2:Average scores for entrepreneurial decision-making qualities*

| Decision-Making Quality | Average Score | Interpretation |
|---|---|---|
| Creative Thinking | 3.71 | Often rely on creative ideas |
| Information Dependence | 4.44 | Always seek relevant information |
| Risk-Taking | 3.56 | Often take risks |
| Monitoring, Modifying, and Evaluating | 4.34 | Often revise decisions after reflection |
| Decision Framing | 3.83 | Often influenced by how situations are framed |

As the data shows, the population confirmed that the managerial-level professionals of SMEs always want to find relevant information prior to decision-making, or are information-dependent, and this measure stands at the top of all the measured qualities. It indicates that there is a high tendency of the participants to obtain correct and useful information prior to the decision-making process of the business. This informed decision preference within the high- risk and details driven construction business improves the planning, risk management and performance reliability. The information also revealed that Sri Lankan professionals usually change their mind after consideration, and this fact demonstrates their potential to become better with the experience. It will imply that the participants actively evaluate the outcomes of decisions and are willing to change the strategies when it is needed. Moreover, such professionals are prone to framing situations, being guided by creative ideas and risk-taking, and average scores of 3.83, 3.71 and 3.56 respectively. reliance on critical ideas. Both studies heavily depend on the role of

information dependence in the decision-making process as compared to the study by Ardakani and Avorgani (2021) in the construction industry in Malaysia. The current study has shown that the mean level of the selected participants was 4.44, which corresponds to a conclusion made by Ardakani and Avorgani according to which information plays a significant role in the process of making entrepreneurial decisions. Nonetheless, there are differences that can be observed on the creative thinking. Although the results of the article by Ardakani and Avorgani (2021) revealed that the effect of creative thinking on the decision-making process was not significant, the respondents in the present study achieved the mean score of 3.71, which indicates that they frequently refer to creative methods. Similarly, the dimension of risk-taking had different results, with the current results showing moderate uncertainty comfort.

## 4.4 PERCEIVED INFLUENCE OF BIG FIVE TRAITS ON DECISION-MAKING

Table 4 presents the average scores for perceived influence of Big Five traits on decision-making.

*Table 3:Average scores for perceived influence of Big Five traits*

| Trait | Average Score | Interpretation |
|---|---|---|
| Openness to Experience | 4.34 | Considered highly influential |
| Conscientiousness | 4.41 | Most influential trait |
| Extraversion | 4.20 | Important for proactive leadership |
| Agreeableness | 4.29 | Valued for promoting harmony |
| Neuroticism | 3.22 | Least influential |

Conscientiousness has the highest average of 4.41, reflecting strong agreement that organisation, diligence, and goal-oriented behaviour play a critical role in entrepreneurial decisions. Given the structured and deadline-sensitive nature of construction projects, this result aligns with expectations. Extraversion (4.20), Openness to Experience (4.34) and Agreeableness (4.29) were highly rated, as well. Neuroticism is the least average score with 3.22 which showed that a substantial number of respondents consider emotional instability and stress sensitivity to not help or even to be a disadvantage in good decision-making.

## 4.5 RELATIONSHIP BETWEEN PERSONALITY TRAITS AND DECISION-MAKING STYLES IN SRI LANKAN SMES

Table 5 presents Pearson's correlation coefficients between personality traits and entrepreneurial decision-making factors.

*Table 4:Pearson's correlation coefficients between personality traits and decision-making factors*

| Trait | Creative Thinking | Information Dependence | Risk-Taking |
|---|---|---|---|
| Openness to Experience | 0.49 (moderate) | 0.25 (low) | 0.11 (very low) |
| Conscientiousness | 0.07 (very low) | 0.52 (moderate) | -0.18 (very low) |
| Extraversion | 0.33(low) | 0.30 (low) | 0.13 (very low) |
| Agreeableness | 0.41 (moderate) | 0.35 (moderate) | -0.09 (very low) |

| Trait | Creative Thinking | Information Dependence | Risk-Taking |
|---|---|---|---|
| Neuroticism | 0.15 (very low) | 0.07 (very low) | -0.13 (very low) |

The analysis shows that there are moderate positive correlations between a number of personality traits and decision-making variables. The correlation of Openness to Experience with creative thinking is moderate (r = 0.49), which indicates that people with imaginative minds and inclined to new experiences are likely to be more involved in innovative opinion making. This implies a moderate relation between agreeableness and creative thinking (r = 0.41) and information dependence (r = 0.35) albeit in the lower category of correlation. The closest medium correlation is found to exist between the Conscientiousness and information dependence (r = 0.52), which shows that organised and disciplined people depend much on the correct data in making decisions. Extraversion exhibits low correlations with the three decision-making traits namely the creative thinking (r = 0.33), information dependence (r = 0.30), and the risk-taking (r = 0.13), indicating a low intensity of the relationship. Neuroticism poses very low to negative correlations among all the decision - making characteristics especially risk taking (r = -0.13) meaning that emotionally unstable subjects may not be more willing to come up with entrepreneurial risk. The results of correlation evidence the theoretical framework identified by Hillson and Murray-Webster (2007) that stated the risk attitude as a response to uncertainty, which does matter, highly dependent on the individual perception. The Conscientiousness-information dependence positive relationship is consistent with Sadler-Smith et al. (2003), who described the entrepreneurial managerial behaviours as a culture of creativeness and risk-taking with opportunity-focused and adaptive behaviours being heavily conditioned by personality traits.

This implies that highly conscientious SME leaders are better inclined to systematically collect and analyse information before decision making in the business, which yields low level of uncertainty and quality decision making.

Openness, Suggests a moderate correlation between openness and creative thinking enables people to consider new ideas more likely to possibly think of new ways to solve business problems. The negative correlation between neuroticism and risk-taking highlights a tendency for some people to forgo entrepreneurship because of fear of risk and uncertainty.

## 4.6 DISCUSSION OF FINDINGS

The results prove that the personality traits play an important role in the decision-making process of the entrepreneur of construction SMEs, particularly in times of uncertainty. These scores of *Openness to Experience* and *Conscientiousness* are also too high according to the entrepreneurial personality profile depicted in the literature (Salmony and Kanbach, 2021). The significance of being organised, disciplined in the decision-making process in the construction industry that require paying attention to detail and planning is strengthened by the high correlation between Conscientiousness and information dependence (r = 0.52). The medium-size relationship between Openness and creative thinking (r = 0.49) confirms the argument put forward by Lee and Foo (2022) that the concept of openness pushes people toward facing uncertainty and new experiences. This feature seems to be especially helpful in construction SMEs, and innovative solution should be found to solve complicated project issues. In the same way,

the relationship between agreeableness and creative thinking (r = 0.41) indicates that cooperative and empathetic people might be more willing to hear different points of view, and this approach to creative problem-solving can be improved. The association between Neuroticism and the negative outcomes in the various dimensions of decision making (r = -0.13) of risk-taking, the inference is that emotional constancy is critical in making effective choice in a highly experienced construction setting. This observation is consistent with the results of Lee and Foo (2022) who observed that high neuroticism individuals have low risk-taking because they are sensitive to the possible adverse consequences. The findings indicate that though some personality traits moderate the decision-making styles, others have a less or even negative impact particularly construction SMEs entrepreneurial behaviour. These implications apply to practicability to leadership development processes, meaning that interventions might target improvement of characteristics of positive decision-making performances.

Hence the second aim of the study "Indirect effect of individual personality traits on entrepreneurial decision-making dimensions" was also fulfilled. Moreover, the achievement of Objective 3 was made by using correlation analysis to show the measurable correlation between personality-based traits and entrepreneurial decision-making styles.

## 5. CONCLUSIONS AND RECOMMENDATIONS

The study examined how attitudes of personality-based traits affect the decision-making of an entrepreneur in construction SMEs in Sri Lanka. The research aimed at achieving the three objectives of the study was achieved. Firstly, the literature review ensured that the Big Five personality dimensions are a resilient construct in explaining entrepreneurial behaviour whereby entrepreneurs have generally high scores on Openness and Conscientiousness and low scores on Neuroticism (*Objective 1*). Second, the quantitative results showed that the Openness, Agreeableness, Extraversion and Conscientiousness are high among construction SME leaders, and the levels of Neuroticism were lower. All of the traits had different effects on the decision-making processes, with Conscientiousness producing the strongest influence on information dependence, and Openness and Agreeableness having connexions to creative thinking (*Objective 2*). Third, correlation analysis has revealed statistically significant correlations of personality characteristics with decision making qualities proving that certain personality set ups are extremely powerful in defining decision-making styles and can be used to formulate strategies in enhancing the entrepreneurial outcomes (*Objective 3*).

The study builds on previous works in the field by expanding the use of the Big Five personality framework into the construction SME sector which is not well studied in entrepreneurship research. In practice, the results will inform entrepreneurial decision-making traits of personality for the user which include SME owners, managers and leadership development programmes.

For the recommendations Suggest that,

For SME Leaders,

- Promote evidence-based decision-making processes.
- Leadership development initiatives – open, conscientious and adaptive thinking.

- Utilise personality assessments in leadership development programs.

For Policymakers

- Provide support SME leadership development initiatives.
- Launch of entrepreneurship building programs focused on decision making skills.
- Organize knowledge sharing forums for management of SMEs.

## 6. ACKNOWLEDGEMENTS

Authors would express sincere gratitude to the industry professionals who generously contributed their time and expertise by participating in the questionnaire survey. Their practical insights and perspectives provided valuable data and greatly enriched this study. The authors also acknowledge the support of Liverpool John Moores University (LJMU) and SLIIT the affiliated academic partners, LJMU for providing the necessary academic resources and support that enabled the successful completion of this research.

## 7. REFERENCES

Ali, I. F. (2021). Contribution of construction SMEs to sustainable development in Nigeria. *International Journal of Small Business and Entrepreneurship Research*, *9*(3), 22–38.

Ardakani, M. F. (2013). Decision making in entrepreneurship. *Journal of Entrepreneurship and Business Innovation*, *5*(1), 1–12.

Ardakani, M. F., & Avorgani, R. K. (2021). Decision making of entrepreneurs in Small and Medium-Sized Enterprises(SMEs). *International Journal of Academic Research in Business and Social Sciences*, *11*(3). https://doi.org/10.6007/ijarbss/v11-i3/8933

Bosma, N., Content, J., Sanders, M., & Stam, E. (2018). Institutions, entrepreneurship, and economic growth in Europe. *Small Business Economics*, *51*(2), 483–499. https://doi.org/10.1007/s11187-018-0012-x

Costa, P. T., & McCrae, R. R. (1992). Four ways five factors are basic. *Personality and Individual Differences*, *13*(6), 653–665. https://doi.org/10.1016/0191-8869(92)90236-i

Easton, A. (1973). Complex managerial decisions involving multiple objectives. In *Medical Entomology and Zoology*. http://ci.nii.ac.jp/ncid/BA04472796

Goldberg, L. R. (1990). An alternative "description of personality": The Big-Five factor structure. *Journal of Personality and Social Psychology*, *59*(6), 1216–1229. https://doi.org/10.1037/0022-3514.59.6.1216

Hillson, D., & Murray-Webster, R. (2007). *Understanding and managing risk attitude*. Gower Publishing. https://doi.org/10.4324/9781315235448

Jones, P., Klapper, R., Ratten, V., & Fayolle, A. (2018). Emerging themes in entrepreneurial behaviours, identities and contexts. *International Journal of Entrepreneurship and Innovation*, *19*(4), 233–236. https://doi.org/10.1177/1465750318772811

Kusmaryono, I., Wijayanti, D., & Maharani, H. R. (2022). Number of response options, reliability, validity, and potential bias in the use of the Likert Scale Education and Social Science Research: A Literature review. *International Journal of Educational Methodology*, *8*(4), 625–637. https://doi.org/10.12973/ijem.8.4.625

Lee, C. K., & Foo, M. Y. (2022). Risk attitudes and the big five personality traits: a study on construction project practitioners in Malaysia. *International Journal of Construction Management*, *22*(13), 2435–2445. https://doi.org/10.1080/15623599.2020.1793506

Markman, G. D., & Baron, R. A. (2003). Person–entrepreneurship fit: why some people are more successful as entrepreneurs than others. *Human Resource Management Review*, *13*(2), 281–301. https://doi.org/10.1016/s1053-4822(03)00018-4

Matthews, G., Deary, I. J., & Whiteman, M. C. (2003). *Personality traits* (2nd ed.). Cambridge University Press.

Mazzarol, T., & Reboud, S. (2020). *Entrepreneurship and innovation: Theory, practice and context* (4th ed.). Springer.

McCrae, R. R., & Costa, P. T. (1987). Validation of the five-factor model of personality across instruments and observers. *Journal of Personality and Social Psychology, 52*(1), 81–90. https://doi.org/10.1037/0022-3514.52.1.81.

McCrae, R. R., & John, O. P. (1992). An introduction to the Five-Factor model and its applications. *Journal of Personality*, *60*(2), 175–215. https://doi.org/10.1111/j.1467-6494.1992.tb00970.x

Mooler, C., Townsend, M., & Pryor, K. (2009). Entrepreneurial decision-making in SMEs. *Journal of Small Business and Enterprise Development*, *16*(3), 399–414.

Sadler–smith, E., Hampson, Y., Chaston, I., & Badger, B. (2003). Managerial behavior, entrepreneurial style, and small firm performance. *Journal of Small Business Management*, *41*(1), 47–67. https://doi.org/10.1111/1540-627x.00066

Salmony, F. U., & Kanbach, D. K. (2021). Personality trait differences across types of entrepreneurs: a systematic literature review. *Review of Managerial Science*, *16*(3), 713–749. https://doi.org/10.1007/s11846-021-00466-9

Sidney, J., Barton, J., & Khan, M. (2012). The complexity of decision-making in construction projects. *Construction Management and Economics, 30*(8), 645–658.

Van Stel, A., Carree, M., & Thurik, R. (2005). The effect of entrepreneurial activity on national economic growth. *Small Business Economics*, *24*(3), 311–321. https://doi.org/10.1007/s11187-005-1996-6

Zarnadze, G., Dika, I., Çera, G., & Ribeiro, H. N. R. (2022). Personality traits and business environment for entrepreneurial motivation. *Administrative Sciences*, *12*(4), 176. https://doi.org/10.3390/admsci12040176

Madhuwantha, H.W.G.V., Sridarran, P. and Maddakandage, M.N.U., 2026. The need for reforming green rating systems for hospitals in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1747-1760. DOI: https://doi.org/10.31705/WCS.2026.127. Available from: https://ciobwcs.com/papers/

# THE NEED FOR REFORMING GREEN RATING SYSTEMS FOR HOSPITALS IN SRI LANKA

**H.W.A.G. Madhuwantha[1], P. Sridarran[2] and M.N.U. Maddakandage[3]**

## *ABSTRACT*

*The healthcare sector combines a significant environmental footprint with strict operational and safety requirements. Although green building rating systems such as LEED, and GREENSL promote sustainability, they typically assess hospitals using the same criteria as other building types. However, hospitals require specialized considerations such as infection control, biomedical waste management, specialized ventilation and continuous operations, which are insufficiently addressed in general GBRS. This creates a research gap, as general GBRS may not adequately address the unique requirements of healthcare facilities in developing countries like Sri Lanka. Therefore, this study evaluates the appropriateness of general GBRS for hospital buildings. A qualitative single case study approach was adopted focusing on Sri Lanka's only green-certified private hospital, which achieved Gold certification under the GREENSL rating. Data were collected through semi-structured interviews with three key stakeholders and on-site observations. A comparative assessment was conducted by applying the IGBC Green Healthcare Rating to the same hospital to evaluate whether it could retain its Gold certification under a healthcare-specific framework. The findings identified that strategic leadership, financial benefits, and green technology implementation supported sustainability adoption, while retrofitting aging infrastructure, operational constraints due to 24-hour healthcare services and limited government support created challenges. The comparative analysis revealed a performance gap, with the hospital scoring 68% (Gold) under GREENSL but only 60% (Silver) under IGBC criteria. Deficiencies were observed in areas such as infection control, medical waste management, specialized ventilation, acoustic design, and healing architecture. The study highlights the need for healthcare-specific green building assessment frameworks for Sri Lanka.*

***Keywords:*** *Green Buildings; Green Building Rating Systems; Healthcare facilities; Hospital Buildings; Sustainability.*

## 1. INTRODUCTION

The green building concept (GBC) is being developed at greater velocity due to the adverse environmental impacts of construction (Ding et al., 2018). The goal of designing

[1] Researcher, Department of Building Economics, University of Moratuwa, Sri Lanka, madhuwanthahwag.20@uom.lk
[2] Head of the Department, Department of Facilities Management, University of Moratuwa, Sri Lanka, psridarran@uom.lk
[3] Lecturer, Department of Facilities Management , University of Moratuwa, Sri Lanka, nadeeraum@uom.lk

healthy indoor environments for humans drives the construction of green buildings (Allen et al., 2015). The implementation of the green concept in hospitals while improving planning, development, services, repair and disposal mitigate health and environmental impacts (Khairunnisa et al., 2022). Implementing greenery into healthcare facilities contributes to the sustainable development aims by mitigating health, environmental, and economic drawbacks (Kalender-Smajlović & Dovjak, 2023).

Application of the green concept can be challenging. The hospitals differ from all other building categories since they need to operate 24/7 and, correspondingly require certain energy-intensive systems. For example, HVAC and lighting are continuously operating to support patient care and safety (Tomanek, 2024). Hospitals face numerous barriers to implementing environmentally sustainable practices. According to the Health Facilities Management (HFM), the American Society for Healthcare Engineering (ASHE), and the Association for the Healthcare Environment (AHE) the top barriers are conflicting priorities for investments or expenditures, insufficient staffing for projects, inadequate funding for operations and maintenance budgets, the perception of higher costs compared to traditional materials or systems, and time constraints (Dhillon & Kaur, 2015). While the concept of sustainability has been effectively used in industrial companies, there has not been adequate research done on its acceptance in the healthcare sector (Tushar et al., 2023). In Sri Lankan context, the examine on transferring hospital buildings towards GBC is significantly less (Dilrukshi et al., 2014).

With the ongoing evolution of green building rating systems (GBRS), the requirement for a healthcare-specific GBRS has also been recognized globally (Huang et al., 2022). However, Sri Lanka continues to rely on the general green building framework that treats hospitals as a traditional commercial building. This approach creates a significant gap between the theoretical application of green principles and the practical requirements of healthcare facilities (Tomanek, 2024). The existing GREENSL system lacks specialized criteria for managing complex biomedical waste streams, infection control protocols, and medical equipment energy loads that are basic needs for hospital operations (Abeysinghe et al., 2023). Furthermore, hospitals often have different energy and water requirements, safe ventilation requirements, high energy consumption, 24/7 operations, and programmatic relationships with other buildings that make pursuing strong efficiency challenging, applying general GBRS to healthcare projects (Tomanek, 2024). The basic issue is applying a general GBRS to hospitals creates a contrast between certification requirements and operational realities, resulting in missed opportunities for improved patient outcomes and operational efficiency (Golbazi & Aktas, 2020). In Sri Lanka, the examination of transferring hospital buildings towards GBC is significantly limited, and most healthcare providers neglect the psychosocial aspects of healthcare delivery (Dilrukshi et al., 2014). This gap limits the effectiveness of green initiatives in healthcare and compromises patient safety, staff well-being, and the overall sustainability goals of the healthcare sector (Tseng et al., 2020). Therefore, the aim of this study is to evaluate appropriateness of general GBRS to hospital buildings in Sri Lanka. This research is crucial in establishing a healthcare-centric GBRS, that addresses the unique challenges and priorities of healthcare facilities.

## 2. LITERATURE REVIEW

Green building practices will do aim to decrease ecological footprints while increasing occupant well-being and reducing operational costs (Zitars et al., 2021). These principles

are especially key in healthcare where the physical environment can directly impact patient recovery and productivity of staff (Chías & Abad, 2017). Therefore, the application of green concepts to hospital design has become an integral part of sustainable development in healthcare (Ding et al., 2018). Developments like intelligent energy control systems, green roofs, and biophilic designs have increased the utility and attractiveness of green buildings (Akpan Umoh et al., 2024).

The building sustainability was assessed globally with the establishment of the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990 and the Leadership in Energy and Environmental Design (LEED) green building standard in 1998, which established quantitative metrics to assess the sustainability of buildings (Christensen et al., 2011). Developed countries such as USA and UK have highly adopted with frameworks such as LEED and BREEAM. However, there are issues in developing countries like low awareness, high initial cost, and lack of technical knowledge (Shan & Hwang, 2018). The GREENSL Rating System was localised for Sri Lanka, while meeting international requirements. However, that there is significant scope available in Sri Lanka to enhance healthcare sustainability using green buildings (Dilrukshi et al., 2014). Zitars et al. (2021) explained green hospitals will lead to environmental sustainability along with better patient outcomes, staff well-being, and operational efficiency.

## 2.1 ANALYSIS OF EXISTING GREEN BUILDING RATING SYSTEMS

Green Building Rating Systems (GBRSs) are optional, market-oriented criteria that evaluate and validate the level of sustainability of buildings (Marchi et al., 2021). The Building Research Establishment Environmental Assessment Method (BREEAM), the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), and Leadership in Energy and Environmental Design (LEED) are the most popular and representative green assessment techniques.

### 2.1.1 Building Research Establishment Environmental Assessment Method

BREEAM is the measure of best practice in environmental design and management, adopted by the U.K. government (Haapio & Viitaniemi, 2008). UK building regulation is used by the energy efficiency assessment as a basis from which to assess improved levels of performance (Awadh, 2017). It classifies aspects of credits based on building impact to the environment such as management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology (Haapio & Viitaniemi, 2008). It evaluates management practices in the entire lifecycle of the building and focuses on environmental stewardship (Marchi et al., 2021).

### 2.1.2 Leadership in Energy and Environmental Design (LEED)

LEED was developed by the U.S. Green Building Council, is one of the most widely recognized green building certifications around the world. It assesses buildings in categories such as energy efficiency, water conservation, indoor air quality, materials selection and innovation (Marchi et al., 2021). LEED certification can be awarded at four levels, Certified, Silver, Gold, and Platinum, depending on points scored (Shan & Hwang, 2018). LEED can be applied to any type of building, whether commercial, residential or in a health care setting. However, costly certification, and the heavy process on documentation, posing hurdles for small-scale projects and in developing countries (Awadh, 2017). LEED-certified health care buildings have been reported to have lower

operational costs, enhanced quality of indoor environmental, and increased employee productivity (Golbazi & Aktas, 2020).

#### 2.1.3 Comprehensive Assessment System for Built Environment Efficiency

CASBEE, which was developed in Japan, assesses buildings through a distinctive balance of environmental load reduction and occupant comfort. It has a new scoring system that puts buildings into four levels -C (Poor), B-, B+, and S, which stands for Excellent (Mahan & Khorramrouei, 2023). Nevertheless, CASBEE's usage is mainly confined to Japan, and its metrics need further adaptation for use in varied climatic environment. This system is suitable for applications like residential and commercial and public buildings (Mahan & Khorramrouei, 2023).

#### 2.1.4 GREENSL

GREENSL is the indigenous Sri Lankan green building rating system, focused on meeting the unique climatic, economic and social contexts of the country (Moramudali & Manawadu, 2022). Yet, adoption is limited by lack of awareness and incentives, especially in industries like healthcare (Dilrukshi et al., 2014). This system includes requirements including energy-efficient designs suitable for tropical climates, the use of locally sourced materials, and water management strategies (Gurupatham et al., 2024). GREENSL offers some localized solutions, but does not quite fit with the daily operational needs of a hospital (Dilrukshi et al., 2014).

Although BREEAM, LEED, CASBEE, and GREENSL all promote environmental sustainability, their assessment priorities differ according to regional, climatic, and operational contexts. Most general GBRSs primarily emphasize environmental and energy performance, while comparatively less attention is given to healthcare-specific operational requirements.

### 2.2 GENERAL GREEN BUILDING RATING SYSTEMS VERSUS HEALTHCARE-SPECIFIC GREEN RATING SYSTEMS

For hospital buildings, which have a unique building operation that goes beyond a typical building operation, there is a need for a GBRS that is more specifically designed than a typical GBRS (Marchi et al., 2021). Indian Green Building Council (IGBC) has been able to identify these unique needs and develop a GBRS specifically for healthcare facilities.

#### 2.2.1 IGBC Green Healthcare Rating System

The unique operational requirements of a hospital include 24/7 operations, critical life-support systems, stringent hygiene protocols and mandatory energy and environmental control requirements compared to similar commercial buildings (Tomanek, 2024). In response to these issues, the IGBC healthcare Facilities rating system can be introduced as an important healthcare-specific GBRS specifically designed for healthcare facilities. This has been designed in the Asian country of India and supports the construction of hospitals in an environmentally friendly manner and the remodelling of existing hospitals to promote healthcare services that are rapidly becoming popular in India (Thapa, 2017). According to Indian Green Building Council (2020), this GBRS has been designed for both air-conditioned and non-air-conditioned healthcare facilities and covers all facilities such as sub-centres, primary health centres, community health centres, district hospitals, clinics, private hospitals and medical institutions. IGBC has been created under 6 essential elements for healthcare facilities. They are, indoor environment quality,

sanitation and hygiene, energy efficiency, water conservation, site selection and planning, Building materials and resources, and innovation design process. This rating system is different from the general GBRS because it has been designed with close attention to the comfort and safety of patients (Sonavane & Mane, 2023).

Thus, the literature suggests that green hospital concepts extend beyond environmental conservation and contribute directly to therapeutic outcomes and staff performance. This demonstrates an interrelationship between building sustainability and patient-centred care, where physical environmental quality becomes part of the healthcare delivery process itself.

## 2.3 GREEN HOSPITALS AND PATIENT-CENTRIC APPROACHES

Green hospitals promote environmental sustainability with the benefit of patient care, and staff wellness (Chías & Abad, 2017). These include energy efficient HVAC, biophilic designs and better air quality for a healing environment (Allen et al., 2015). Green hospitals are known to enhance recovery rates in patients to with lesser stress and better patient satisfaction (Kalender-Smajlović & Dovjak, 2023). Better indoor air quality and ergonomic designs result in fewer sick days and more productive health care workers (Dilrukshi et al., 2014). Buildings with enhanced ventilation systems have remarkably reduced respiratory issues (Golbazi & Aktas, 2020). Green hospitals also include sound-reducing strategies such as sound-absorptive materials and quieter equipment, contributing to a more soothing environment (Tomanek, 2024). Green hospitals with patient-centric designs such as, healing gardens help provide patients with a quiet space for relaxation and focusing on the psychosocial aspects (Chías & Abad, 2017). Exposure to nature supports to reduce anxiety, decrease blood pressure and increase mood and offers therapeutic benefits, alleviating stress, pain, and fostering an enhanced emotional state for patients, staff, and visitors (Kalender-Smajlović & Dovjak, 2023). Green hospitals provides positive impacts such as reduce operating costs, increase building value, and improve indoor air quality (Kumari & Kumar, 2020).

## 2.4 CHALLENGES AND BARRIERS TO IMPLEMENTING GREEN CONCEPTS IN HOSPITALS

In developing countries green construction has high initial costs for advanced energy systems, sustainable materials and certification fees (Golbazi & Aktas, 2020). Sepetis (2020) explained these investments generate long-term savings; however, many healthcare facilities have difficulties in justifying this upfront expenditure (Cowie et al., 2020). Financial barriers can be addressed by targeting subsidies, grants and low-interest loans to motivate more hospitals to adopt sustainable (Dhillon & Kaur, 2015). The second major barrier is operational difficulties. Continuous operation is essential to healthcare facilities; energy demand systems, including HVAC, lighting, and medical equipment, in these facilities make this point clear (Tomanek, 2024). The major issue here is that the services offered in these hospitals need to continue while old buildings are being refurbished for green compliance (Kalender-Smajlović & Dovjak, 2023).As hospital decision-makers are not familiar with the advantages of green buildings, there is initial resistance to adopt sustainable practices (Cowie et al., 2020). Furthermore, regulatory challenges do not motivate hospitals to adopt green concepts (Dhillon & Kaur, 2015). Hospitals often operate in high-pressure environments where immediate patient care takes priority over long-term sustainability (Golbazi & Aktas, 2020). These challenges

are exacerbated by the misunderstanding that green practices can disrupt clinical processes (Dhillon & Kaur, 2015).

## 3. METHODOLOGY

The initial step of the study was conducting a comprehensive literature review. This focused on understanding the green building concept (GBC), assessing existing Green Building Rating Systems (GBRS), and identifying the importance and relevance of green building concepts for hospital facilities. A qualitative research approach was adopted due to the limited number of green-certified hospitals in Sri Lanka. Since only one private hospital has achieved green certification, a large sample was not available for quantitative analysis. Therefore, a qualitative approach was considered more appropriate to explore the suitability of general GBRS for hospitals and to highlight the importance of establishing a healthcare-specific GBRS. This study was conducted as a single case study because only one private hospital in Sri Lanka has achieved green certification. The selected hospital is a leading private hospital in Sri Lanka and is a Gold-rated Green Hospital (GH), certified by the Green Building Council of Sri Lanka (GBCSL), which is the second-highest recognition for green compliance in the country. Three semi-structured interviews were conducted with professionals who contributed to obtaining and maintaining the hospital's green certification. The selected participants were directly involved in the hospital's green certification and operational sustainability practices, enabling the study to obtain expert and context-specific insights relevant to the research objectives. The respondents included:

- R1-Engineer & Facilities Manager (9+ years' experience): managing soft and hard services, infrastructure handling, project coordination, and sustainable management.
- R2-Engineer Executive (3+ years' experience): system maintenance, engineering resource management, and technical implementation.
- R3-Operations Manager (8+ years' experience): strategic operations planning, policy implementation, and performance monitoring.

In addition, observations were conducted to reassess the hospital's rating under a healthcare-specific GBRS and compare it with the existing general GBRS rating. To minimize observation bias, observations were conducted using predefined assessment criteria based on the IGBC Green Healthcare rating system and were verified collaboratively with the hospital's senior facilities executive to ensure consistency and accuracy. Data were analyzed using thematic analysis, where interview transcripts were coded, categorized, and organized into themes, and findings were compared with observation results.

## 4. DATA ANALYSIS AND RESEARCH FINDINGS

Phase I of data collection involved interviews and phase II involved observations. Table 1 represents the barriers to green concept implementation and the enablers that make it successful, in the healthcare sector.

## 4.1 PHASE I- INTERVIEW FINDINGS

*Table 1: Interview findings*

| Theme | Codes | Categories |
|---|---|---|
| Barriers to integrating the green concept into existing hospitals | Infrastructure Obsolescence | Old and outdated building systems |
| | | Electrical System Deficiencies |
| | | Structural Constraints |
| | | Technology Integration Difficulties |
| | Financial Constraints and Investment Burdens | High Implementation Costs |
| | | Certification and Consultancy Fees |
| | | Limited Government Support |
| | Operational Complexities | 24/7 Operational Constraints |
| | | Difficulties in balancing patient care and Sustainability |
| | | Workflow Disruption Concerns |
| | | Certification Process Complexity |
| | | Difficulties in KPI Tracking and Performance Monitoring |
| | Human Factors and Behavioural Change Challenges | Staff and Patient Awareness Issues |
| | | Resistance to Change |
| | | Continuous Education Needs |
| Enablers to integrating the green concept into existing hospitals | Strategic Leadership | Top Management Support |
| | | Strategic Vision and Commitment |
| | | Brand Building and Marketing |
| | | Green Team Formation |
| | | Staff Training Programs |
| | Financial Benefits | Long-term returns of green hospitals |
| | Successful Green Technology Implementation | Water conservation |
| | | Waste Management |

### 4.1.1 Barriers to Integrating the Green Concept into Existing Hospitals

Considering the infrastructure obsolescence, R1 stated that, "*when integrate sustainable systems with existing systems, issues can be arisen. Our hospital buildings are old and systems also outdated. Because of that integrating process is difficult".* This is proved the literature about older healthcare facilities facing unique challenges in adopting modern green technologies (Tomanek, 2024). While literature discusses retrofitting challenges, the interviews documented precise technical difficulties. In addition, system alignment problems were identified. According to R2, *"To optimize the energy efficiency we had to install variable frequency drives (VFD) for old HVAC systems. In electrical system also using thermal cameras we had to find issues of the electrical line, leakages and fixed those problems".* R1 noted that physical building limitations hindered rainwater harvesting, as underground lines connect directly to the main sewer.

Financial constraints are another practical challenge in implementing the GBC in the hospital sector. R1 supported this stating, the total project investment was substantial. *"We had to pay consultancy fee, altogether we had to invest more than 2 million for this whole project".* Direct certification costs also added to the financial burden. R3 stated that *"we had to invest for registration fee and instruction fee to GBCSL".* Sri Lankan evidence shows minimal government support, *"we have to expend some cost for maintain the green practices. For an example, we have to allocate money for solar panel services and sometimes invertor repairs or replacements".* R3 stated that, *" we still have not received any incentives. But government said tax will be reduced in 2026".*

Hospitals with unique characteristics face operational complexities when balancing the implementation of the green concept and meeting patient care requirements. Critical healthcare operations impose non-negotiable energy requirements. R1 stated that energy use cannot be significantly reduced because operating theatres require constant air conditioning at 16°C. Similarly, R2 stated, *"we have medical machine rooms those are needed to air conditioning 24/7"* supports Allen et al.'s (2015) theoretical frameworks about energy-intensive healthcare operations. In addition, patient safety takes precedence over sustainability goals. R1 stated that clinical priorities require maintaining air quality and HVAC in critical care units, even if it increases energy use. R3 emphasized that, *"we follow the green concept in a way that does not cause inconvenience to our patients".*

However, the interview findings revealed operational complexities extending beyond literature discussions, particularly regarding technology infrastructure gaps in developing countries. The participant explained that *"we don't have BMS system in the hospital. We manually do every function"* highlights implementation realities not adequately addressed in literature, which typically assumes basic building management system availability. Further R2 stated that, "*we have to complete upgrades without disturbing the patients was a major issue throughout the construction".* Certification is burdensome for hospitals, and KPI tracking is challenging due to complex measurements of energy, water, and waste. There are variations in factors such as staff awareness, patient behaviour, top management attitudes and training needs that can cause challenges. While Zitars et al. (2021) discusses occupant behavior in green buildings generally, healthcare-specific challenges were highlighted in this study. R3 noted that employees resist change, fearing increased workload or unclear relevance to their roles. Consequently, both new and existing staff require ongoing education on sustainability and hospital green policies.

### 4.1.2 Enablers to Integrating the Green Concept into Existing Hospitals

R3 identified leadership commitment was a key success factor by stating, "*the main thing is the will of top management to do this without any concern."* Further R1 explained that forward-thinking leadership approach is required to improve the morality of the workers in hospital. Also, R2 explained the brand building and marketing which received through implementing green concept. Additionally, specialized teams were established for sustainability. According to R3, *"for increase the efficiency we initiate a team called green team to support the system".* R2 explained that awareness programs were conducted, and responsibilities were assigned to staff. Respondents also highlighted the financial benefits of green hospitals. R2 reported that, "*we consider about the solar power generation is a profit for us. We have already received the return that we invested in this project, even though it is not visible".* In terms of green technology implementation, R1 emphasized water conservation and waste management initiatives. To reduce water

consumption, the hospital plans to use treated wastewater for gardens, employs dual-flush toilets, and installs water aerator taps. For waste management, medical and non-medical waste is segregated into categories such as infectious, sharp, biodegradable, glass, paper, and plastic waste. These strategies and technologies drive the hospital toward a sustainable hospital.

## 4.2 PHASE II- OBSERVATIONS

The observations were conducted to see the possibility of obtaining the same green certification level of GBCSL to the selected hospital, using the GBRS specifically designed for healthcare facilities by IGBC in India. The hospital's senior facilities executive was involved in the successful implementation of the observation. Their involvement in the observations improved the accuracy and reliability. The observation was faced with several significant limitations. Permission to observe the ICU and Radiology departments, identified as high energy-consuming areas—was denied due to access restrictions. Another limitation was the lack of technical equipment, which prevented the measurement of lux, indoor air quality and acoustic levels in the hospital. Although accurate measurements were not possible, the executive facilitated access to previously documented data and reports. Furthermore, the observation was limited to a single time frame, restricting the identification of seasonal and climate-related variations in sustainability factors such as energy use and daylight efficiency. The observations later confirmed by the interview respondents. The hospital under observation has achieved gold certification under the GREENSL rating system for existing building. The observations are conducted to investigate whether this hospital could regain the gold certificate through the IGBC green rating system which is a GBRS specified for hospitals.

### 4.2.1 Performance Comparison Between Rating Systems

The observational checklist assessment shows significant variance in hospital performance across different criteria of the two rating systems. Table 2 highlights the points achieved, based on the data obtained from the observation conducted. The total number of credits available in GREENSL ratings for hospital buildings is 100, while existing hospital buildings are evaluated under total 90 points in IGBC green healthcare system.

*Table 2: Performance comparison between rating systems*

| Aspect | GREENSL System | | IGBC Green Healthcare System | | Key Observations |
|---|---|---|---|---|---|
| | ***Available points*** | ***Claimed points*** | ***Available points*** | ***Claimed points*** | |
| Site Selection & Planning | 18 | 14 | 8 | 8 | Strong performance in both systems |
| Indoor Environmental Quality | 14 | 13 | 19 | 10 | Significant gap in healthcare-specific criteria |
| Sanitisation & Hygiene | N/A | N/A | 12 | 8 | Category unique to healthcare rating |

| Aspect | GREENSL System | | IGBC Green Healthcare System | | Key Observations |
|---|---|---|---|---|---|
| | ***Available points*** | ***Claimed points*** | ***Available points*** | ***Claimed points*** | |
| Building Materials & Resources | 11 | 7 | 6 | 4 | Comparable relative performance |
| Energy Efficiency | 28 | 22 | 23 | 19 | Strong in both, but missed commissioning points |
| Water Conservation | 15 | 7 | 16 | 8 | Underperformance in both systems |
| Innovation | 6 | 0 | 4 | 0 | No points achieved in either system |
| Management | 4 | 4 | 2 | 2 | Full compliance in both systems |
| Social & Cultural Awareness | 4 | 4 | N/A | N/A | Category unique to GREENSL system |
| ***Total*** | ***100*** | ***68*** | ***90*** | ***54*** | |
| ***% of claimed points from total points*** | ***68%*** | | ***60%*** | | |
| ***Certification*** | ***GOLD*** | | ***SILVER*** | | |

Table 2 provides a comparative summary of the hospital's performance in both systems. Even though under GREENSL rating hospital achieved a gold rating, under the IGBC rating system, this hospital only achieved a silver rating. Accordingly, by observing the same hospital facility undergoing certification under a general GBRS and a hospital-specific GBRS, the number of points earned under a hospital-specific GBRS is significantly lower than the point level earned under a general GBRS. This represents a difference of 8%.

A key difference between the GREENSL rating system and the IGBC green rating system is that it includes five specific healing architecture requirements under Indoor Environmental Quality aspect, that are not included in GREENSL. In addition to that, The IGBC has a separate category for sanitization and hygiene criteria, which are not included in the GREENSL system. Thus, further analysis on the variations of IGBC rating is required.

### 4.2.2 Analysis of Healing Architecture Requirements in Healthcare Facilities

The important aspects of healing architecture are shown in the comparative Table 3 below, and the data obtained from the observation conducted shows that the healing architecture of the hospital is at a weak level. It can also affect the recovery rate of patients.

*Table 3:Analysis of Healing Architecture Requirements*

| Element of Healing Architecture | Available Points of IGBC | Points Claimed | GREENSL Equivalent |
|---|---|---|---|
| Day-lit Spaces | 2 | 2 | Partial coverage in general daylighting |
| Connectivity to Nature | 2 | 0 | Not specifically addressed |
| Green Open Spaces | 2 | 1 | General open space requirements |
| Patient-centric Healing Garden | 2 | 0 | Not addressed |
| Colour Psychology | 3 | 1 | Not addressed |

As shown in the Table 4, the IGBC states that day-lit spaces, connectivity to nature, green open spaces, healing gardens, and colour psychology are the elements that should be present in a green hospital building to support therapeutic productivity. In contrast, the GREENSL does not provide an in-depth coverage of these factors. Although, some coverage is given to day-lit spaces and green open spaces, they are not included under any of the healing-focused criteria. More critically, connectivity to nature, patient-centric healing gardens and colour psychology are not clearly identified within the GREENSL.

### 4.2.3 Sanitization and Hygiene Requirements

Sanitization and Hygiene requirements criteria is a crucial gap when applying conventional green building certification standards to healthcare facilities, as infection control and medical waste management are fundamental to hospital operations and patient safety. Significant gaps in extent and coverage were observed between IGBC Green Healthcare Rating System and GREENSL Rating System when sanitation and hygiene were compared in Table 4.

*Table 4:Analysis of Sanitization and Hygiene Requirements*

| Sanitization & Hygiene Element | IGBC Points Available | Points Achieved | GREENSL Coverage |
|---|---|---|---|
| Municipal Solid Waste Management | Required | Compliant | Covered under general waste management |
| Bio-medical Waste Management | Required | Compliant | Not specifically addressed |
| Infection Control within Spaces | 5 | 3 | Not addressed |
| Isolation Room | 2 | 1 | Not addressed |
| Sanitation Facilities | 1 | 1 | Basic coverage |
| Eco-friendly Cleaning Practices | 2 | 1 | Limited coverage |
| Organic Waste Management | 2 | 2 | General coverage |

GREENSL does not cover the specific aspects of healthcare, including biomedical waste management, infections control or having separate isolation spaces for patients. This study indicates that the hygiene and sanitation provisions within healthcare settings are inadequately supported by the conventional Green Rating systems. However, the IGBC

system is a system specifically designed for the healthcare sector and provides a broader framework. As a result, it is clear that implementing a framework that integrates with medical hygiene regulations in Sri Lankan private hospitals will enable them to achieve green certification while protecting public health interests, achieving operational excellence, and ensuring patient safety. Therefore, healthcare facilities evaluated under the general green building framework are not able to assess some of their most critical operational characteristics. Therefore, this is a measure that shows a significant gap in suitability in certification. This finding directly supports Tomanek's (2024) theoretical argument about the unique hygiene requirements of healthcare facilities.

## 5. CONCLUSIONS

The study identified that conventional Green building rating systems such as LEED, BREEAM and GREENSL treat hospitals similarly to other building types. In contrast, healthcare-specific systems like IGBC incorporate critical medical facility requirements that recognize the unique operational demands of hospitals. Several barriers and enablers to integrating the green concept into existing hospitals were identified using a case study. The enablers include strategic leadership toward green hospital formation; financial benefits gain through the green hospitals and successful green technology implementation. Barriers include technical challenges in retrofitting antiquated infrastructure, especially when attempting to combine the advanced mechanisms with aging building designs. Operational constraints due to 24/7 service requirements created gaps between energy conservation goals and patient safety needs, while limited government financial support, combined with staff and patient behavioural change requirements, added challenges to implementation. The practical application of the IGBC Green Healthcare Rating System to the GREENSL-certified hospital, providing evidence of performance differences. The comparative analysis demonstrated a scoring difference, with the hospital achieving 68% under GREENSL versus 60% under IGBC criteria, resulting in a certification level reduction from Gold to Silver. This variance highlighted critical gaps in healthcare-specific performance areas. In indoor environmental quality, the hospital was achieved high compliance under GREENSL. However, low compliance was achieved under healthcare-specific criteria due to missing acoustic design, specialized ventilation, and infection control requirements. Most notably, the application exposed the absence of healing architecture requirements in general systems, with elements such as connectivity to nature, healing gardens, and therapeutic colour schemes receiving no recognition under GREENSL. The assessment revealed that GREENSL completely lacks sanitization and hygiene categories, resulting in average compliance when evaluated against healthcare standards for medical waste management and infection control protocols. This practical application validated the need for specialized assessment frameworks to comprehensively evaluate hospitals' unique sustainability challenges and opportunities. Further, the research demonstrated that general systems inadequately assess healthcare-specific requirements, with the 8% scoring difference and qualitative gaps providing concrete evidence of this inadequacy. This study provides empirical evidence demonstrating the inadequacy of general green building rating systems when applying to healthcare facilities in Sri Lanka. The lack of specialized technical equipment for measuring indoor environmental quality parameters limited the ability to conduct comprehensive environmental assessments required for an accurate healthcare-specific rating system application. Future research should focus on evaluating multiple healthcare facilities using healthcare-specific green building rating systems and incorporating

detailed quantitative assessments of indoor environmental quality and patient well-being outcomes. Also, policymakers and regulatory bodies need to develop healthcare-specific green building standards within the existing GREENSL framework. These standards should incorporate mandatory elements such as infection control protocols, medical waste management, healing architecture requirements, and patient-centric design criteria.

# 6. REFERENCES


Abeysinghe, S., De Zoysa, C. J., Siriwardana, C., Bandara, C., & Dissanayake, R. (2023). Integrating disaster resilience into green rating systems – a modification of the Sri Lankan green building rating tool. *Smart and Sustainable Built Environment*, *12*(4), 765–786. https://doi.org/10.1108/SASBE-10-2021-0182

Akpan Umoh, A., Adefemi, A., Ibewe, K. I., Etukudoh, E. A., Ilojianya, V. I., & Nwokediegwu, Z. Q. S. (2024). Green architecture and energy efficiency: A review of innovative design and construction techniques. *Engineering Science & Technology Journal*, *5*(1), 185–200. https://doi.org/10.51594/estj.v5i1.743

Allen, J. G., MacNaughton, P., Laurent, J. G. C., Flanigan, S. S., Eitland, E. S., & Spengler, J. D. (2015). Green buildings and health. *Current Environmental Health Reports*, *2*(3), 250–258. https://doi.org/10.1007/s40572-015-0063-y

Awadh, O. (2017). Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. *Journal of Building Engineering*, *11*, 25–29. https://doi.org/10.1016/j.jobe.2017.03.010

Chías, P., & Abad, T. (2017). Green hospitals, green healthcare. *International Journal of Energy Production and Management*, *2*(2), 196–205. https://doi.org/10.2495/EQ-V2-N2-196-205

Christensen, P., Sayce, S., & Falkenbach, H. (2011). Assessing Assessment: Toward a more holistic rating system for sustainability performance. *18th Annual European Real Estate Society Conference*. https://eres.architexturez.net/doc/oai-eres-id-eres2011-336

Cowie, J., Nicoll, A., Dimova, E. D., Campbell, P., & Duncan, E. A. (2020). The barriers and facilitators influencing the sustainability of hospital-based interventions: a systematic review. *BMC Health Services Research*, *20*(1), 588. https://doi.org/10.1186/s12913-020-05434-9

Dhillon, V. S., & Kaur, D. (2015). Green hospital and climate change: Their interrelationship and the way forward. *Journal of Clinical and Diagnostic Research : JCDR*, *9*(12), LE01-LE05. https://doi.org/10.7860/JCDR/2015/13693.6942

Dilrukshi, H., Mallawarachchi, H., & Karunasena, G. (2014). Application of green building concept to enhance indoor environmental quality in hospital buildings in Sri Lanka. *The 3rd World Construction Symposium*, 80–88. https://ciobwcs.com/downloads/WCS2014-Proceedings.pdf

Ding, Z., Fan, Z., Tam, V. W. Y., Bian, Y., Li, S., Illankoon, I. M. C. S., & Moon, S. (2018). Green building evaluation system implementation. *Building and Environment*, *133*, 32–40. https://doi.org/10.1016/j.buildenv.2018.02.012

Golbazi, M., & Aktas, C. B. (2020). Leed certification and patient wellbeing in green healthcare facilities. *Journal of Green Building*, *15*(4), 3–18. https://doi.org/10.3992/jgb.15.4.3

Gurupatham, S. V., Jayasinghe, C., Perera, P., & Lepakshi, R. (2024). Building material selection framework for tropical climatic conditions: Eco-design-based approach. *Green Technologies and Sustainability*, *2*(3), 100103. https://doi.org/10.1016/j.grets.2024.100103

Haapio, A., & Viitaniemi, P. (2008). A critical review of building environmental assessment tools. *Environmental Impact Assessment Review*, *28*(7), 469–482. https://doi.org/10.1016/j.eiar.2008.01.002

Huang, Y., Pi, Y., Ma, K., Miao, X., Fu, S., Zhu, Z., Cheng, Y., Zhang, Z., Chen, H., Wang, H., Gu, H., Shao, Y., Duan, Y., Feng, A., Zhuo, W., & Xu, Z. (2022). Deep learning for patient-specific quality assurance: Predicting gamma passing rates for IMRT based on delivery fluence informed by log files. *Technology in Cancer Research & Treatment*, *21*. https://doi.org/10.1177/15330338221104881

IGBC. (2020). *IGBC Green Healthcare Facilities Rating System*. Indian Green Building Council.

Kalender-Smajlović, S., & Dovjak, M. (2023). Advantages of greenery in hospital environment - a literature review. *Sanitarno Inženirstvo International Journal of Sanitary Engineering Research*, *16*(1), 4–13. https://doi.org/10.2478/ijser-2023-0002

Khairunnisa, R. A., Setyonugroho, W., & Ulfa, M. (2022). Green hospital implementation in health aspects: a systematic review. *United International Journal for Research & Technology*, *3*(9), 46–58.

Kumari, S., & Kumar, R. (2020). Green hospital - A necessity and not option. *Journal of Management Research and Analysis*, *7*(2), 46–51. https://doi.org/10.18231/j.jmra.2020.010

Mahan, A., & Khorramrouei, R. (2023). CASBEE Assessment system, a technical approach to assessing the environmental sustainability of green buildings in Japan. *Journal of Renewable and New Energy*, *10*(1), 177–187. https://doi.org/10.52547/jrenew.10.1.177

Marchi, L., Antonini, E., & Politi, S. (2021). Green Building Rating Systems (GBRSs). *Encyclopedia*, *1*(4), 998–1009. https://doi.org/10.3390/encyclopedia1040076

Moramudali, W., & Manawadu, G. (2022). Adoption of green practices in hotel industry in Sri Lanka: An evaluation based on the Green SL rating system. *Conference: 15th. International Conference on Business Management; Sustainability through Going Green.*

Sepetis, A. (2020). Sustainable finance in sustainable health care system. *Open Journal of Business and Management*, *08*(01), 262–281. https://doi.org/10.4236/ojbm.2020.81016

Shan, M., & Hwang, B. (2018). Green building rating systems: Global reviews of practices and research efforts. *Sustainable Cities and Society*, *39*, 172–180. https://doi.org/10.1016/j.scs.2018.02.034

Sonavane, P. B., & Mane, A. S. A. (2023). Analysis and study of credits for IGBC green new building. *Interantional Journal of Scientific Research in Engineering and Management*, *07*(02). https://doi.org/10.55041/IJSREM17797

Thapa, D. (2017). *Rating System Pilot Version Abridged Reference Guide IGBC Green Healthcare Facilities*. https://www.academia.edu/35401446/Rating_System_Pilot_Version_Abridged_Reference_Guide_IGBC_Green_Healthcare_Facilities

Tomanek, M. (2024). Energy efficiency in hospitals –towards sustainable healthcare. *BUILDER*, *320*(3), 38–41. https://doi.org/10.5604/01.3001.0054.3461

Tseng, M.-L., Tan, P., Wu, K.-J., Lin, R., Todumrongkul, N., Juladacha, P., & Christianti, G. (2020). sustainable total resource management in thailand healthcare industry under uncertain situations. *Sustainability*, *12*(22), 9611. https://doi.org/10.3390/su12229611

Tushar, S. R., Moktadir, M. A., Kusi-Sarpong, S., & Ren, J. (2023). Driving sustainable healthcare service management in the hospital sector. *Journal of Cleaner Production*, *420*, 138310. https://doi.org/10.1016/j.jclepro.2023.138310

Zitars, J., Spadafore, B., Coulombe, S., Riemer, M., Dreyer, B. C., & Whitney, S. (2021). Understanding the psycho-environmental potential functions of a green building to promote employee health, wellbeing and productivity: A theoretical perspective. *Building and Environment*, *205*, 108268. https://doi.org/10.1016/j.buildenv.2021.108268

Thilakasiri, P.L.T.T., Waidyasekara, K.G.A.S. and Ranasinghe, P.H.G.M.A., 2026. Theft and vandalism in infrastructure construction: A review of sustainability impacts In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1761-1773. DOI: https://doi.org/10.31705/WCS.2026.128. Available from: https://ciobwcs.com/papers/

# THEFT AND VANDALISM IN INFRASTRUCTURE CONSTRUCTION: A REVIEW OF SUSTAINABILITY IMPACTS

**P.L.T.T. Thilakasiri[1], K.G.A.S. Waidyasekara[2] and P.H.G.M.A. Ranasinghe[3]**

## *ABSTRACT*

*Infrastructure construction projects are complex and resource-intensive systems that significantly influence economic development, environmental sustainability, and societal well-being. Despite their importance, such projects remain highly vulnerable to operational risks, particularly theft and vandalism arising from inadequate site security. While existing research has extensively examined cost overruns and delays, limited attention has been given to the broader sustainability implications of security-related incidents, especially within developing economies. This study adopts a narrative literature review approach to examine how theft and vandalism influence the sustainability performance of infrastructure construction projects in developing countries. The review identifies key environmental, economic, and social impact pathways resulting from security breaches, drawing upon both international and Sri Lankan literature. Furthermore, the study synthesises mitigation strategies, including technological, managerial, contractual, and governance-based interventions. Based on these insights, a conceptual framework is developed to illustrate the relationship between infrastructure vulnerabilities, security risks, and sustainability degradation mechanisms. The findings highlight the importance of integrating security considerations into sustainability assessment practices to enhance the resilience and long-term performance of infrastructure projects. The study provides practical guidance for construction practitioners in developing more robust security and sustainability strategies and identifies avenues for further empirical research to validate and expand the proposed framework.*

***Keywords:*** *Infrastructure construction; Mitigation strategies; Security and Risk; Sustainability; Theft and Vandalism.*

## 1. INTRODUCTION

Theft and vandalism are common problems in the construction industry and include unauthorized removal of materials, equipment, and fuel or deliberate damage or destruction of project assets (Arthur-Aidoo et al., 2023). They do not occur as isolated incidents, but as systemic risks that have a serious impact on project performance (Armitage & Ekblom, 2019). Construction sites are easily identified as targets for opportunistic or organised theft and vandalism activities because of their open

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, thilakasiripltt.21@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradha@uom.lk
[3] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, ranasinghephgma.20@uom.lk

environment, temporary operation, and grouping of materials that are valuable to thieves and vandalism Arthur-Aidoo et al., 2023). Therefore, construction site theft costs the world significant amounts of money in addition to the cost of the stolen materials, due to project delays, disruption, and increased security costs (Arthur-Aidoo et al., 2023).

Theft and vandalism also have a negative effect on construction projects, as it can lead to decreased productivity, disruptions in the construction process, and unexpected resources lost, resulting in delayed projects and increased costs (Almashhour & Ojiako, 2025). The risks are especially high for infrastructure construction projects because of their size and complexity and exposure risks. Many infrastructure projects involve vast areas spread out over a large geographical area, and often there is a high demand for materials storage, which makes them more vulnerable to security threats than traditional construction projects (Arthur-Aidoo et al., 2023). In addition, these risks are heightened by the remote location of the projects and the lack of ongoing surveillance, especially outside of the operational hours (Arthur-Aidoo et al., 2023).Although this is a very vulnerable situation, theft and vandalism have received comparatively little attention in infrastructure projects, alongside other construction issues like cost overruns, procurement inefficiency and contractual disputes (Almashhour & Ojiako, 2025).There are also low levels of technological use, weak regulatory systems, fragmented governance and resource limitations that add to the vulnerability of these infrastructure construction projects to theft and vandalism, especially in less developed countries with less developed security management practices (Arthur-Aidoo et al., 2023; Foster et al., 2020). This means that security incidents have more significant operational and sustainability impacts in developing countries, as there are less institutional capacity and enforcement to address them.

Theft and vandalism also have implications beyond their impact on operations, for sustainability is now seen as a key aim in infrastructure development (Zhao et al., 2016). Environmentally, the loss of material requires replacement, which involves further extraction, manufacturing, and transportation, thus generating more embodied carbon (Kumanayake & Luo, 2018; Nawarathna et al., 2021; Rathnayake et al., 2022). On an economic side, the incidents result in financial instability and cost overruns, and on a social side, they cause delayed delivery of infrastructure and less confidence from stakeholders (Zhao et al., 2016).These inefficiencies are a further challenge to sustainable delivery of infrastructure and long-term development goals given the rapid expansion of infrastructure in developing countries like Sri Lanka, Nigeria and Malasiya where the achievement of these goals is hindered by governance and resource constraints (Foster et al., 2020). While research on construction sustainability and project risk management is plentiful, there is little research addressing the relationship between theft and vandalism and the performance of construction sustainability. The sustainability impacts of security-related incidents are not well discussed in the literature while there are other issues such as financial constraints, delays, productivity concerns, and general security risk management (Sivarajah, 2021; Dolage & Dasantha, 2022). Furthermore, previous research on construction security has focused primarily on technological and crime prevention solutions and in the context of developed countries (Armitage & Ekblom, 2019; Oliva et al., 2021). Hence, there is a big theoretical gap in dealing with construction site security risks and sustainability performance in the context of infrastructure project management.

Globally, theft and vandalism in construction projects tend to be more prevalent in developing regions such as parts of Africa, South Asia, and Latin America, where weak regulatory enforcement, informal markets for stolen materials, and limited technological adoption increase project vulnerabilities. In contrast, developed regions including North America and Western Europe generally experience comparatively lower levels of construction-related theft and vandalism due to stronger governance frameworks, advanced surveillance systems, and stricter security regulations (Arthur-Aidoo et al., 2023; Foster et al., 2020).Concurrently, there is a practical requirement to explore this issue in developing countries, where regulatory enforcement is weak, technological capability is limited, and institutional constraints make projects more vulnerable to theft and vandalism, while also intensifying the long-term environmental, economic, and social impacts of such incidents (Arthur-Aidoo et al., 2023; Foster et al., 2020).

Accordingly, this study aims to examine how theft and vandalism influence the sustainability performance of infrastructure construction projects in developing countries To achieve this aim, the study examines the critical vulnerabilities contributing to theft and vandalism, evaluates their environmental, economic, and social sustainability impacts, analyses mitigation strategies for sustainable security management, and develops a conceptual framework illustrating the relationship between construction site security risks and sustainability performance.

## 2. METHODOLOGY

The method used in this study is the narrative literature review method, which aims to review the literature to obtain the relationship between construction site security and construction site sustainability performance in infrastructure construction. In this study, the aim is to connect and interpret the knowledge from various disciplines, such as construction management, sustainability, and infrastructure governance, so the narrative approach is chosen instead of the systematic literature review in which the study selection and screening is strictly followed. This flexibility can be useful for a much more open and critical examination of ideas, especially when research is in its initial stages, with many studies that have different conceptual emphases and not much cohesion (Snyder, 2019).

Secondary data were gathered from various academic databases, especially Google Scholar, peer-reviewed journal papers, conference papers, institutional reports, relevant industry publications etc. Relevant literature was identified by following a structured keyword search using terms related to construction site security, theft and vandalism, sustainability performance, and mitigation strategies. The identified publications were subsequently screened to ensure their relevance to the research scope. The data were then analysed and critically synthesised to identify key themes and patterns within the context of developing countries.

## 3. REVIEW FINDINGS

The review findings are presented under three main headings: construction site security and vulnerabilities; impacts of theft and vandalism on sustainability aspects; and mitigation strategies for sustainable security management, followed by the development of a theoretical framework to summarise the key findings.

### 3.1 CONSTRUCTION SITE SECURITY AND VULNERABILITIES

Infrastructure construction sites, particularly within large-scale infrastructure projects, are widely recognised as highly vulnerable environments due to their temporary, dynamic, and spatially dispersed nature (Oliva et al., 2021). Unlike permanent facilities, construction sites operate under continuously changing conditions, where materials, equipment, and labour are frequently mobilised and demobilised, creating operational instability and exposure to risk (Szymański, 2017). This transient nature limits the effectiveness of traditional security systems and creates multiple points of exposure, making such sites particularly susceptible to theft and vandalism (Arthur-Aidoo et al., 2023). Furthermore, the authors argue that the absence of integrated security planning during the early stages of project development significantly increases the likelihood of security failures, as risk mitigation measures are often implemented reactively rather than proactively.

Empirical studies on construction site crime indicate that theft and vandalism are not merely opportunistic incidents but are often facilitated by systemic weaknesses in project management practices (Arthur-Aidoo et al., 2023). Moreover, the same authors identified several recurring vulnerabilities, including inadequate surveillance systems, insufficient lighting, lack of access control, and poor inventory management. These conditions create an enabling environment in which high-value materials such as steel reinforcement, copper cables, fuel, and mechanical components can be easily misappropriated (Oliva et al., 2021). Theft in construction sites typically occurs in multiple forms, including material theft, fuel siphoning, equipment component removal, and organised bulk material diversion, while vandalism may involve deliberate damage to machinery, storage facilities, or partially completed structures (Armitage & Ekblom, 2019). The high resale value, portability, and low traceability of construction materials further increase their attractiveness to organised theft networks, particularly in contexts where regulatory enforcement is weak (Armitage & Ekblom, 2019).

The vulnerability of theft and vandalism is significantly amplified in infrastructure construction projects due to their scale and operational complexity. Large project footprints, remote locations, and reliance on temporary storage facilities complicate the implementation of effective security measures and increase exposure to external threats (Oliva et al., 2021). In many infrastructure projects, materials are stored in open or semi-secured areas due to logistical constraints, which further elevates the risk of theft (Oliva et al., 2021). Additionally, the fragmentation of responsibilities across multiple contractors and subcontractors creates ambiguity in accountability, making it difficult to establish clear ownership and control over materials and assets. Dolage and Dasantha (2022), highlight that such coordination challenges are particularly prevalent in developing countries, where weak organisational structures and communication gaps contribute to inefficiencies and increased risk exposure.

Construction site security challenges are further intensified by institutional and governance limitations. Studies by Dolage and Dasantha (2022) and Sivarajah, (2021) demonstrate that project management practices in the local construction industry tend to prioritise cost and schedule performance, often at the expense of comprehensive risk management. As a result, security-related risks such as theft and vandalism are frequently underestimated and inadequately addressed. This issue is compounded by the absence of standardised guidelines or benchmarks for managing material losses, leading to

inconsistencies in reporting and accountability. Consequently, theft-related losses often remain unquantified, masking their true impact on project performance.

Critically, existing literature on construction risk management has focused on macro-level risks such as cost overruns, design changes, and contractual disputes, while security-related risks remain underrepresented (Almashhour & Ojiako, 2025). Moreover, conceptualise construction risks as interconnected systems influencing project outcomes, yet their framework does not explicitly incorporate theft and vandalism as contributing factors. Similarly, Almashhour and Ojiako (2025) emphasises stakeholder-related risks and project complexity but does not integrate site security into the broader risk structure. This omission highlights a significant gap in current theoretical frameworks, suggesting that construction site security has not been adequately recognised as a critical component of project risk management.

Because of this exclusion of theft and vandalism from conventional risk frameworks limits the ability to fully understand their long-term impacts on environmental, economic, and social performance. In infrastructure projects, where material volumes and resource consumption are significantly higher, the consequences of theft-related losses extend beyond immediate financial impacts to include increased material waste, duplication of embodied carbon, and inefficiencies in resource utilisation (Kumanayake & Luo, 2018; Nawarathna et al., 2021). Therefore, integrating construction site security into sustainability and risk management frameworks is essential to achieve more comprehensive and effective project outcomes.

## 3.2 IMPACTS OF THEFT AND VANDALISM ON PROJECT SUSTAINABILITY

The impacts of theft and vandalism extend beyond immediate material loss and operational disruptions, influencing the broader sustainability performance of infrastructure construction projects (Arthur-Aidoo et al., 2023). Sustainability in this context is understood through its three interconnected dimensions environmental, economic, and social each of which is adversely affected by security-related incidents (Oliva et al., 2021). While existing research has primarily examined construction inefficiencies from a productivity and cost perspective, the implications of theft and vandalism on sustainability remain insufficiently explored (Szymański, 2017).

From an environmental perspective, material theft contributes to inefficient resource utilisation by necessitating the replacement of lost or damaged materials. This process involves additional extraction, manufacturing, and transportation activities, thereby increasing the overall environmental burden of the project. While traditional construction waste studies primarily focus on on-site inefficiencies, the role of theft-induced waste remains significantly underexplored (Szymański, 2017). A particularly important dimension of this issue is embodied carbon, which refers to the total greenhouse gas emissions associated with the lifecycle of construction materials (Nawarathna et al., 2021). Although existing literature has focused on material selection and lifecycle optimisation, the duplication of embodied carbon due to theft-related replacement cycles has received limited attention (Almashhour & Ojiako, 2025). Lifecycle assessment principles suggest that repeated material procurement directly increases carbon emissions, thereby undermining sustainability objectives. This indicates the major impact

to the environmental sustainability which occurred due to security related inefficiencies (Zhao et al., 2016).

Building upon the environmental impacts, theft and vandalism also have significant economic implications that directly affect the financial sustainability of infrastructure projects. From an economic standpoint, these incidents introduce both direct and indirect financial burdens (Arthur-Aidoo et al., 2023). Direct impacts include the cost of replacing stolen materials and repairing damaged assets, while indirect impacts arise from inefficiencies in project execution. Falana et al. (2019) argue that even small-scale material losses can accumulate over time, significantly reducing contractor profitability. This issue is compounded by the fact that such losses are often not fully documented, leading to inaccuracies in cost estimation and financial reporting. Dolage and Dasantha (2022) highlight that unreliable cost data weakens financial control mechanisms, contributing to cost overruns. In addition, security-related incidents frequently cause project delays, which generate secondary financial impacts such as increased overhead costs, extended labour requirements, and idle time equipment. Almashhour and Ojiako (2025) emphasise that construction delays are the result of interconnected risk factors, suggesting that theft and vandalism should be considered as part of a broader network of risks influencing economic sustainability.

Beyond environmental and economic consequences, theft and vandalism also produce critical social impacts, particularly in infrastructure projects where outcomes are intricately linked to public service delivery. Infrastructure developments play a vital role in supporting community well-being, and delays caused by security incidents can postpone access to essential services such as transportation, energy, and water supply (Foster et al., 2020). Zhao et al. (2016) highlight the importance of stakeholder trust and governance in achieving sustainable infrastructure outcomes, noting that repeated disruptions can erode public confidence in project delivery systems. Therefore, theft and vandalism can disrupt social pillar in sustainability.

These challenges are further intensified by governance limitations and the absence of standardised benchmarks for acceptable material loss, which reduces accountability and allows security-related inefficiencies to persist (Emmanuella, 2019; Foster et al., 2020). Consequently, theft and vandalism contribute to environmental impacts through increased material waste and duplicated embodied carbon, economic losses in the form of cost overruns and resource inefficiencies, and social challenges such as reduced stakeholder trust and weakened institutional credibility. More broadly, in developing countries, these impacts are often amplified due to weaker regulatory frameworks, limited enforcement capacity, and resource constraints. As a result, security-related risks tend to have more severe and long-lasting implications on overall project sustainability and performance. To illustrate the interconnected impacts of theft and vandalism across all three sustainability dimensions, Table 1 presents key incident types, their immediate effects, and their environmental, economic, and social consequences within infrastructure construction projects.

*Table 1: Sustainability impact pathways of theft and vandalism*

| Incident Type | Immediate Effect | Environmental Impact | Economic Impact | Social Impact | Reference |
|---|---|---|---|---|---|
| **Steel theft** | Re-purchase of materials | Increased embodied carbon | Additional material costs | Project delays affecting public services | [2],[3] |
| **Fuel theft** | Increased fuel consumption | Higher emissions | Increased operational costs | Reduced project efficiency | [1],[3] |
| **Concrete vandalism** | Demolition & rework | Waste generation | Labour and material rework cost | Delayed infrastructure delivery | [1] |
| **Cable theft** | Reinstallation | Resource depletion | Replacement and installation cost | Disruption to service provision | [2].[3] |
| **Equipment damage** | Repair/replacement | Additional resource use | Repair cost and downtime | Reduced productivity and trust | [1].[4] |

(Arthur-Aidoo et al., 2023) [1]; (Nawarathna et al., 2021) [2]; (Oliva et al., 2021) [3]; (Foster et al., 2020) [4]

### 3.3 MITIGATION STRATEGIES FOR SUSTAINABLE SECURITY MANAGEMENT

Mitigating the impacts of theft and vandalism in infrastructure construction projects requires a comprehensive and integrated approach that extends beyond isolated security measures. As discussed in the previous section, security-related incidents affect environmental, economic, and social sustainability dimensions; therefore, mitigation strategies must be aligned with these broader sustainability objectives. The literature emphasises that effective security management should combine technological, managerial, contractual, and governance-based interventions to address the complex and interconnected nature of construction site risks (Fédération Internationale des Ingénieurs-Conseils [FIDIC], 1999; Zhao et al., 2016). However, the effectiveness of these strategies depends not only on their individual implementation but also on their integration within overall project management systems.

From an environmental sustainability perspective, technological interventions play a critical role in minimising material loss and reducing unnecessary resource consumption. Advanced tracking systems such as RFID and GPS enable real-time monitoring of materials and equipment, thereby reducing theft and preventing duplication of resource use (Wijerathna et al., 2024). Similarly, digital surveillance systems, including CCTV and sensor-based monitoring, enhance site visibility and act as deterrents to potential offenders. By preventing material loss, these technologies contribute directly to reducing embodied carbon and construction waste. However, their adoption is often constrained by high implementation costs and technical limitations, particularly in developing countries such as Sri Lanka, Nigeria and Malaysia, where resource availability and technological awareness remain limited (Oliva et al., 2021).

Managerial strategies further support environmental and economic sustainability by improving operational control and resource efficiency. Szymański (2017) highlights the importance of initiative-taking risk management practices such as site zoning, access control, and inventory audits, which help identify vulnerabilities and prevent security breaches. Secure storage practices and controlled access systems reduce material exposure, thereby minimising waste and associated environmental impacts. In addition, improved inventory management enhances cost control and reduces financial losses. However, the success of these strategies depends heavily on organisational commitment and the effectiveness of project leadership in enforcing security protocols (Armitage & Ekblom, 2019).

From an economic sustainability perspective, contractual mechanisms provide a structured approach to risk allocation and financial accountability. Standard forms of contract, such as those developed by FIDIC (1999) establish clear provisions for material ownership, liability, and risk transfer, which help reduce disputes and improve financial transparency. Almashhour and Ojiako (2025) emphasise that clear contractual arrangements enhance project performance by reducing uncertainty and strengthening stakeholder accountability. However, existing contractual frameworks often fail to explicitly address theft and vandalism, resulting in ambiguity and potential conflicts. Integrating security-specific clauses into contracts can therefore improve financial stability and support more effective management of sustainability-related risks (Zhao et al., 2016). At a broader level, governance and policy interventions are essential for addressing the social sustainability implications of theft and vandalism. Effective governance frameworks promote accountability, transparency, and stakeholder confidence in infrastructure projects (Zhao et al., 2016). In the absence of such frameworks, security-related losses are often normalised and inadequately addressed.

In developing countries, the effectiveness of mitigation strategies is strongly shaped by institutional, financial, and technical constraints that limit their consistent implementation across construction projects. Although technological solutions such as RFID tracking, GPS systems, and CCTV surveillance offer significant potential for reducing material loss and improving environmental performance, their adoption is often restricted by high initial investment costs and limited technical capacity within local construction organisations (Oliva et al., 2021; Wijerathna et al., 2024). Similarly, managerial, and contractual measures may exist in principle but are not always effectively enforced due to weak organisational structures and inconsistent regulatory oversight. Economically, these limitations make projects more vulnerable to cost overruns and financial instability, as even small-scale theft incidents can have amplified impacts in low-margin construction environments (Al-Hazim et al., 2017; Almashhour & Ojiako, 2025). From a social and governance perspective, the absence of standardised security benchmarks and weak enforcement mechanisms reduces accountability and allows variations in site security practices, which can undermine stakeholder confidence and public trust in infrastructure delivery (Arthur-Aidoo et al., 2023; Foster et al., 2020). As a result, while mitigation strategies are conceptually effective across environmental, economic, and social dimensions, their real-world performance in developing countries remains highly dependent on governance maturity and resource availability.

Lack of standardised guidelines and performance benchmarks for construction site security limits the ability of project stakeholders to monitor and control risks effectively (Arthur-Aidoo et al., 2023). Establishing national-level policies and reporting

mechanisms can enhance accountability and improve public trust, thereby strengthening the social sustainability of infrastructure development (Foster et al., 2020). Despite the availability of these mitigation strategies, a critical limitation identified in the literature is their fragmented implementation (Almashhour & Ojiako, 2025). While technological, managerial, contractual, and governance approaches may be effective individually, their lack of integration reduces their overall impact. This highlights the need for a systems-based approach that aligns these strategies within a unified framework, enabling a coordinated response to security risks. Such integration not only enhances the effectiveness of security management but also directly contributes to sustainability outcomes by reducing material waste, improving cost efficiency, and strengthening governance structures. Table 2 illustrates how different mitigation strategies align with environmental, economic, and social sustainability objectives, providing a structured basis for their integration within the proposed conceptual framework.

*Table 2: Mitigation strategies and sustainability outcomes*

| Strategy Type | Example | Environmental Benefit | Economic Benefit | Social/Governance Benefit | References |
|---|---|---|---|---|---|
| **Technological** | RFID, GPS tracking, CCTV | Reduces material loss and embodied carbon | Minimises replacement costs | Improve monitoring and site control | [3],[5] |
| **Managerial** | Secure storage, inventory audits, access control | Reduces waste and resource inefficiency | Improves cost control and reduces losses | Enhances accountability among workers | [4],[1] |
| **Contractual** | Risk allocation clauses, liability provisions | Indirectly reduces waste through accountability | Improves financial stability and reduces disputes | Clarify roles and responsibilities | [2] |
| **Governance** | National benchmarks, reporting systems | Supports sustainable resource management policies | Enhances transparency and financial oversight | Strengthens accountability and public trust | [6],[7] |

(Armitage & Ekblom, 2019) [1]; (FIDIC, 1999) [2]; (Oliva et al., 2021) [3]; (Szymański, 2017) [4]; (Wijerathna et al., 2024) [5]; (Foster et al., 2020) [6]; (Zhao et al., 2016) [7]

## 3.4 CONCEPTUAL FRAMEWORK

The conceptual framework developed in this study presents construction site security as a dynamic and interrelated system rather than a simple linear cause and effect relationship. It integrates concepts from construction risk management, lifecycle assessment, and infrastructure governance to explain how theft and vandalism influence sustainability performance through multiple interconnected stages. The proposed framework is illustrated in Figure 1. The conceptual framework was developed by

synthesising findings from Sections 3.1, 3.2, and 3.3 to establish the relationship between construction site vulnerabilities, theft and vandalism risks, sustainability impacts, and mitigation strategies. The framework integrates key themes identified in the literature to demonstrate how security-related incidents influence environmental, economic, and social sustainability performance in infrastructure construction projects in developing countries.

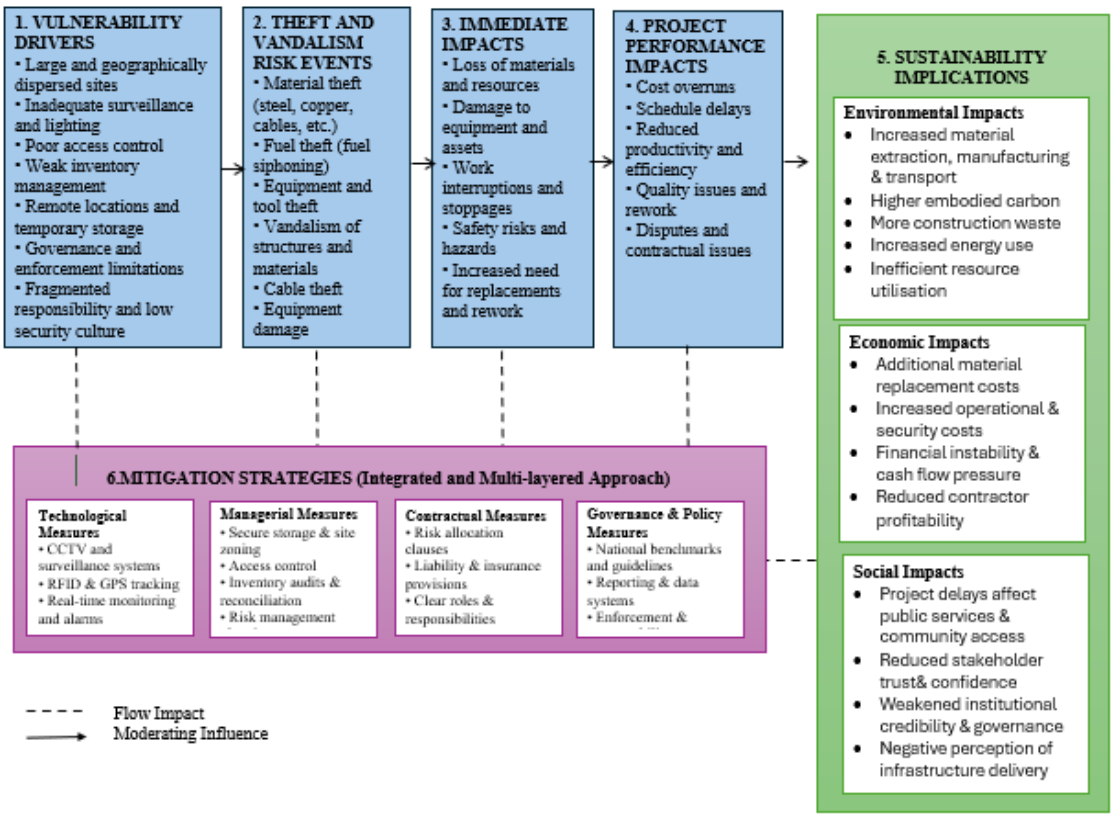



*Figure 1: Conceptual framework*

Initially, infrastructure project characteristics act as key vulnerability drivers, including large and geographically dispersed sites, temporary material storage, complex supply chains, and exposure to external environments. These conditions inherently increase susceptibility to security risks (Arthur-Aidoo et al., 2023). However, vulnerabilities alone do not directly result in risk events, as their impact depends on moderating factors such as governance quality, enforcement of security policies, contractor competence, and technological adoption. Weak governance and poor supervision amplify risks, while strong management practices mitigate them (Goh & Loosemore, 2017; Zhao et al., 2016). As a result of this interaction, vulnerabilities materialise into risk events such as theft and vandalism, marking the transition from potential exposure to actual project disruptions (Almashhour & Ojiako, 2025).

Following the occurrence of these risky events, projects experience immediate impacts, including material loss, equipment damage, work interruptions, and safety concerns. These direct effects disrupt site operations and reduce efficiency in the short term (Goh & Loosemore, 2017). Over time, such disruptions extend to broader project performance impacts, leading to cost overruns, schedule delays, productivity losses, and potential quality issues. This progression demonstrates that security incidents are not isolated

problems but have significant implications for the overall success of construction projects (Almashhour & Ojiako, 2025). Beyond project performance, following impacts contribute to wider sustainability implications across environmental, economic, and social dimensions.

The framework explains that construction site security risks, such as theft and vandalism, generate interconnected impacts across the environmental, economic, and social dimensions of sustainability. Rather than occurring in isolation, these impacts emerge simultaneously and extend throughout the project lifecycle. Material losses contribute to increased embodied carbon and resource depletion, while financial losses, delays, and productivity reductions affect economic performance (Almashhour & Ojiako, 2025; Nawarathna et al., 2021). At the same time, disruptions to project delivery influence community access and reduce stakeholder trust and institutional credibility (Al-Hazim et al., 2017). The framework further highlights that these effects are cumulative, where repeated minor incidents can intensify long-term consequences through feedback within the project system, reinforcing the need to adopt a systems-thinking perspective (Al-Hazim et al., 2017).

To manage these interconnected impacts, the framework integrates a multi-layered mitigation approach embedded within the system itself. It emphasises that technological, managerial, contractual, and governance-based measures function as dynamic feedback mechanisms rather than isolated solutions. These strategies support continuous improvement by enabling better monitoring, informed decision-making, and strengthened accountability over time (FIDIC, 1999). In addition, the framework incorporates key performance indicators, such as incident frequency, material loss rates, carbon impacts, and delay durations, to support data-driven decision-making and performance evaluation (Nawarathna et al., 2021). This ensures that construction site security is proactively managed while enhancing overall sustainability performance.

Through this integrated approach, the framework demonstrates that construction site security is not an isolated issue but a critical factor affecting sustainable infrastructure development. It provides a comprehensive structure for understanding how security risks emerge, how they impact sustainability, and how they can be effectively managed through initiative-taking and feedback-driven strategies as presented in Figure 1.

### 3.5 IMPLICATIONS OF THE STUDY

This study provides important implications for both industry practice and future academic research by repositioning construction site security as a critical component of sustainable project performance rather than a purely operational concern. From an industry perspective, the conceptual framework offers a structured approach for project stakeholders including clients, contractors, and policymakers to better understand how theft and vandalism extend beyond immediate financial losses and influence long-term environmental, economic, and social outcomes. By identifying vulnerability drivers, impact pathways, and feedback-based mitigation strategies, the framework enables practitioners to adopt a more initiative-taking and integrated risk management approach. This can support improved decision-making in areas such as resource planning, security investment, and contract administration. Additionally, the framework highlights the importance of governance and institutional strength, suggesting that strengthening policy enforcement and accountability mechanisms can significantly reduce risk exposure in construction projects.

From a research perspective, this study contributes by bridging the gap between construction security management and sustainability assessment. It introduces a systems-based view that integrates risk events with lifecycle impacts and feedback mechanisms, providing a foundation for future empirical validation. Researchers can build upon this framework by evaluating the proposed relationships using case studies, quantitative modelling, or simulation techniques. Furthermore, the study opens new avenues for exploring cross-disciplinary approaches, particularly in areas such as digital construction technologies, smart monitoring systems, and sustainable infrastructure governance. Future research can also expand the framework by incorporating additional variables such as behavioural factors, regional differences, and emerging risks.

## 4. CONCLUSIONS AND FUTURE DIRECTIONS

This study examined how theft and vandalism influence the sustainability performance of infrastructure construction projects in developing countries on sustainability aspects through a narrative literature review approach. The findings demonstrate that security breaches are not merely operational issues but significant factors influencing environmental, economic, and social sustainability outcomes. The review highlights that theft and vandalism contribute to increased material waste, duplication of embodied carbon, financial instability, and reduced stakeholder trust. These impacts collectively undermine the sustainability performance of infrastructure projects, particularly in developing countries where governance and security mechanisms may be less robust. The study also emphasizes the importance of adopting integrated mitigation strategies that combine technological innovations, managerial practices, contractual frameworks, and policy interventions. The proposed conceptual framework provides a comprehensive understanding of how security risks interact with sustainability dimensions and offers a foundation for improving decision-making in infrastructure projects. Future research should focus on empirical validation of the framework, particularly in quantifying the environmental and economic impacts of theft-related losses. By incorporating security considerations into sustainability assessment models, infrastructure projects can achieve greater resilience, efficiency, and long-term value.

## 5. REFERENCES

Al-Hazim, N., Salem, Z.A., & Ahmad, H. (2017). Delay and cost overrun in infrastructure projects in Jordan. In *7th International Conference on Engineering, Project, and Production Management* (pp.18-24). Procedia Engineering. doi: 10.1016/j.proeng.2017.03.105

Almashhour, R., & Ojiako, U. (2025). Traditional to sustainable risk management in the construction industry: A systematic literature review. *International Journal of Managing Projects in Business, 18*(3), 528-565. https://doi.org/10.1108/IJMPB-01-2025-0021

Armitage, R. & Ekblom, P. (Eds.). (2019). *Rebuilding crime prevention through environmental design: Strengthening the links with crime science* [1st ed.]. Routledge. https://www.routledge.com/Rebuilding-Crime-Prevention-Through-Environmental-Design-Strengthening-the-Links-with-Crime-Science/Armitage-Ekblom/p/book/9780367661250

Arthur-Aidoo, B. M., Coffie, H. G., Abeka, H. K., Osae-Ansah, T., & Ametsikor, K. (2023). Theft and vandalism control measures on construction sites. *African Journal of Applied Research, 9*(2), 284–301. https://doi.org/10.26437/ajar.v9i2.595

Dolage, D. A. R., & Dasantha, O. M. C. (2022). Critical factors affecting cost overrun in foreign funded road construction projects in Sri Lanka: A case study of road development authority and provincial road development authorities. *Engineer: Journal of the Institution of Engineers, Sri Lanka, 55*(2), 21-30. https://doi.org/10.4038/ENGINEER.V55I2.7505

Emmanuella, O. O. (2019). Strategic construction oversight for sustainable infrastructure development across national significant construction sectors. *International Journal of Computer Applications Technology and Research, 8*(2), 516–531. https://www.researchgate.net/profile/Emmanuella-Osifo-2/publication/391597723_Strategic_Contract_Oversight_for_Sustainable_Infrastructure_Development_Across_Nationally_Significant_Construction_Sectors/links/681e365bded4331557450563/Strategic-Contract-Oversight-for-Sustainable-Infrastructure-Development-Across-Nationally-Significant-Construction-Sectors.pdf

Falana, J. N., Falana, J. N., & Ghazaly, N. M. (2019). Examination of causes and effects of accident on construction sites: (Case Study of Lagos, Lagos State, Nigeria). *International Journal of Advanced Science and Technology, 28*(16), 1687–1694. https://www.researchgate.net/publication/338083905

Fédération Internationale des Ingénieurs-Conseils. (1999). *Conditions of contract for construction: For building and engineering works designed by the employer* (1st ed.). https://lauwtjunnji.weebly.com/uploads/1/0/1/7/10171621/fidic_-_conditions_of_contract_for_construction_for_building_and_engineering_works_designed_by_the_employer_(1999).pdf

Foster, V., Hawkesworth, I., Harris, C., Brumby, J., Sobjak, A., Ibanez, M.T., Rana, A., & Bilous, A. (2020). *Infrastructure governance assessment framework: December 2020*. World Bank Group. https://thedocs.worldbank.org/en/doc/96550c14d62154355b6edc367d4d7f33-0080012021/infrastructure-governance-assessment-framework-december-2020

Goh, E., & Loosemore, M. (2017). The impacts of industrialization on construction subcontractors: a resource-based view. *Construction Management and Economics, 35*(5), 288–304. https://doi.org/10.1080/01446193.2016.1253856

Kumanayake, R. P., & Luo, H. (2018). Cradle-to-gate life cycle assessment of energy and carbon of a residential building in Sri Lanka. *Journal of the National Science Foundation of Sri Lanka, 46*(3), 355–367. https://doi.org/10.4038/jnsfsr.v46i3.8487

Nawarathna, A., Siriwardana, M., & Alwan, Z. (2021). Embodied carbon as a material selection criterion: Insights from Sri Lankan construction sector. *Sustainability 2021, 13*(4), 1–20. https://doi.org/10.3390/su13042202

Oliva, G., Faramondi, L., Setola, R., Tesei, M., & Zio, E. (2021). A multi-criteria model for the security assessment of large-infrastructure construction sites. *International Journal of Critical Infrastructure Protection, 35*, 100460. https://doi.org/10.1016/J.IJCIP.2021.100460

Rathnayake, R. M. L. D., Madushantha, R. M. L., Gunawardana, W. A. P. C. P., & Dissanayake, P. B. R. (2022). Unveiling construction and demolition waste dynamics: a case study of the building construction. *Engineer, LVII*(4), 47-54. https://doi.org/10.4038/engineer.v57i4.7665

Sivarajah, T. (2021). Construction project delays in Sri Lanka. *Journal of Research Technology & Enineering*, *2*(4), 25-29. https://www.researchgate.net/publication/355170739_Construction_Projects_delays_in_Sri_Lanka

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*(1), 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Szymański, P. (2017). Risk management in construction projects. *Procedia Engineering, 208*, 174–182. https://doi.org/10.1016/J.PROENG.2017.11.036

Wijerathna, M. R. D. P., Waidyasekara, K. G. A. S., & Atapattu, A. M. D. S. (2024). Unveiling the benefits of radio frequency identification (RFID) technology for enhancing technological applications in Sri Lankan construction industry. In Y.G. Sandanayake, K.G.A.S. Waidyasekara, K.A.T.O. Ranadewa, & H. Chandanie (Eds). *Proceedings of the 12th World Construction Symposium* (pp. 1088–1100). https://doi.org/10.31705/WCS.2024.86

Zhao, D., McCoy, A. P., Kleiner, B. M., Mills, T. H., & Lingard, H. (2016). Stakeholder perceptions of risk in construction. *Safety Science, 82*, 111–119. https://doi.org/10.1016/J.SSCI.2015.09.002

Hettiarachchi, K., Kulatunga, U. and Uduwage, D.N.L.S., 2026. Typological synthesis of cost overrun determinants in road construction using "K-means": A narrative synthesis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1774-1787. DOI: https://doi.org/10.31705/WCS.2026.129. Available from: https://ciobwcs.com/papers/

# TYPOLOGICAL SYNTHESIS OF COST OVERRUN DETERMINANTS IN ROAD CONSTRUCTION USING "K-MEANS": A NARRATIVE SYNTHESIS

**K. Hettiarachchi[1], U. Kulatunga[2], and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Road projects are indispensable for a country's economic and social development. Despite the importance, road construction projects are vulnerable to cost overruns. Thus, the identification of causative factors is prudent to mitigate the risk of cost overruns. While previous studies have identified cost overrun factors in isolation even lack systematic clustering of factors. Furthermore, few studies have employed unsupervised clustering techniques to objectively classify cost overrun factors, whereas most have relied on subjective categorisation methods. This study conducted a data-driven typology of cost overruns in global road construction projects through a narrative synthesis. The data were extracted from peer-reviewed literature in the Scopus, Taylor & Francis and ProQuest databases, which provide comprehensive coverage of construction management and engineering literature from 2020 to 2025, to capture contemporary road cost overrun factors. Subsequently, hierarchical clustering was applied to determine the number of clusters, followed by K-means clustering to optimise the classification of cost overrun factors. Results identified 253 cost overrun factors, which were first organised into nine thematic categories and subsequently grouped into the three identified clusters. The most frequently cited factors across the literature were 'political instability, supply chain disruptions, contractor's incompetence, inaccurate cost estimation, project scope changes, claims due to uncertainty incidents, financial mismanagement by contractor, delays in obtaining permits, delays in contractor's payments and inappropriate procurement systems. The unsupervised clustering offers a systematic classification of cost overrun factors that can be applied to different domains in future.*

***Keywords:*** *Hierarchical Clustering; K-Means; Road Cost Overruns; Typology.*

## 1. INTRODUCTION

A well-developed road network is essential for economic growth, reducing transportation costs, boosting trade and fostering regional integration in a country. Even though roads are important, recurring cost overruns are a global issue that affects the expansion of roads (Asiedu & Adaku, 2019). Nonetheless, cost overruns in road projects result in project

[1] MPhil. Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, hettiarachchikn.25@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ukulatunga@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

prolongation, project termination and construction disputes suffered by stakeholders (Babalola et al., 2022). In one of the earliest studies in construction, Love et al. (2015) found that nearly 90% of the transportation projects experienced cost overruns based on the analysed project samples. Aljohani (2017) reported cost overruns within a range of 15% to 28%. One of the most cited studies is that of Flyvbjerg et al. (2018), who determined the probability of cost overrun is 86% based on analysed project datasets. Further, recent studies have also emphasised the growing prevalence of cost overruns in road construction projects as well. According to Zhao et al. (2024), the actual cost spent on the development of the England highway system from 2020 to 2025 was estimated to exceed the original estimate by approximately 31%. Empirical evidence has established that cost overruns have experienced unprecedented growth over the past ten years, emphasising the necessity of a formal classification to facilitate the prioritisation of management efforts. Numerous studies have been conducted to study a multitude of cost overrun factors in construction projects e.g. road projects (Wibowo & Santoso, 2024), mega construction projects (Elshamy et al., 2025), building projects (Alshihri et al., 2022), and categorised by the attributes of the factors. One of the most common classifications was technical, economic, contractual, psychological and political factors (Plebankiewicz, 2018). However, environmental factors were not included in Plebankiewicz (2018) classification. In contrast to Plebankiewicz (2018) classification, Isfahani et al. (2024) divided 85 factors into six groups according to the conceptual basis as external, material, labour, equipment, subcontractor and finance. Zhao et al. (2024) identified seven most critical cost overrun factors into two categories, as per the scope of application, named expertise-related factors and personal factors. Additionally, prior studies relied on expert reviews and deductive taxonomies, failing to fully address the multidimensional, data-driven nature of road cost overrun factors (Isfahani et al., 2024; Zhao et al., 2024). Furthermore, past studies have failed to consider certain unexpected costs emerging after tendering (Love et al., 2025). Certain traditional typologies incompletely represented cost overrun factors by omitting emerging factors such as climate change impacts and digital transformation challenges (Plebankiewicz, 2018). In summary, existing classifications are subjective and fragmented; a reproducible data-driven typology is needed (Gómez-Cabrera et al., 2024). To address the methodological and empirical gap, this study utilises statistically validated unsupervised clustering techniques to develop a comprehensive, data-driven road cost overrun typology based on global literature synthesis.

## 2. METHODS

This study was conducted as a structured narrative synthesis combined with data-driven clustering to synthesise cost overrun factors in road construction projects. A structured narrative synthesis provides a synthesis of cost overrun factors across the rapidly evolving construction sector, where heterogeneous study designs preclude traditional systematic meta-analysis (Green et al., 2006). Literature searches were performed in Scopus, Taylor & Francis, ProQuest and Google Scholar using search terms 'roads', 'road network', 'rural roads', 'road project', 'highway', 'road construction', 'factors causing cost overrun', 'cost overrun', 'cost exceed' and 'cost contingency'. The references included English-language journal articles and conference papers for further screening. The findings were informed by recent empirical evidence published between 2020 and 2025 to ensure that the evidence reflects current economic, technological, and institutional conditions affecting road construction projects. The post-2020 period represented a

transformation in construction costs, driven by supply-chain disruptions, inflation volatility, pandemic-induced project delays, fuel and material price escalation, and the rapid digitalisation of project management practices. However, pre-2020 findings were less focused on contemporary factors driving road cost overruns. Additionally, recent studies emphasised that contemporary road projects experience greater cost overruns than in the past (Eliasson, 2024). Therefore, restricting the review to the 2020-2025 period is not a limitation rather a methodological necessity. Literature was analysed using thematic analysis to identify recurring cost overrun factors. The frequency of occurrence for each factor was recorded through the studies to recognise patterns. Factors were then compared conceptually to identify similarities and group related factors using the inductive coding method. Moreover, agglomerative hierarchical clustering was first applied to determine the optimal number of clusters using dendrogram analysis. Subsequently, K-means was utilised in this study to refine cluster assignments compared to a single method (Ling & Weiling, 2025) (refer Figure 1).

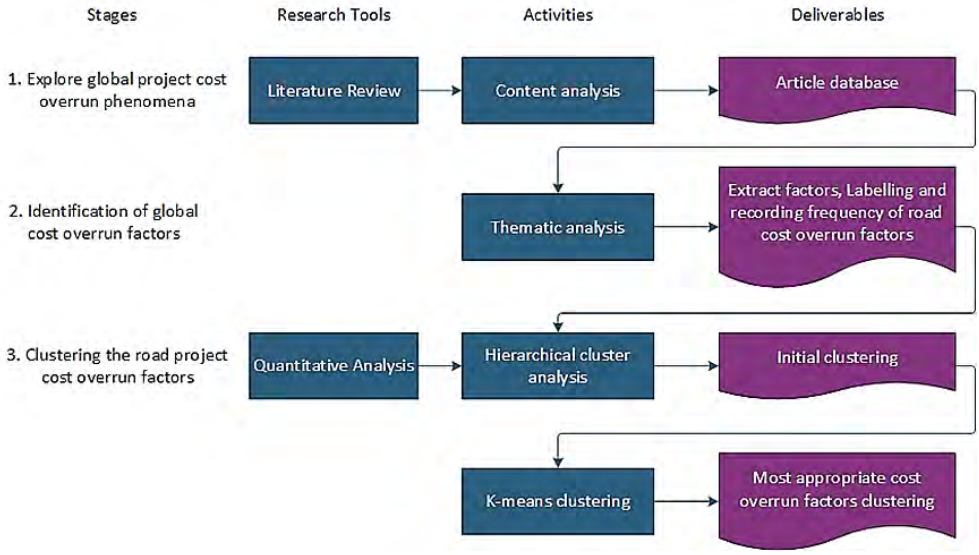



*Figure 1: Research method*

Agglomerative clustering merges clusters until all observations form a single cluster (Sieranoja & Fränti, 2025). The Ward's method was applied to minimise within-cluster variance. Nevertheless, the hierarchical technique has a slow computational speed and limited operational scalability for large datasets. Therefore, K-means was employed to partition heterogeneous data points into a predetermined number of clusters (K) without overlapping groups. The refined iteration process of K-means optimises clustering by minimising variance within clusters (Khan et al., 2024) and has less influence by outliers than hierarchical clustering, thereby producing more balanced clusters (Izuzquiza et al., 2026). The optimal number of clusters (K) was first determined by analysing the agglomerative clustering dendrogram. The optimal K value was then used as input for K-means clustering (Govender & Sivakumar, 2020). Eventually, the resulting clusters were labelled based on the dominant factor characteristics, which resulted in distinct, well-separated clusters.

## 3. RESULTS

This study examines the prominence of causative factors of road project cost overrun. Since the frequency of the factors was captured using content analysis and examined by

thematic analysis. Subsequently, hierarchical clustering and K-means clustering were applied for systematic grouping of the factors into typologies. The methodology enhances the reliability and robustness of data-driven typology through a combination of frequency patterns with thematic similarity to categorise cost overrun factors systematically.

## 3.1 COST OVERRUN DEFINITION

The definition of cost overrun has evolved. Cost overrun has been consistently defined as the difference between actual and estimated costs (Enrica et al., 2021; Flyvbjerg et al., 2003, 2018), though the specific baseline for comparison varies across studies. Conversely, Shehu et al. (2014) defined cost overrun as an increase in project costs that stakeholders did not anticipate. Love et al. (2015) drew on the work of Shehu et al. (2014), suggesting that the difference between a 'cost overrun' and a 'cost escalation' is that cost overruns are typically not anticipated in the pre-tendering stage, while cost escalation is pre-determined. While a variety of definitions of the term cost overrun have been suggested, this study adopts Love et al. (2015) definition of cost overrun as 'the deviation where actual expenditures surpass the budgetary baseline agreed upon by stakeholders prior to the tendering process' to recognise the global road cost overrun factors. This selected cost overrun definition identifies cost overrun factors that represent genuine project control failures rather than foreseeable external conditions at the time of contracting.

## 3.2 FACTOR IDENTIFICATION

Identifying the causative cost overrun factors is a stepping stone towards improving the cost performance of a road project. Therefore, this study identified major factors causing road cost overrun through content analysis of recent literature from developed and developing countries, including the United Kingdom, United States, Canada, Australia, Ethiopia, Kenya, Benin, Bangladesh, and Pakistan etc. (refer Figure 2).

*Figure 2: Road cost overrun reported in different countries*

The factors were selected based on the definition of cost overrun, whereas this study did not encompass controversial factors like 'inflation in construction commodities' and 'volatility in fuel prices' (refer Figure 3).

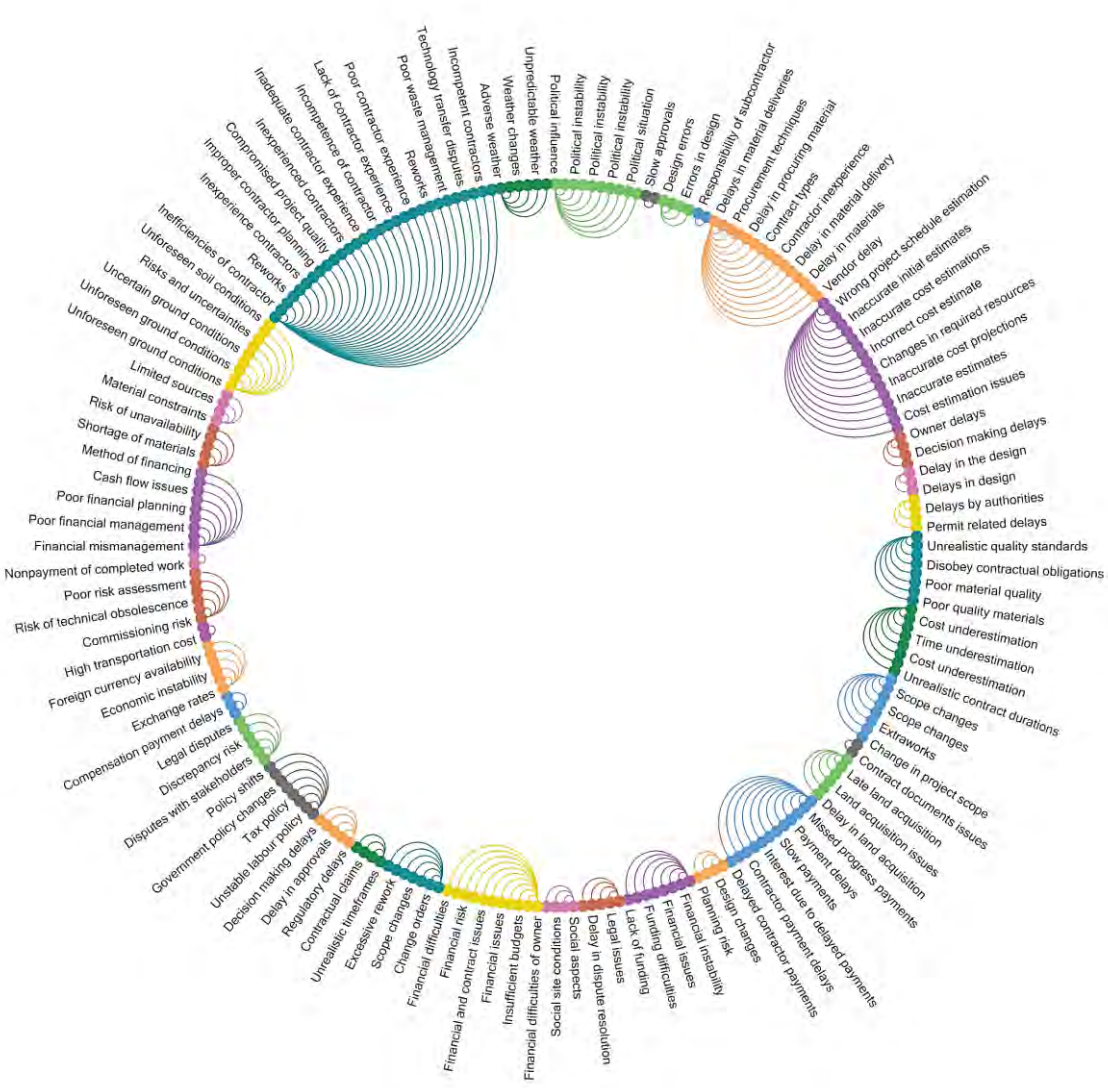



*Figure 3: Road cost overrun factors reported in last five years*

Unlike traditional deductive classifications, this study adopted an inductive coding modelled on a grounded theory approach that allowed categories to emerge from the extracted cost overrun dataset. The coding process comprised three systematic phases. First, open coding was applied to identify initial concepts and patterns. Second, axial coding recognised trends across each category by examining thematic topics of concern, manifest content and latent content. Third, selective coding yielded brief summaries of patterns within the coded categories (Hagen et al., 2022) (refer Table 1). Hence, the inductive categorisation approach enhanced the reliability and accuracy of the primary factor classification compared to predetermined frameworks (Sanders & Cuneo, 2010).

*Table 1: Literature review of factors of cost deviations in road projects*

| No. | Selective Coding | Label | Frequency |
|---|---|---|---|
| 1 | Political & Regulatory Risks | Approval issues | 27 |
| 2 | Scope Variation Risks | Claims & variations | 31 |
| 3 | Contractual & Legal Risks | Construction disputes | 11 |

| No. | Selective Coding | Label | Frequency |
|---|---|---|---|
| 4 | Design Risks | Design issues | 11 |
| 5 | Cost Estimation Risks | Estimation issues | 26 |
| 6 | Financial Risks | Financial issues | 42 |
| 7 | Contractor Performance Risks | Performance issues | 37 |
| 8 | Resource Procurement Risks | Procurement issues | 33 |
| 9 | External Environmental Risks | Unforeseen events | 35 |

The nine thematic categories were further analysed using agglomerative hierarchical clustering and K-means clustering methods to systematically cluster the categories based on thematic similarities.

## 3.3 STATIC CLUSTERING

The clustering process consists of data normalisation, hierarchical clustering and K-means clustering. The thematic data (refer Table 1) underwent Z-score normalisation to standardise the significance of each attribute in the distance matrix to ensure that each attribute contributed equally to the clustering analysis. Afterwards, the Z-score data were clustered using hierarchical clustering with Ward's linkage and the Squared Euclidean distance metric. Ward's linkage encourages creating homogeneous clusters in hierarchical clustering (Jolliffe & Philipp, 2010; Tufféry, 2011). The hierarchical clustering algorithm results are presented as follows (refer Figure 4).

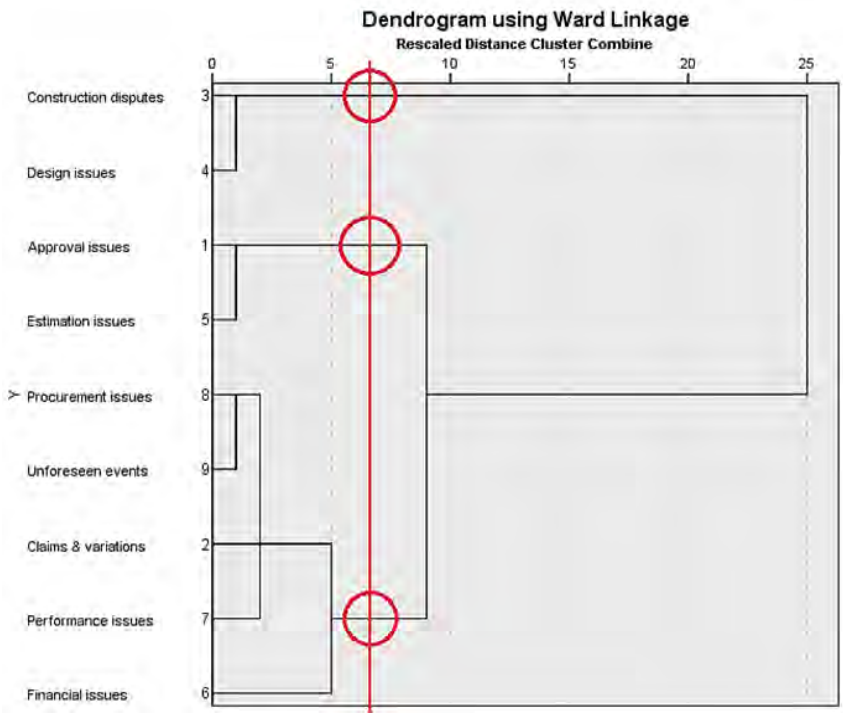



*Figure 4: Dendrogram of the hierarchical clustering*

The dendrogram (refer Figure 4) shows the hierarchical relationships among the nine thematic categories. Construction disputes (3) and Design issues (4) show closer proximity than the distance between Claims and variations (2) and Estimation issues (5). Meanwhile, data on Procurement issues (8) and Performance issues (7) are grouped

together due to the proximity of the data points. Conversely, Financial issues (6) are isolated from Construction disputes (3) due to the significant distance gap. However, segmenting the dendrogram at a desired level yields a set of clusters (Kassomenos et al., 2010). After evaluating the results and manually inspecting the dendrogram, the best configuration consisted of three clusters. The analysis was further refined by K-means clustering. Unlike hierarchical techniques, K-means produces a flat clustering structure. The optimal number of clusters was predetermined by the hierarchical clustering. Accordingly, the K-means cluster analysis was run with three preconceived clusters after two iterations. The ANOVA table reveals that the clusters are statistically significant (refer Figure 5).

**ANOVA**

| | Cluster | | Error | | F | Sig. |
|---|---|---|---|---|---|---|
| | Mean Square | df | Mean Square | df | | |
| Zscore(Frequency) | 3.751 | 2 | .083 | 6 | 45.148 | .000 |

*Figure 5: ANOVA table*

**Cluster Membership**

| Case Number | Factor | Cluster | Distance |
|---|---|---|---|
| 1 | Approval issues | 1 | .207 |
| 2 | Claims & variations | 1 | .161 |
| 3 | Construction disputes | 3 | .000 |
| 4 | Design issues | 3 | .000 |
| 5 | Estimation issues | 1 | .299 |
| 6 | Financial issues | 2 | .368 |
| 7 | Performance issues | 2 | .092 |
| 8 | Procurement issues | 1 | .345 |
| 9 | Unforeseen events | 2 | .276 |

**Number of Cases in each Cluster**

| | | |
|---|---|---|
| Cluster | 1 | 4.000 |
| | 2 | 3.000 |
| | 3 | 2.000 |
| Valid | | 9.000 |
| Missing | | .000 |

*Figure 6: Cluster breakdown*

The final solution allocated four thematic labels to Cluster 1, another three to Cluster 2, and the remaining two to Cluster 3, without missing data (refer Figure 6). This categorical distribution emphasises a unique thematic stratification within the factors, reflecting the heterogeneity of road project cost overruns. The integration of descriptive thematic labels improves the clustering analysis and provides a more comprehensive understanding of the data. Clusters were labelled according to the dominant thematic characteristics of factors within each cluster. The results from the cluster breakdown were denoted as Cluster 1: Pre-construction and Contractual Uncertainties, Cluster 2: Integrated Project Risk and Performance Constraints, and Cluster 3: Contractual and Design Coordination Failures (refer Figure 7). Further analysis showed that the factors in Cluster 2 have been reported more frequently. Cluster 2 suggested that systemic risks and performance barriers are frequently cited as major threats to budgetary integrity in road projects globally. The single most striking observation to emerge from the data comparison was the highest occurrence frequency of ‘Political instability’ in Cluster 2. Political influence, political connections, project termination due to economic policy change, persistent political instability, unstable labour policy, political force majeure (war, riot, terrorism, strike, etc.), and availability of foreign currency were all categorised under the 'Political

instability' factor. Road projects are highly susceptible to broader socio-political conditions and are often beyond the immediate control of project stakeholders. Moreover, several factors showed moderate reporting frequencies, including supply chain disruptions, contractor incompetence, financial mismanagement by the contractor, and delays in the contractor's payments. In contrast, other factors were reported less frequently, including inappropriate procurement systems, insufficient budgets, administrative bottlenecks, slow payment process, adverse weather conditions, poor construction quality, contract types, lack of technical expertise, nonpayment of completed work, project planning issues, pandemics, and quantity changes. The factors in Cluster 2 were the most frequently cited, and the factors in Cluster 1 were less frequently cited. Frequency patterns suggested that macro-level systemic risks (Cluster 2) may be more common and salient in the literature than site-specific contractual issues (Cluster 1). Cluster 1 included inaccurate cost estimation, project scope changes, other claims due to uncertainty incidents, delays in permit acquisition, delays in land acquisition, delays in decision-making by stakeholders, project underestimation, unrealistic time schedules, and contractor claims, highlighting the vulnerabilities inherent in the early lifecycle stages of road construction. Cluster 3 contained the barely cited road cost overrun factors, yet the cluster remained theoretically significant for understanding technical failures. 'Design errors' was the most frequently cited factor in Cluster 3. Errors and omissions in the design, inadequate designer capabilities, and a lack of proper basic engineering led to an increase in the severity of design errors. While 'design errors' were reported less frequently, the factor's presence remains a persistent driver of secondary cost overruns in road projects. Together, the results provided important insights into a proper cost overrun typology. Nonetheless, the below typology assists project stakeholders to prioritise road cost overrun mitigation strategies (refer Figure 7).

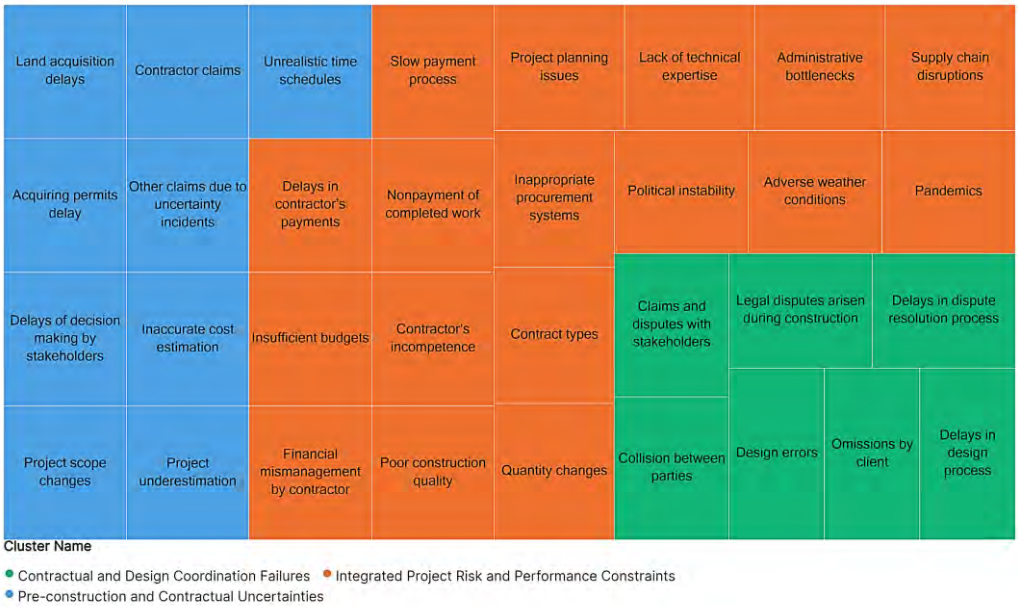



*Figure 7: Cost overrun typology*

A considerable amount of recent research has been done to study the characteristics of factors affecting cost overruns. Earlier typologies focused on a few cost overrun factors related to the road construction sector and prioritised high-impact factors only. In

contrast, contemporary studies have expanded the scope by adopting a multidimensional aspect (refer Table 2).

*Table 2: Past road cost overrun typologies*

| No. | Classification | Source |
|---|---|---|
| 1 | Contractor related, Project management and contract administration related, Design and documentation related, Financial management related, Information and communication technology related, Labour management related, Material management related, Environment related, Psychological related, Political related | Atapattu et al. (2023) |
| 2 | Client related, Design related, Contractor related, External related and Other stakeholders related | Al Adawi & Yahia (2021) |
| 3 | External factors and Internal factors (Project and Activities) | Ammar et al. (2022) |
| 4 | Project owner perspective and Contractor perspective | Anwari (2022) |
| 5 | Technical, Financial, Political, Legal, Environmental and Social factors | Verma et al. (2020) |
| 6 | Design, Consultant, Owner, Contractor, Material, Equipment, Contract, Labour risk, External (corona virus effects), External (others) and operational factors | Gamal et al. (2023) |
| 7 | Consultant, Contract, Contractor, Contractual relationships, Design, Equipment, External, Financial, Laws and regulations, Materials, Owner, Personal, Programming and control, Project and Site factors | Herrera et al. (2020) |

Building on the work of Rahman et al. (2013), Atapattu et al. (2023) advanced the cost overrun classification framework with three additional and significant areas. Accordingly, most articles identified ‘poor project management’ as a significant cause of road cost overrun. In addition, ‘frequent design changes’, ‘unpredictable weather conditions’, ‘lack of experience in similar projects’ and ‘shortage of technical personnel’ were also identified as significant factors among the fifty-three factors examined. Similarly, Al Adawi & Yahia (2021) ranked the top five most critical cost overrun factors amongst fifty-two factors in Oman road projects as ‘contractors are not paid on time’, ‘incomplete design at the time of tender’, ‘design errors’, ‘cost underestimation’ and ‘funding difficulties’. Ammar’s cross-country analysis (2022) identified fifty-six road cost overrun factors, including the two most critical, namely ‘political interference’ and ‘inflation’. The remaining six factors were related to internal factors, namely ‘inaccurate cost estimates’, ‘design modifications’, ‘quantity changes’, ‘variation orders’, ‘specification changes’ and ‘scope of work’. Furthermore, the results revealed that ‘design modifications’ and ‘low estimates for budgets and quantities’ were the main factors affecting road cost overruns. Another important finding of the study was no relationship between project size or duration and cost overrun percentage. Anwari (2022) identified the top eight causes among twenty-five factors in Afghan road projects: weather and climate conditions, improper planning, financial issues, land acquisition and community challenges, fluctuations in material prices, shortages of resources/ materials/ equipment, and delays in payments. Deferment in land acquisition, cash flow the throughout construction process, mishandling by the contractor (finance, supplier,

support, sub-contract), inappropriate planning and variation in the scope of the project or extra work were the top five risk factors among thirty five factors that had the greatest impact on cost overrun of Public Private Partnership constructed roads and highway projects in India (Verma et al., 2020). Gamal et al. (2023) reported similar effects of road cost overrun when prioritising eleven high-risk categories from one hundred sixty-two variables: operation risk, external risk (Coronavirus effects), external risk (Others), contract risk, equipment, material, contractor, design risk, owner, labour risk and consultant risk. The results also indicated that the two biggest influences on cost overruns in road projects were operational and external risks. A recent systematic literature review by Herrera et al. (2020) identified the ten most important and frequent cost overrun factors from thirty-eight determinants: failures in design, price variation of materials, inadequate project planning, project scope changes, design changes, unrealistic contract duration, inadequate bidding method, legal issues, late decision-making by the owner, and political situation. The factors identified in this study corroborate earlier findings. On the other hand, the frequency of key factors in this investigation is more influential compared to the seminal studies (refer Figure 8).

| Most Infulential Cost Overrun Factors Based On This Study | Cost Overrun Factors Based on The Previous Studies |
|---|---|
| • Political instability<br>• Supply chain disruptions<br>• Contractor's incompetence<br>• Inaccurate cost estimation<br>• Project scope changes<br>• Claims due to uncertainty incidents<br>• Financial mismanagement by contractor<br>• Acquiring permits delays<br>• Delays in contractor's payments<br>• Inappropriate procurement systems | • Planning and design failures<br>• Inaccurate cost estimates<br>• Payment issues<br>• Price fluctuations<br>• Variations and claims<br>• Late decisions-making<br>• Shortage of technical personnel<br>• Shortage of material and equipment<br>• Unpredictable weather<br>• Political interference |

*Figure 8: Comparison of the cost overrun typology and ordinary cost overrun factors*

The conceptual framework presented below (refer Figure 9) illustrates the comprehensive interconnections between cost overrun of rural road projects as dependent variables and the multifaceted factors which are causing the problem as independent variables. Referring to the cost overrun typology (refer Figure 7), 33 most influential cost overrun factors were systematically identified and classified under nine different core themes, providing a structured approach to understanding this complex phenomenon. The themes encompass various dimensions, including approval issues, claims and variations, estimation issues, performance issues, procurement issues, unforeseen events, construction disputes, design issues and financial issues that contribute to project cost overrun. Clients often suffer significant financial and operational consequences due to road project cost overrun, as demonstrated in strategic consequences, which may include delayed project completion, reduced return on investment, project suspension, project abandonment, stakeholder dissatisfaction, and compromised project quality. Furthermore, the framework below incorporates evidence-based mitigation strategies to minimise cost overrun in road projects, offering practical interventions that stakeholders

can implement throughout the project lifecycle to enhance cost control and improve overall project performance (refer Figure 9).

*Figure 9: Conceptual framework for mitigate cost overrun in road construction projects*

The results revealed a typology of road cost overruns rather than individual factors. Traditional typologies are mostly deductive and expert-based classifications that do not fully capture the complex, multidimensional nature of road cost overruns revealed by data-driven approaches. In contrast, this study discovered three clusters using an unsupervised hybrid clustering method rather than relying on predetermined expert labels. The clusters derived from statistically validated similarity patterns better reflect the rigorous factors that affect road cost overruns. This comprehensive study conducted

a systematic analysis of road cost overrun factors that were categorised according to the stipulated definition. Thus, this study provides theoretical insight and practical guidance by synthesising the latest factors influencing road cost overruns. The relative infrequency of some factors does not necessarily diminish the criticality of the road cost overrun factors.

# 4. CONCLUSIONS

Road cost overruns are an endemic problem. Cost overruns are a significant concern and financial risk for project owners. In the worst cases, cost overruns lead to interruption of construction activities and even the abandonment of projects. Despite the consequences, systematic typologies that provide a comprehensive overview of the phenomenon and global solutions are lacking. This investigation aimed to develop a comprehensive, data-driven typology of global road cost overruns. Accordingly, 253 project cost overrun factors derived empirically from literature patterns were grouped into 'approval issues, claims and variations, construction disputes, design issues, estimation issues, financial issues, performance issues, procurement issues and unforeseen events' labels and categorised into three clusters using 'Hierarchical clustering' and 'K-means'. This study advanced the field from expert groupings toward the discovery of empirical structure. The findings clearly indicated that the most frequently reported factor in the analysed literature is 'political instability', which belonged to Cluster 2. Strategically, multi-dimensional political and economic volatility may be mitigated through strong Political Risk Insurance (PRI). The necessary stabilisation clauses must be contained in host-government contracts to protect projects from arbitrary fiscal or policy shifts. Furthermore, companies must adopt adaptive financial engineering strategies in particular multi-currency financing and local sourcing and a holistic risk management framework such as Enterprise Risk Management (ERM) to help maintain operational continuity amid foreign exchange fluctuations and force majeure events. Additionally, contractors must exercise due diligence and duty of care to mitigate 'supply chain disruptions, incompetencies, inaccurate cost estimation and financial mismanagement'. Remarkably, continuous changes in scope are a crucial cause of cost overruns, which may be minimised by modifying design development methodologies and implementing advanced technologies (e.g., BIM). Additionally, this data-driven typology may support stakeholders in accurate estimation, take pre-emptive actions to mitigate future cost overrun risk and prioritise investments. The study was limited in several ways. First, the study used four academic databases to capture the road cost overrun factors from 2020 to 2025, which may not capture all relevant factors or regional variations. Second, the analysis was based on citation frequency rather than project-level empirical data, which may not reflect the relative importance of cost overrun factors. Third, the interpretation of cluster names is subject to judgments that may affect reproducibility. The study should be repeated to strengthen the results of this data-driven typology across different project datasets and geographic regions. Moreover, examine the relative impact magnitude of road cost overrun factors within each cluster.

# 5. REFERENCES

Al Adawi, O. S., & Yahia, H. (2021). Causes of costs overrun in road construction project in Oman. *Journal of Student Research*, *10*(3), Retrieved from https://www.researchgate.net/publication/356572993_Causes_of_Costs_Overrun_in_Road_Construction_Project_in_Oman

Aljohani, A. (2017). Construction projects cost overrun: what does the literature tell us? *International Journal of Innovation, Management and Technology*, *8*(2), 137–143. https://doi.org/10.18178/ijimt.2017.8.2.717.

Alshihri, S., Al-Gahtani, K., & Almohsen, A. (2022). Risk factors that lead to time and cost overruns of building projects in Saudi Arabia. *Buildings*, *12*(7), 902. https://doi.org/10.3390/buildings12070902.

Ammar, T., Abdel-Monem, M., & El-Dash, K. (2022). Risk factors causing cost overruns in road networks. *Ain Shams Engineering Journal*, *13*(5), 101720. https://doi.org/10.1016/j.asej.2022.101720.

Anwari, Z. (2022). Causes of time delay and cost overrun of rural road projects in Afghanistan. *Kardan Journal of Economics and Manangement Sciences*, *5*(2), 2. https://doi.org/10.31841/KJEMS.2022.118.

Asiedu, R. O., & Adaku, E. (2019). Cost overruns of public sector construction projects: A developing country perspective. *International Journal of Managing Projects in Business*, *13*(1), 66–84. https://doi.org/10.1108/IJMPB-09-2018-0177.

Atapattu, C. N., Domingo, N., & Sutrisna, M. (2023). Significant factors affecting the New Zealand transportation infrastructure project cost – quantity surveyors' perception. *Built Environment Project and Asset Management*, *13*(5), 756–777. https://doi.org/10.1108/BEPAM-07-2022-0105.

Babalola, A. J., Aderogba, A. M., & Adetunji, O. O. (2022). Inflation and cost overrun in public sector construction projects in Nigeria. *ECS Transactions*, *107*(1), 16137–16147. https://doi.org/10.1149/10701.16137ecst.

Eliasson, J. (2024). *Cost overruns of infrastructure projects – distributions, causes and remedies*. *Transportation Research Part A: Policy and Practice*, 198, 104532. https://doi.org/10.2139/ssrn.5044048.

Elshamy, M. M. N. A., Elghaish, F., & Brooks, T. (2025). Exploring risk factors causing delays in mega project in Gulf region: An industrial qualitative approach. *Smart and Sustainable Built Environment*, https://doi.org/10.1108/SASBE-10-2024-0419.

Enrica, M., Purba, H., & Purba, A. (2021). Risks leading to cost overrun in construction projects: A systematic literature review. *Advance Researches in Civil Engineering*, *3*(1), https://doi.org/10.30469/arce.2021.130147.

Flyvbjerg, B., Ansar, A., Budzier, A., Buhl, S., Cantarelli, C., Garbuio, M., Glenting, C., Holm, M. S., Lovallo, D., Lunn, D., Molin, E., Rønnest, A., Stewart, A., & Van Wee, B. (2018). Five things you should know about cost overrun. *Transportation Research Part A: Policy and Practice*, *118*, 174–190. https://doi.org/10.1016/j.tra.2018.07.013.

Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2003). How common and how large are cost overruns in transport infrastructure projects? *Transport Reviews*, *23*(1), 71–88. https://doi.org/10.1080/01441640309904.

Gamal, Y. A. S., Abd Allah, E. M., Maged, M., & Enieb, M. (2023). Evaluation of the risk factors impacting the cost overruns in the construction of roads in Egypt during the covid-19 pandemic. *Mansoura Engineering Journal*, *48*(4). https://doi.org/10.58491/2735-4202.3047.

Gómez-Cabrera, A., Gutierrez-Bucheli, L., & Muñoz, S. (2024). Causes of time and cost overruns in construction projects: A scoping review. *International Journal of Construction Management*, *24*(10), 1107–1125. https://doi.org/10.1080/15623599.2023.2252288.

Govender, P., & Sivakumar, V. (2020). Application of k-means and hierarchical clustering techniques for analysis of air pollution: A review (1980–2019). *Atmospheric Pollution Research*, *11*(1), 40–56. https://doi.org/10.1016/j.apr.2019.09.009.

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. *Journal of Chiropractic Medicine*, *5*(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6.

Hagen, L., Fox, A., O'Leary, H., Dyson, D., Walker, K., Lengacher, C. A., & Hernandez, R. (2022). The role of influential actors in fostering the polarized covid-19 vaccine discourse on twitter: Mixed methods of machine learning and inductive coding. *JMIR Infodemiology*, *2*(1), e34231. https://doi.org/10.2196/34231.

Herrera, R. F., Sánchez, O., Castañeda, K., & Porras, H. (2020). Cost overrun causative factors in road infrastructure projects: A frequency and importance analysis. *Applied Sciences*, *10*(16), 5506. https://doi.org/10.3390/app10165506.

Isfahani, M. N., Romadhon, E. S., & Romadhon, M. I. (2024). Cost overrun factor of toll road project construction. *IOP Conference Series: Earth and Environmental Science*, *1321*(1), 012025. https://doi.org/10.1088/1755-1315/1321/1/012025.

Izuzquiza, A., Patricio, M. A., Cuadrado-Gallego, J. J., Berlanga, A., & Molina, J. M. (2026). Integrating static and dynamic hierarchical clustering and its application to retail segmentation. *Computers in Industry*, *174*, 104410. https://doi.org/10.1016/j.compind.2025.104410.

Jolliffe, I. T., & Philipp, A. (2010). Some recent developments in cluster analysis. *Physics and Chemistry of the Earth, Parts A/B/C*, *35*(9–12), 309–315. https://doi.org/10.1016/j.pce.2009.07.014.

Kassomenos, P., Vardoulakis, S., Borge, R., Lumbreras, J., Papaloukas, C., & Karakitsios, S. (2010). Comparison of statistical clustering techniques for the classification of modelled atmospheric trajectories. *Theoretical and Applied Climatology*, *102*(1–2), 1–12. https://doi.org/10.1007/s00704-009-0233-7.

Khan, F., Khan, O., Parvez, M., Ahmad, S., Yahya, Z., Alhodaib, A., Kumar Yadav, A., & Ağbulut, Ü. (2024). K-means clustering optimization of various quantum dots and nanoparticles-added biofuels for engine performance, emission, vibration, and noise characteristics. *Thermal Science and Engineering Progress*, *54*, 102815. https://doi.org/10.1016/j.tsep.2024.102815.

Ling, L. S., & Weiling, C. T. (2025). Enhancing segmentation: A comparative study of clustering methods. *IEEE Access*, *13*, 47418–47439. https://doi.org/10.1109/ACCESS.2025.3550339.

Love, P. E. D., Matthews, J., & Ika, L. A. (2025). Breaking the sisyphean loop: Reconceptualizing the treatment of risk and uncertainty in transport projects. *Production Planning & Control*, *36*(9), 1206–1228. https://doi.org/10.1080/09537287.2024.2352838.

Love, P. E. D., Sing, C.-P., Carey, B., & Kim, J. T. (2015). Estimating construction contingency: Accommodating the potential for cost overruns in road construction projects. *Journal of Infrastructure Systems*, *21*(2), 04014035. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000221.

Plebankiewicz, E. (2018). Model of predicting cost overrun in construction projects. *Sustainability*, *10*(12), 4387. https://doi.org/10.3390/su10124387.

Rahman, I. A., Hameed Mem, A., & Abd. Karim, A. T. (2013). Significant factors causing cost overruns in large construction projects in Malaysia. *Journal of Applied Sciences*, *13*(2), 286–293. https://doi.org/10.3923/jas.2013.286.293.

Sanders, C. B., & Cuneo, C. J. (2010). Social reliability in qualitative team research. *Sociology*, *44*(2), 325–343. https://doi.org/10.1177/0038038509357194.

Shehu, Z., Endut, I. R., Akintoye, A., & Holt, G. D. (2014). Cost overrun in the Malaysian construction industry projects: A deeper insight. *International Journal of Project Management*, *32*(8), 1471–1480. https://doi.org/10.1016/j.ijproman.2014.04.004.

Sieranoja, S., & Fränti, P. (2025). Fast agglomerative clustering using approximate traveling salesman solutions. *Journal of Big Data*, *12*(1), 21. https://doi.org/10.1186/s40537-024-01053-x.

Tufféry, S. (2011). *Data mining and statistics for decision making* (1st ed.). Wiley. https://doi.org/10.1002/9780470979174

Verma, S., Lyall, B. W., & Ramswaroop, S. (2020). Time and cost overrun analysis in ppp based roads and highway projects in India. *International Journal of Innovative Technology and Exploring Engineering*, *9*(4), 1761–1768. https://doi.org/10.35940/ijitee.D1690.029420.

Wibowo, A., & Santoso, S. R. (2024). Cost overruns arising from government-led risks in Indonesian toll roads. *Public Works Management & Policy*, *29*(3), 446–470. https://doi.org/10.1177/1087724X241237986.

Zhao, L., Wang, J., & Zhang, S. (2024). Critical factors influencing cost estimators' judgements on cost contingencies in highway construction projects: An empirical study in the UK. *PLOS ONE*, *19*(12), e0314665. https://doi.org/10.1371/journal.pone.0314665.

Uthayakumar, S., Thiruchelvam, K. and Uduwage, D.N.L.S., 2026. Understanding the status quo of consultant selection in Sri Lankan Public construction projects. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1788-1801. DOI: https://doi.org/10.31705/WCS.2026.130. Available from: https://ciobwcs.com/papers/

# UNDERSTANDING THE STATUS QUO OF CONSULTANT SELECTION IN SRI LANKAN PUBLIC CONSTRUCTION PROJECTS

**S. Uthayakumar[1], K. Thiruchelvam[2], and D.N.L.S. Uduwage[3]**

## *ABSTRACT*

*Consultant selection is a critical aspect of public construction procurement, as consultants significantly influence project performance in terms of cost, time, quality and risk management. In Sri Lanka, consultant selection methods for public construction projects in governed by national procurement guidelines. However, concerns remain regarding their practice application. This study examines the status quo of consultant selection practices in Sri Lankan public construction projects, with a focus on decision making approaches and commonly used consultant selection methods. A mixed methods approach was adopted, comprising a structured questionnaire survey administered to 52 construction professionals including quantity surveyors, engineers and architects who were directly involved in consultant selection decisions in public and institutionally funded projects. Quantitative data were analysed using mean ranking to identify dominant consultant selection methods, while content analysis was applied to qualitative responses to identify key challenges and suggested improvements. The findings reveal that consultant selection decisions are largely experience-based and guideline driven, with limited use of systematic decision-making models. The results indicate that Quality and Cost Based Selection (QCBS) is the most widely used method in both government-funded and institutionally funded projects. Key challenges include the absence of structured decision-making frameworks, overemphasis on cost, lack of standardised evaluation criteria, and subjectivity in selection. Respondents recommended formal decision support models, standardised criteria, and performance-based monitoring to improve effectiveness, highlighting the need for more systematic consultant selection practice in Sri Lanka.*

***Keywords:*** *Consultant Procurement; Decision Making Models; Public Projects; Sri Lanka.*

## 1. INTRODUCTION

The construction industry plays a pivotal role in national economic growth, infrastructure development and social wellbeing (Ofori, 2015). In developing countries such as Sri Lanka, public construction projects are particularly significant as they deliver essential

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka,suvethauthayakumar18@gmail.com
[2] Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, thiruchelvamk.20@uom.lk
[3] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, nuwanthas@uom.lk

infrastructure that supports national development objectives and economic stability (Thiruchelvam & Uduwage, 2025). Since these projects are financed through public funds they demand high levels of transparency, accountability and value for money to ensure effective utilisation of national resources (Abu et al., 2024).

Within public construction projects, consultants hold critical position by providing technical expertise necessary to transform policy and client requirements into feasible and sustainable project outcomes (Abu et al., 2024). Consultants including architect, engineers and quantity surveyors deliver professional services across the project lifecycle, significantly influencing cost, time, quality and risk management (Assaf et al., 2017). Given their strategic influence, proper consultant selection in the public sector is essential to ensure technical competence and balanced consideration of quality and cost (Daemei et al., 2025). Ineffective selection practices have been associated with design deficiencies, cost overruns, delays and disputes in construction projects (Ha et al., 2015).

In Sri Lanka, consultant selection for public construction projects is governed by national procurement guideline and manuals that outline a range of approved consultant selection methods (Jayasinha et al., 2021). These include various quality and cost-based approaches intended to promote fairness and consistency in selection decisions (World Bank, 2011). Consultant selection methods play a pivotal role in determining the suitability and competence of the appointed consultant (Ha et al., 2015). Identifying the most appropriate selection method for a given project is therefore critically important to achieving desired project outcomes (Hummadi et al., 2022). However, despite the availability of such guidelines, evidence from expert opinion and industry observations suggests that the practical application of these methods is often influenced by excessive emphasis on cost, limited methodological flexibility, and capacity constraints within procuring entities (Hasan, 2018; National Procurement Agency of Sri Lanka, 2007). Consequently, the potential benefits of applying the most suitable consultant selection method for a specific project may not be fully realised (Moos, 2017). Understanding the existing practice and status quo of consultant selection is therefore essential (Jayasinha et al., 2021).

The term “status quo” refers to the current situation, existing choice, or practice held by an agent at the time of deciding (Asamoah et al., 2019). In this study, the status quo encompasses the prevailing consultant selection methods, evaluation criteria, decision making processes, and institutional practices currently adopted in Sri Lankan public construction projects. Examining this status quo provides a foundation for identifying gaps between policy intentions embedded in national procurement guidelines and the actual implementation of consultant selection methods in practice, as well as area requiring systematic improvement (Naidoo & Magakwe, 2024). Without a comprehensive understanding of these existing practices, efforts to reform consultant selection methods or introduce new decision-making models aimed at improving transparency, enhancing quality considerations and optimising selection methods may fail to address the underlying structural and operational challenges within procuring entities (Navarro & Tanghal, 2017)

A notable characteristic of the Sri Lankan public construction sector is the significant volume of projects funded through international institutions such as the World Bank and Asian Development Bank (ADB). These institutionally funded projects operate under procurement frameworks established by the respective funding agencies, which may

differ from national guidelines in their approach to consultant selection (World Bank, 2011). Understanding how consultant selection practices differ between government funded and institutionally funded projects is therefore important for a complete picture of the status quo, and for identifying opportunities for improvement across both procurement environments. This distinction forms part of the research scope of the current study.

Despite the availability of nationally prescribed consultant selection methods, there is limited empirical evidence on how these methods are applied in practice within Sri Lankan public construction projects (Jayasinha et al., 2021). Existing literature provides insufficient insight into the decision-making approaches adopted by procuring entities when determining the most appropriate consultant selection method, creating uncertainty regarding the basis of such choices (Rodgers et al., 2022). Moreover, there is a lack of systematic understanding of which consultant selection methods are predominantly implemented in practice, as opposed to those merely recommended within policy frameworks (Asamoah et al., 2019). Additionally, practitioner perspectives on how consultant selection methods can be improved to enhance transparency and overall effectiveness in the public sector remain underexplored (Rodgers et al., 2022). These gaps highlight the need to examine prevailing decision-making approaches, identify the dominant methods applied, and explore opportunities for methodological improvement.

Accordingly, the following objectives were formulated for this study.

1. To examine current decision-making approaches adopted in determining the consultant selection methods in Sri Lankan public construction projects.
2. To identify the dominant consultant selection methods adopted in public construction projects in Sri Lanka.
3. To explore perceived improvements required to enhance the effectiveness of consultant selection methods in the public construction projects in Sri Lanka.

# 2. LITERATURE REVIEW

## 2.1 PROCUREMENT IN PUBLIC CONSTRUCTION PROJECTS

Public procurement refers to the process by which government institutions acquire goods, works, and services using public funds, with the objectives of achieving value for money, transparency, fairness, and accountability (Islam, 2013). In the construction sector, public procurement plays a vital role due to the significant financial investment involved and the long-term socio-economic impact of infrastructure development (Procurement Manual, 2024). As public construction projects are funded by taxpayers, procurement decisions are subjected to strict regulatory frameworks to ensure efficient utilisation of resources and public trust (Jebur & Rashid, 2024).

Procurement of public construction projects differed from other sectors due to the complexity, uncertainty, and multidisciplinary nature of projects (Abu et al., 2024). Decisions made during early procurement stages, particularly those related to consultant selection, have a lasting influence on project performance (Daemei et al., 2025). Effective procurement systems are therefore essential to ensure that competent professionals are engaged to manage project risks, technical requirements, and contractual obligations (Bolomope et al., 2022).

## 2.2 ROLE AND IMPORTANCE OF CONSULTANT IN PUBLIC CONSTRUCTION PROJECTS

Consultants play a central role in the planning, design, and execution of construction projects (Sarda & Dewalkar, 2016). Their responsibilities typically include feasibility studies, design development, cost planning, contract documentation, tender evaluation, and contract administration (Abu et al., 2024; Choudhry, 2016; Botwe et al., 2015). In public construction projects, consultants act as professional advisors to the client, supporting informed decision making throughout the project lifecycle (Abu et al., 2024).

In the context of public projects, the selection of appropriate consultants is widely recognised as a key success factor in achieving project objectives (Masengesho et al., 2021). According to National Procurement Agency of Sri Lanka (2007), the importance of consultant in public construction projects can be understood in relation to the following key aspects.

1. The need to ensure high quality and professional standards of services.
2. Maximising economy, timeliness and efficiency in project delivery.
3. Adhering to prescribed standards, rules, regulations and principles of good governance.
4. Maintaining confidentiality of information provided during consultancy services.
5. Strengthening anti-corruption measures and adherence to professional ethics.

## 2.3 CONSULTANT SELECTION METHODS IN PUBLIC CONSTRUCTION PROJECTS

Consultant selection differs fundamentally from contractor selection because it involves procurement of intellectual and professional services rather than physical outputs (FIDIC, 2019). As a result, selection methods must prioritize quality, expertise, and experience rather than cost alone (Alkaabi & Mahjoob, 2022). Internationally, several consultant selection methods are commonly adopted in public construction projects which are shown in Table 1.

*Table 1: Consultant procurement method and characteristic*

| Selection Method | Key Characteristics |
|---|---|
| **Quality Based Selection (QBS)** | Selection based primarily on technical competence and experience. Financial negotiations are conducted after identifying the most qualified consultant. |
| **Quality and Cost Based Selection (QCBS)** | Selection based on a combined evaluation of technical quality and financial proposals using predefined weightings. |
| **Least Cost Selection (LCS)** | Selection of the consultant offering the lowest price among technically acceptable proposals. |
| **Fixed Budget Selection (FBS)** | Selection of consultants whose technical proposals meet requirements within a predefined budget limit. |
| **Single Source Selection (SSS)** | Selection of a single consultant without competition, typically justified by continuity of services, specialised expertise, or emergency situations. |

| Selection Method | Key Characteristics |
|---|---|
| **Consultant's Qualifications Selection (CQS)** | Selection based on the consultant's qualifications and experience relevant to the assignment, without requesting detailed technical or financial proposals. |

*Source: (National Procurement Agency of Sri Lanka, 2007)*

As shown in Table 1, six consultant selection methods are applied in public construction projects, each possessing distinct strengths and limitations. QBS emphasises technical excellence, whereas QCBS seeks to balance quality and cost through weighted evaluation criteria. LCS prioritise affordability among technically compliant proposals, while FBS ensures that services are delivered within a predetermined financial ceiling. SSS is typically adopted under exceptional circumstances such as continuity requirement or emergencies and CQS focuses on relevant experience for relatively small or specialised assignments. Consequently, the appropriateness of each consultant selection methods depends on project complexity, risk exposure, budget constraints and client priorities.

## 2.4 CRITERIA INFLUENCING CONSULTANT SELECTION METHODS

Within the public construction projects, selection criteria are applied differently depending on the consultant selection method adopted. These methods utilise selection criteria to compare competing firm during the procurement (Bolomope et al., 2022). Commonly adopted criteria across these methods include quality level, cost certainty, project complexity, speed, scope of project, risk allocation, flexibility and client experience (Ariftama et al., 2024; National Procurement Agency of Sri Lanka, 2007; Zhao et al., 2022). In public procurement, these criteria are often assigned different weightings depending on the selection method to balance technical quality and cost considerations.

However, determining appropriate criteria and corresponding weightings within each consultant selection methods remain a challenge (Ha et al., 2015). Excessive reliance on cost-oriented methods may result in the appointment of less competent consultants, whereas strong emphasis on subjective technical assessment within quality focused methods may raise concerns regarding transparency (Ha et al., 2015). Furthermore, inconsistent application of criteria across consultant selection methods and the absence of standardised assessment frameworks can undermine the effectiveness of method implementation in public sector projects processes (National Procurement Agency of Sri Lanka, 2007).

## 2.5 CONSULTANT SELECTION IN SRI LANKAN PUBLIC CONSTRUCTION PROJECTS

In Sri Lanka, consultant selection methods for public construction projects are governed by national procurement guidelines and manuals issues by the government (Jayasinha et al., 2021). These documents outline approved consultant selection methods, evaluation procedures, and institutional responsibilities and procuring entities are required to follow structured processes involving technical evaluation committees, financial evaluations, and multi-level approvals to ensure transparency and accountability (National Procurement Agency of Sri Lanka, 2007).

Despite the existence of formal guidelines, several challenges have been reported in the Sri Lankan public procurement system. Studies indicate that application of consultant

selection methods is often characterised by procedural rigidity, lengthy approval timelines, and limited flexibility in method selection (Jayasinha et al., 2021). In some cases, certain consultant selection methods may overly prioritise cost considerations, potentially at the expense of consultant quality and suitability. Capacity constraints within procuring entities and evaluation committees further complicate effective implementation of prescribed consultant selection methods (World Bank, 2011).

### 2.6 CHALLENGES IN CURRENT CONSULTANT SELECTION PRACTICES

Globally and locally, consultant selection methods in public construction projects face several challenges and these include inadequate terms of reference, limited availability of experienced evaluators, administrative delays and external influences on decision making (Abu et al., 2024). In developing countries, economic pressures and institutional limitations often intensify these challenges (Barajei et al., 2024). In Sri Lankan context, delays in consultant appointment, lack of alignment between project complexity and consultant selection methods, and insufficient emphasis on past performance have been identified as key concerns (Weerasingha et al., 2025). Such challenges may reduce the effectiveness of consultant services and adversely affect overall project performance, highlighting the need for a clearer understanding of current practices (Abu et al., 2024).

Although numerous studies have examined public procurement system and contractor selection in construction projects, comparatively limited attention has been given to consultant selection practices, particularly in Sri Lankan public sector (Jayasinha et al., 2021). Existing local studies tend to focus on procurement methods, regulatory compliance, or contractor performance, with minimal emphasis on how consultant selection guidelines are applied in practice (Hummadi et al., 2022). According to Jayasinha et al. (2021) study, providing a comprehensive review of regulatory frameworks in Sri Lanka, focused on the adequacy of legal and institutional structures rather than on the empirical examination of how consultant selection methods are implemented at the project level by industry professionals. Furthermore, there is a lack of recent empirical research that systematically investigates current consultant selection approaches, criteria, and challenges from the perspective of industry professionals. This evidence gap creates uncertainty regarding whether existing consultant selection practices effectively support project success (Rodgers et al., 2022). Therefore, there is a clear need to examine the status quo of consultant selection in Sri Lankan public construction projects, which this study seeks to address.

## 3. RESEARCH METHODOLOGY

This study adopts mixed research approach to examine the current practices associated with consultant selection methods in Sri Lankan public construction projects. Figure 1 illustrates the research design.

As shown in Figure 1, the research design commenced with an extensive literature review to identify consultant selection methods applicable to Sri Lanka, with reference to public procurement guidelines and previous empirical studies. This was followed by the determination of the target population, sample frame and sample size.

The target population comprised construction professionals directly involved in consultant selection method decisions in public construction projects in Sri Lanka, namely quantity surveyors, engineers and architects. These professions were selected as

they constitute the principal members of technical evaluation committees in Sri Lankan public procurement.

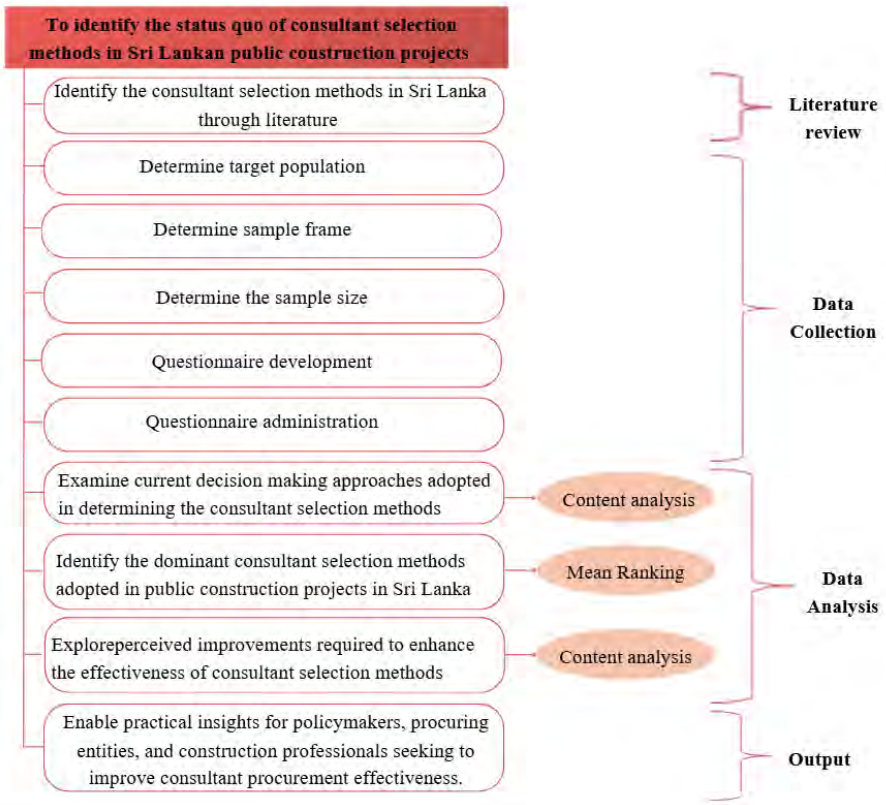



*Figure 1: Research design*

The target population characteristics were defined with reference to the professional membership criteria maintained by the Sri Lanka Institute of Architects (SLIA), the Institution of Engineers Sri Lanka (IESL) and the Institute of Quantity Surveyors Sri Lanka (IQSSL), specifically, membership of a recognised professional body, more than five years of experience in public sector projects, and direct involvement in consultant selection decisions. While formal membership lists were not directly accessible for sampling purposes, the target population was defined by these characteristics, which represents a recognised approach in construction management research where centrally maintained sampling frames are not publicly available. This limitation is acknowledged in the study.

A purposive sampling technique was adopted to select respondents with relevant expertise and practical knowledge. Accordingly, 75 questionnaires were distributed electronically via email, WhatsApp and professional networking platforms to enhance accessibility. The sample selection criterion required respondents to possess more than five years of experience in public sector projects, ensuring adequate exposure to consultant selection method applications.

The data collection instrument was a structured questionnaire developed based on the literature review relating to consultant selection methods. The questionnaire consisted of closed ended questions using yes/no responses and five-point Likert scales to evaluate the applicability and dominance of consultant selection methods, together with open ended questions to capture perceived improvements for enhancing their effectiveness.

The data analysis was aligned with the study objectives. To examine current decision-making approaches and to explore perceived improvements, qualitative responses were analysed using content analysis. This involved systematically reviewing open-ended responses, coding recurring words and phrases, and grouping them into meaningful themes related to perceived challenges and suggested improvements in consultant selection practice (Anastasiei & Georgescu, 2020). To identify the dominant consultant selection methods, quantitative data were analysed using mean ranking based on five-point Likert scale responses. This approach enabled the prioritisation of consultant selection methods according to their relative significance in practice.

# 4. RESULT AND DISCUSSION

## 4.1 RESPONDENT'S DEMOGRAPHIC INFORMATION

The questionnaire was distributed to 75 professionals. Out of these, 52 completed questionnaires were returned, resulting in a response rate of 69.33%.

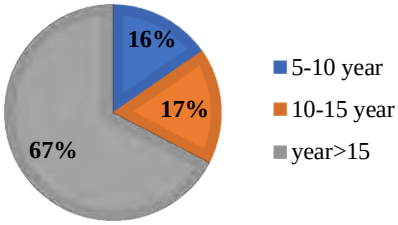



*Figure 3: Respondent's experience*

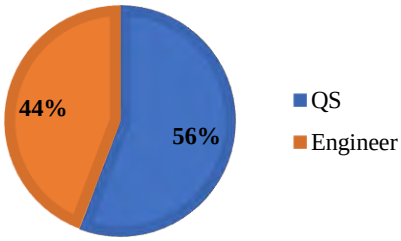



*Figure 2: Respondent's profession*

The questionnaire survey was distributed among three professional categories, namely quantity surveyors, engineers and architects. Figure 2 represent the majority of 56% respondents were quantity surveyors, followed by 44% respondents were engineers. Figure 3 illustrate the professional experience of the respondents. A substantial proportion of participants demonstrated extensive industry familiarity with approximately 67% reporting more than 15 years of experience, 17% having 10 -15 years, 16% having 5 -10 years. All respondents satisfied the minimum criterion of five years of experience. In terms of educational background, most respondents held postgraduate qualifications, primarily master's degrees, followed by bachelor's degrees and institutional corporate memberships. It is acknowledged that the low representation of architects is a limitation of this study, as their perspectives on consultant selection may differ from those of engineers and quantity surveyors. Future studies should endeavour to ensure more balanced representation across professional categories. Notwithstanding this limitation, the diversity in professional roles, educational background, and level of experience confirms that participants possess adequate knowledge to comprehend the survey questions and sufficient practical experience to provide informed responses.

## 4.2 CURRENT USE OF DECISION-MAKING APPROACHES IN DETERMINING THE CONSULTANT SELECTION METHOD IN PUBLIC CONSTRUCTION PROJECTS IN SRI LANKA

To examine the decision-making approaches adopted in determining consultant selection methods, respondents were asked "Are systematic decision-making models currently applied in selecting consultant procurement methods for Sri Lankan public construction

projects? If Yes, please specify the model(s) and indicate their effectiveness and If No, please specify the approach currently used" Qualitative responses were subsequently analysed using content analysis.

The findings indicate that systematic decision-making approaches are not widely adopted in selection of consultant selection methods in Sri Lankan public construction projects. Only 31% of respondents confirmed the use of formal decision-making models, such as structured evaluation frameworks aligned with National Procurement Agency (NPA) guidelines and established prequalification criteria, when determining the appropriate consultant selection methods. In contrast, 69% of respondents relied on traditional or experience-based approaches in the selection of consultant selection methods, primarily through the routine application of QCBS, committee deliberation and professional judgement informed by prior project experience.

This demonstrate that structured decision-making approaches are not yet well established within the public sector for the selection of consultant selection methods, as decisions regarding consultant selection methods mainly rely on traditional and professional judgement rather than structured analytical decision-making approaches. Such reliance might increase the potential for subjectivity and inconsistency in selection of consultant selection methods. The absence of formalized frameworks for the selection of consultant selection methods might limit transparency and consistency, thereby, reinforcing the need for structured decision-making tools such as Multi Criteria Decision Making (MCDM) models to improve objectivity and ensure alignment with project specific requirement in public sector procurement (Anelli et al., 2025).

## 4.3 CONSULTANT SELECTION METHODS USED IN GOVERNMENT FUNDED PROJECTS IN SRI LANKA

To identify the most used consultant selection method in government funded projects, an assessment was carried out using mean ranking to determine the dominant consultant selection method. The results based on mean ranking are shown in Table 2.

*Table 2: Ranking of consultant selection methods for government funded projects in Sri Lanka*

| Consultant selection method | | N | Mean | Std. Deviation | Rank |
|---|---|---|---|---|---|
| Quality and Cost Based Selection | QCBS | 52 | 4.27 | 0.910 | 1 |
| Least Cost Selection | LCS | 52 | 3.35 | 1.235 | 2 |
| Consultant's Qualifications Selection | CQS | 52 | 3.25 | 0.926 | 3 |
| Quality Based Selection | QBS | 52 | 2.96 | 1.028 | 4 |
| Fixed Budget Selection | FBS | 52 | 2.75 | 1.082 | 5 |
| Single Source Selection | SSS | 52 | 2.02 | 0.939 | 6 |

*Note: Scale (1 = Not widely used, 2 = Rarely used, 3 = Moderately used, 4 = Frequently used, 5 = Most widely used)*

As shown in Table 2, based on the mean ranking results, QCBS has the highest mean value 4.27, ranking it as the most used consultant selection method in government funded projects in Sri Lanka. This is followed by LCS and CQS. Other methods, such as FBS and SSS were reported to be used less frequently. SSS recorded the lowest mean value of

2.02, indicating it is the least preferred method. This indicates that preference has consistently been given to QCBS in the selection of consultant selection methods for government funded projects in Sri Lanka.

The dominance of QCBS reflects the consultant selection methods that places balanced importance on both technical quality and cost efficiency. From a public sector perspective this might particularly be important as government funded projects are required to achieve value for money while ensuring adequate quality. QCBS allows evaluators to systematically assess consultant's technical proposal alongside financial considerations, thereby reducing the risk of selecting consultants based solely on the lowest price, which could compromise project outcomes (World Bank, 2011). This preference aligns with Sri Lankan public procurement guideline which emphasise transparency, accountability and fairness in consultant selection. The relatively high ranking of LCS suggests continued cost sensitivity (Fath et al., 2024), while the lower preference for SSS might reflect efforts to maintain transparency and competitive fairness.

## 4.4 CONSULTANT SELECTION METHOD USED IN INSTITUTIONALLY FUNDED PROJECTS IN SRI LANKA

Institutionally funded projects in Sri Lanka refer to those financed through international institutions such as the World Bank and the Asian Development Bank. These projects operate under specific procurement frameworks that may impose requirements distinct from national NPA guidelines, particularly with respect to technical quality and transparency in consultant selection. As noted in the Introduction, examining this category separately provides important comparative insights into how funding source influences consultant selection practice. The results are shown in Table 3.

*Table 3: Ranking of consultant selection method for institutionally funded projects*

| Consultant selection method | | N | Mean | Std. Deviation | Rank |
|---|---|---|---|---|---|
| Quality and Cost-Based Selection | QCBS | 52 | 4.35 | 0.883 | 1 |
| Quality-Based Selection | QBS | 52 | 3.60 | 0.975 | 2 |
| Consultant's Qualifications Selection | CQS | 52 | 3.25 | 1.027 | 3 |
| Least-Cost Selection | LCS | 52 | 2.46 | 1.038 | 4 |
| Fixed-Budget Selection | FBS | 52 | 2.42 | 0.997 | 5 |
| Single-Source Selection | SSS | 52 | 1.94 | 0.938 | 6 |

*Note: Scale (1 = Not widely used, 2 = Rarely used, 3 = Moderately used, 4 = Frequently used, 5 = Most widely used)*

As shown in Table 3, based on the mean ranking results, QCBS achieved the highest mean value 4.35, ranking it as the most used consultant selection method in institutionally funded projects. This is followed by QBS and CQS. Other methods, such as FBS and SSS were reported to be used less frequently. SSS recorded the lowest mean value of 1.94, indicating it is the least preferred method. This indicates that preference has consistently been given to QCBS in the selection of consultant selection methods for institutionally funded projects.

According to the findings both government and institutional funded projects widely use QCBS. The institutionally funded projects have a stronger preference toward quality based procurement methods (Poudel, 2025). The higher ranking of QBS might highlight the donor agencies emphasis on technical competence and long term project performance and reduced reliance on LCS might suggests greater flexibility in budgeting and focus on expected project outcome.

## 4.5 CHALLENGES AND SUGGESTED IMPROVEMENTS

Of the 52 valid respondents, 48 provided qualitative responses relating to challenges in consultant selection practice, and 46 provided suggested improvements. These open-ended responses were analysed using content analysis, involving systematic coding of recurring words and phrases and their grouping into dominant themes. The frequency of each theme was recorded based on the number of respondents who raised it. Table 4 presents the key challenges and corresponding improvements identified from this analysis.

*Table 4: Key challenges and suggested improvements*

| Frequency (n) | Identified challenges | Frequency (n) | Suggest improvement |
|---|---|---|---|
| 38 | Excessive emphasis on lowest cost over quality | 41 | Increase technical weighting and prioritise quality based selection |
| 35 | Lack of structured decision-making framework | 39 | Introduce formal and structured decision-making models |
| 31 | Absence of standardised evaluation criteria | 34 | Develop uniform and transparent evaluation criteria |
| 28 | Subjectivity and political influence in selection | 32 | Strengthen transparency, fairness and regulatory oversight |
| 22 | Weak monitoring of evaluation process | 26 | Implement performance-based consultant evaluation system |

*Note: n = number of respondents (out of 48 for challenges and 46 for improvements) who raised each challenge and improvement*

As shown in Table 4, respondents consistently highlighted the absence of systematic, transparent and quality orientated methods as a major challenge in public sector consultant selection. The most frequently cited challenge was the excessive emphasis on lowest cost over quality (n=38), which aligns with the quantitative finding that QCBS is a cost inclusive method that dominates both funding categories. The second most common challenge was the lack of structured decision-making frameworks (n=35), consistent with the finding that 69% of respondents rely on experience-based approaches rather than formal models. These findings suggest that the consistent reliance on QCBS may partly stem from the absence of decision support frameworks that would help procuring entities identify the most project appropriate method. The misapplication of QCBS to projects where QBS or CQS may be more appropriate could lead to the selection of unsuitable consultants, quality deficiencies, and time delays. Respondents strongly recommended the introduction of formal decision support models (n=39), standardised evaluation criteria (n=34), and performance-based monitoring systems (n=26) as priority

improvements to enhance the effectiveness, transparency, and project specific suitability of consultant selection methods.

## 5. CONCLUSIONS

Effective consultant selection methods are critical in public construction projects, as they determine how technical quality, cost, and risk considerations are systematically evaluated and balanced. In the public sector, where accountability, transparency and value for money are essential, the use of appropriate and well-structured consultant selection methods directly influences the fairness, consistency, and effectiveness of procurement decisions. This study examined the status quo of consultant selection methods in Sri Lankan public construction projects, with a focus on decision-making approaches, dominant methods and areas requiring improvement. Using a questionnaire survey administered to 52 construction professionals, and applying mean ranking and content analysis techniques, the study provides empirical insights into how consultant selection methods are currently applied in practice. The findings reveal that decision-making approaches adopted for the selection of consultant selection methods are largely experienced-based and guideline-driven, with limited use of structured analytical frameworks. This indicates a gap between the intended objectives of procurement guidelines and their practical implementation in selecting the most suitable consultant selection method for specific project characteristics. Mean ranking analysis highlights that QCBS is the dominant consultant selection method in both government-funded and institutionally funded projects, though institutionally funded projects demonstrate a relatively strong preference for quality-based approaches (QBS ranking second). The overall consistent reliance on QCBS suggests limited systematic evaluation when determining the most appropriate consultant selection method, which may increase the risk of selecting an unsuitable method, potentially leading to quality deficiencies, time delays and reduced project performance. Key challenges identified include the absence of structured decision-making frameworks, lack of standardised evaluation criteria, excessive cost consideration, and susceptibility to subjectivity and political influence. Respondents strongly recommended the introduction of formal decision-support models, standardized evaluation criteria, and performance-based monitoring systems to enhance objectivity, consistency and project-specific suitability. Overall, the findings underscore the need to strengthen consultant selection methods in Sri Lankan public construction projects by moving beyond procedural compliance towards more systematic and criteria-based decision-making approaches.

The study has certain limitations including the relatively low representation of architects in the sample and the absence of a formal sampling frame. Future research may address these limitations by extending the sample to ensure broader professional representation and by developing and validating MCDM based decision making models tailored to Sri Lanka's public construction context. Comparative studies examining the effectiveness of different consultant selection methods across project types and funding categories would further enrich the evidence base for procurement reform in Sri Lanka.

## 6. REFERENCES

Abu, S., Kheni, N. A., & Abudi, A. (2024). Evaluating the effectiveness of consultants' roles in improving value for money in public infrastructure projects in Ghana. *Journal of Building Construction and Planning Research*, *12*(03), 69–85. https://doi.org/10.4236/jbcpr.2024.123004

Al Fath, A. A., Herwindiaty, D. E., Wibowo, M. A., & Sari, E. M. (2024). Readiness for implemented sustainable procurement in Indonesian government construction project. *Buildings*, *14*(5). https://doi.org/10.3390/buildings14051424

Alkaabi, S. A. M., & Mahjoob, A. M. R. (2022). Identifying the selection criteria of design consultant for Iraqi construction projects. *Journal of the Mechanical Behavior of Materials*, *31*(1), 290–297. https://doi.org/10.1515/jmbm-2022-0036

Anastasiei, I. D., & Georgescu, M. R. (2020). Automated vs manual content analysis - A retrospective look. *Scientific Annals of Economics and Business*, *67*, 57–67. https://doi.org/10.47743/SAEB-2020-0025

Anelli, D., Morano, P., Acquafredda, T., & Tajani, F. (2025). Structuring multi-criteria decision approaches for public procurement: Methods, standards and applications. *Systems*, *13*(9), 777. https://doi.org/10.3390/systems13090777

Ariftama, K., Subroto, A., & Ariftama, K. (2024). Construction design consultant selection using the analytic network process method. *EKOMBIS Review: Journal Ilmiah Ekonomi Dan Bisnis*, *12*(3), 12. https://doi.org/10.37676/ekombis.v12i3

Asamoah, D., Annan, J., Rockson, S. B., & Effah-Baah, D. (2019). *The influence of the Status Quo Bias Theory in the Compliance to Public Procurement Regulations in a Sub-Saharan Economy*. Kwame Nkrumah University of Science & Technology.

Assaf, S., Hassanain, M. A., Hadidi, L., & Amman, A. (2017). A systematic approach for the selection of the architect/engineer professional in construction projects. *Architecture Civil Engineering Environment, 10(4)*, 5-14.

Barajei, C., Kusi, E., Ackon, F., Osman, A. M., Mohammed, A. M. Z., Simpeh, F., & Gyimah, F. (2024). Success factors of the consultant selection stage of the Ghanaian public construction projects: The road sector's perspective. *Construction Economics and Building*, *24*(1–2), 144–162. https://doi.org/10.5130/AJCEB.V24I1/2.8660

Bolomope, M., Amidu, A. R., Ajayi, S., & Javed, A. (2022). Decision-making framework for construction clients in selecting appropriate procurement route. *Buildings*, *12*(12). https://doi.org/10.3390/buildings12122192

Choudhry, R. M. (2016). Appointing the design consultant as supervision consultant on construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *8*(4). https://doi.org/10.1061/(asce)la.1943-4170.0000195

Daemei, A. B., Lovreglio, R., Feng, Z., & Paes, D. (2025). Identifying the long-term effects of construction safety training methods: A systematic literature review. *Lecture Notes in Civil Engineering*, *562*, 377–386. https://doi.org/10.1007/978-981-96-1181-2_30

Eyiah-Botwe, E., Aigbavboa, C., & Thwala, W. (2015). Managing construction stakeholders for effective project delivery: A case of consultant quantity surveyors. *Journal of Construction Project Management and Innovation*, *5*(2), 1296–1309.

FIDIC. (2019). *Selection of consultants: FIDIC guidelines for the selection of consultants* (3rd ed.). International Federation of Consulting Engineers.

Ha, T. T., Hoai, L. Le, & Lee, Y. D. (2015). A fuzzy AHP model for selection of consultant contractor in bidding phase in Vietnam. *Journal of Construction Engineering and Project Management*, *5*(2), 35–43. https://doi.org/10.6106/jcepm.2015.5.2.035

Hasan, M. R. (2018). *A comparative study on PPR-2008, Bangladesh and Asian Development Bank (ADB) procurement guidelines 2015: Strength and weakness*. Institute of Governance Studies, BRAC University.

Hummadi, M. A., Perera, S., Jin, X. H., & Alashwal, A. (2022). Selection approaches and methods of construction industry consultant: A systematic literature review. In Y. G. Sandanayake, S. Gunatilake, & K. G. A. S. Waidyasekara (Eds.), *Proceedings of the 10th World Construction Symposium* (pp. 720–730). https://doi.org/10.31705/WCS.2022.58

Jayasinha, U., Abeyanayake, S., Arangala, M., & Mushin, N. (2021). *Opportunities to protect public interest in public infrastructure: Review of regulatory frameworks in Sri Lanka.* Verité Research. https://www.veriteresearch.org

Jebur, A. K., & Rashid, H. A. (2024). A review of the challenges related to governance public private partnership in construction projects. *AIP Conference Proceedings*, *3009*(1), 030050. https://doi.org/10.1063/5.0193891

Masengesho, E., Wei, J., Niyirora, R., & Umubyeyi, N. (2021). Relationship between project consultants' performance and project success in the Rwandan construction industry. *World Journal of Engineering and Technology*, *09*(01), 138–154. https://doi.org/10.4236/wjet.2021.91011

Moos, M. F. (2017). *The impact of the current public sector procurement system on the consulting engineering industry* [Master's thesis, University of Cape Town]. UCT Open Access Repository.

Naidoo, G., & Magakwe, J. (2024). Assessing the efficacy of public procurement policy and legal framework to combat corruption in selected regions in the western cape province, South Africa. *Rocznik Administracji Publicznej*, *10*, 385–402. https://doi.org/10.4467/24497800rap.24.023.20241

Navarro, A. M., & Tanghal, J. A. O. (2017). *The promises and pains in procurement reforms in the Philippines* (PIDS Discussion Paper Series No. 2017-16). Philippine Institute for Development Studies. https://hdl.handle.net/10419/173593

National Procurement Agency of Sri Lanka. (2007). *Guidelines for selection and employment of consultants.* Democratic Socialist Republic of Sri Lanka.

Ofori, G. (2015). Nature of the construction industry, its needs and its development: A review of four decades of research. In *Journal of Construction in Developing Countries, 20(2),* 115-135.

Poudel, K. (2025). The procurement process of world bank funded projects and government funded projects in Nepal: Exploring sustainability through procurement. *Academia Journal of Humanities & Social Sciences*, *2*, 153–164. https://doi.org/10.3126/ajhss.v2i1.77167

Procurement manual. (2024). *Democratic Socialist Republic of Sri Lanka.*

Rodgers, C., Wood, A., & Nguyen, T. H. (2022). Selection and engagement of professional consulting services: Decision-making processes used by project management offices in South Australia. *Journal of Modern Project Management*, *9*(3), 125–137. https://doi.org/10.19255/JMPM02808

Sarda, A., & Dewalkar, S. (2016). Role of project management consultancy in construction. *International Journal of Technical Research and Applications*, *4*(2), 317–320. https://www.ijtra.com

Islam, M. R. (2013). *Comparison of intellectual and professional service contract evaluation procedure: PPR-2008 vs World Bank and ADB* [Master's dissertation, BRAC University]. Institute of Governance Studies, BRAC University.

Thiruchelvam, K., & Uduwage, D. N. L. S. (2025). Assessing SDG 7 performance: Identifying relevant KPIs for the Sri Lankan construction industry. *Proceeding of the 13th World Construction Symposium*, 15-16 August 2025, Sri Lanka. (pp. 203–215). https://doi.org/10.31705/WCS.2025.16

Weerasingha, W. A. M. N., Jayasooriya, S. D., Kawmadi, W. N., & Lakmal, A. H. (2025). Impact of successful timely completion of construction projects on the economic development of Sri Lanka. *KDU Journal of Built Environment*, *1*(2), 32–42. https://doi.org/10.4038/kdujbe.v1i2.9

World Bank. (2011). *Guidelines: Selection and employment of consultants under IBRD loans and IDA credits & grants by World Bank borrowers*. International Bank for Reconstruction and Development/The World Bank. https://documents.worldbank.org.

Zhao, N., Ying, F. J., & Tookey, J. (2022). Construction procurement selection criteria: A review and research agenda. *Sustainability*, *14*(22), 15242. https://doi.org/10.3390/su142215242

Hettithanthri, U. and Krishantha, N.D.K., 2026. Unheard stakeholder voices: Evaluating the functional performance of manning market building. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1802-1815. DOI: https://doi.org/10.31705/WCS.2026.131. Available from: https://ciobwcs.com/papers/

# UNHEARD STAKEHOLDER VOICES: EVALUATING THE FUNCTIONAL PERFORMANCE OF MANNING MARKET BUILDING

**Upeksha Hettithanthri[1] and Nalaka Krishantha[2]**

## *ABSTRACT*

*Understanding how end users experience a building and evaluating its performance are essential for linking design decisions with actual operational behavior. This study investigates how architectural design influences user experiences and performance at Manning Market Complex in Peliyagoda, Sri Lanka. Using a qualitative approach, data was collected through observations and semi-structured interviews with market users. Thematic analysis identified patterns related to building performance and user experiences. Results showed architectural changes caused social, environmental, and health challenges, impairing its function as a market. Five themes emerged i.e. (i) operational contradictions, (ii) support issues, (iii) environmental vulnerabilities, (iv) architectural–functional misalignment, and (v) waste/hygiene problems. The building's design poorly responds to Sri Lanka's tropical climate, causing heat, rain disruptions, and discomfort. Its high-roofed structure and environmental features conflict with market needs, while waste management issues hinder hygiene and operations. Overall, the study reveals that current architectural solutions fail to meet market needs, negatively affecting user experience and performance. The findings highlight the need for user-centered and context-aware design in future markets.*

***Keywords:*** *Architecture of a Building; End User; Functionality; User experiences.*

## 1. INTRODUCTION

The architecture of the building gives life to its occupants (Vischer, 2008). The structure, designed by the architect and a team of architects, possesses the potential to influence the lifestyle of its inhabitants. Buildings are not merely physical structures; they are dynamic environments that continuously interact with their users, activities, and surrounding conditions. The success of an architectural design is determined not only by its aesthetic qualities or technical composition yet by its ability to support intended functions, enhance user experiences, and respond effectively to environmental and operational demands (Boissonneault & Peters, 2025). Therefore, evaluating the performance of a building after occupation is essential to understanding how architectural decisions translate into real-life experiences and functional outcomes. Post-occupancy evaluation provides valuable insights into the relationship between design intentions and actual building performance, revealing whether a built environment successfully accommodates user requirements or

[1] Department of Design Studies, NSBM Green University, Homagama, Sri Lanka , upeksha@nsbm.ac.lk
[2] Nalaka Krishantha Architects, Mount Lavinia, Sri Lanka , nalakakrishanthaarchitects@gmail.com

creates unintended challenges (Hay et al., 2018). The building's design must address the complex needs of its users. These needs extend beyond mere spatial requirements and include socio-cultural and economic aspects of the dwellers. In the discipline of architecture, the design process begins with understanding the user and exploring contextual demands and scenarios. The primary principle of the design process is to commence with empathising, which involves exploring user needs, requirements, and understanding the underlying human requirements behind the proposed functionality (Kanstrup, 2012; Castillo et al., 2022). Therefore, conducting thorough investigations of user needs, requirements, and comprehending the complexities and consequences beforehand are regarded as fundamental responsibilities of the architect (Hart et al., 2022; Luck, 2007).

Public market buildings represent a unique category of functional spaces where architectural design must respond to complex social, economic, environmental, and operational requirements (Francis & Griffith, 2011). Unlike conventional commercial buildings, markets are highly dynamic environments characterised by continuous movement of people, frequent exchange of goods, intensive daily activities, and changing environmental conditions (Ruiz, 2025; Hay et al., 2018). The effectiveness of a market facility depends on its ability to provide appropriate spatial organisation, environmental comfort, hygiene, accessibility, and operational efficiency (Hart et al., 2022; Kaminer, 2023; Luck, 2007; Pervaiz et al., 2025). Particularly in tropical climates, market buildings require careful consideration of climatic responses such as ventilation, solar heat control, rain protection, and waste management to ensure healthy and comfortable working conditions for both vendors and customers (Chen et al., 2023).

In Sri Lanka, public market complexes serve a vital function in facilitating local economic activities, especially in the distribution and sale of fresh agricultural commodities. Nevertheless, numerous market facilities face challenges related to climatic exposure, overcrowding, insufficient infrastructure, waste buildup, and suboptimal spatial configurations. These concerns underscore the necessity of investigating how architectural design impacts the daily experiences of users and whether such environments adequately fulfill their designated roles.

## 1.1 ARCHITECTURE OF THE MANNING MARKET AND ITS USABILITY

The Manning Market in Peliyagoda serves as a primary commercial hub specialising in vegetables and fruits within Sri Lanka. It functions as a vital node within the nation's food distribution infrastructure. The market operates as an active center and a congregation point for various stakeholders, including farmers, as well as retail and wholesale buyers and sellers of produce. The principal aim of this complex is to provide adequate shelter for the trading activities conducted on-site. Its structure is characterised by a substantial form, distinguished by a prominent roof at its upper levels. The architecture exerts a commanding presence in the surrounding environment, demonstrating significant architectural prominence through its massing. Architecturally, the Manning Market was designed with an open-plan layout to accommodate high volumes of trade. Although the building complex comprises several floors, only two levels are exclusively designated for purchasing and selling activities. The basement, designated for parking, and the ground level are primarily utilised for loading and unloading operations.

The large two-winged structures extend outward, forming substantial volumes. The roof features a curved steel truss, enhancing the feeling of openness inside. Natural elements

like air, wind, heat, and rain enter freely without barriers. However, the structure shows limitations in fulfilling its primary purpose. The building's orientation, span, height, and openness have heightened disturbances for the daily users involved in the buying and selling process.

*Figure 1: Excessively utilized ground floors and abandoned upper floors at Manning Market*

The investigation into the building performance at Manning Market in Colombo is warranted owing to its essential function as one of Sri Lanka's major wholesale produce distribution centers. This facility experiences high daily user density, intense commercial activities, and persistent logistical operations. As a longstanding urban marketplace, it faces considerable environmental and operational challenges, rendering it an exemplary case for assessing the performance of traditional market typologies under modern requirements.

From a performance perspective, the building exhibits potential challenges related to occupancy, ventilation efficiency, hygiene and waste management, spatial congestion, and circulation inefficiencies. These issues are further intensified by Colombo's tropical climate, high humidity, and heavy rainfall patterns, which directly impact both user experience and product quality. Additionally, the market represents an important intersection of formal infrastructure and informal economic practices, providing a relevant context to assess how architectural design supports or constrains operational efficiency. Therefore, this study aims to generate empirical insights that can inform future market redesigns, urban regeneration strategies, and climate-responsive public infrastructure development.

## 1.2 PROBLEM STATEMENT

Architecture is expected to support the activities it accommodates by responding to functional, environmental, and user requirements (Mustafa, 2017). In public buildings such as markets, architectural design directly influences operational efficiency, user experiences, product quality, and overall building performance (Altomonte et al., 2021; Hay et al., 2018). Particularly, wholesale markets handling fresh produce require specific environmental conditions, including protection from excessive heat, sunlight, rain, effective ventilation, hygiene, and efficient spatial organisation. Therefore, the success of a market building should be evaluated not only through its visual or spatial qualities yet through its ability to support its intended function (Debrah et al., 2025; Simelane et al.,

2024). Public markets represent complex functional environments where architectural performance directly influences economic activities, user interactions, product quality, and operational efficiency (Bertaud, 2024). Unlike conventional commercial buildings, wholesale markets dealing with fresh produce require specific environmental conditions, including controlled exposure to sunlight, protection from adverse weather conditions, effective ventilation, hygiene management, circulation efficiency, and appropriate spatial organisation (Sinha & Choudhury, 2023; Aramburu, 2024). The architectural configuration of such spaces has a direct impact on preserving the quality of perishable goods, facilitating transactions, and supporting the daily activities of vendors, buyers, and service providers. Therefore, the success of a market building cannot be evaluated solely based on its physical appearance or spatial arrangement but must be assessed through its ability to support the intended function (Anabtawi & Bleibleh, 2025).

The Manning Market Complex in Peliyagoda, Sri Lanka, provides an important context to examine the relationship between architectural design decisions and functional performance. Although the building was designed as a modern wholesale market, its architectural and structural solutions appear to have limited contribution towards enhancing its core function of buying and selling fresh produce. The market deals with perishable goods that are highly sensitive to environmental conditions; however, the existing design, which emphasises openness and natural exposure through its large roof structure and spatial arrangement, may contribute to increased heat exposure and monsoon rain penetration. These conditions can negatively affect product preservation, user comfort, and daily market operations.

Previous studies have extensively examined architectural design principles, building performance evaluation, and user satisfaction in other countries (Anabtawi & Bleibleh, 2025; Bertaud, 2024; Hay et al., 2018; Sinha & Choudhury, 2023; Pervaiz et al., 2025). However, limited attention has been given to understanding how architectural characteristics influence users lived experiences and functional performance in public market environments, particularly within the Sri Lankan context. There is a lack of empirical research investigating whether architectural decisions continue to support the intended functions of market buildings after implementation.

Therefore, this study addresses this gap by investigating the influence of architectural design on user experiences and the functional performance of the Manning Market Complex. By examining existing architectural conditions, user experiences, and observed building performance, the study aims to identify how effectively the building design supports or hinders the operational requirements of a wholesale market.

The study was conducted aiming to answer the following research question:

1. How does the architectural design and spatial configuration of the Manning Market building influence its functional performance as a wholesale market?

## 2. RESEARCH METHODOLOGY

To investigate the identified research problem, a qualitative research approach was adopted, incorporating both direct observation and semi-structured interviews with open-ended questions. This approach enabled an in-depth understanding of user experiences, behaviours, and perceptions within the market context.

## 2.1 DATA COLLECTION

This study used a qualitative method to explore how architectural design relates to the actual use of Manning Market Complex in Peliyagoda, Sri Lanka. The approach focused on understanding users' experiences, perceptions, and behaviors, as architectural performance depends on human interaction, spatial practices, and context. Direct engagement with users and observing real-time activities were key to capturing the link between design and use. The selected market represents a highly active public facility where architectural decisions directly influence daily commercial activities, user movement, environmental comfort, hygiene conditions, and operational efficiency. Data collection was conducted over a continuous three-day period through a combination of participant observations, semi-structured interviews, photographic documentation, and video recordings. The integration of multiple data collection methods enabled methodological triangulation, improving the reliability and depth of the findings by examining building performance from both observed and user-experienced perspectives.

### 2.1.1 Participant Selection and Sampling Strategy

A total of 50 participants were selected via convenience sampling: 25 vendors and 25 buyers actively engaged in the market during data collection. These groups were chosen because vendors and buyers, as primary users, experience the building differently, vendors through activities e.g. display, storage, and waste management, and buyers through circulation, accessibility, environment, and purchasing. Including both offered a comprehensive view of the building's functional performance from operational and experiential perspectives.

The sample included 33 males and 17 females aged 30-60, representing diverse perceptions of spatial usability, environmental conditions, and challenges. As the focus was on user experiences rather than statistical generalisation, the purposive sampling of active users ensured participants had direct knowledge of the building's daily operation. Prior to data collection, participants were informed about the objectives, procedures, and scope of the study (Mertens & Ginsberg, 2009). Ethical principles were maintained throughout the research process. Participation was voluntary, informed consent was obtained before conducting interviews and audio recordings, and participants were assured that their identities and personal information would remain confidential (Comstock, 2013). All collected information was anonymised during analysis and reporting to protect participant privacy.

### 2.1.2 Observation

Systematic observations were conducted within the natural operational setting of the market to understand actual patterns of spatial use, user behavior, circulation flows, functional conflicts, and environmental responses (DeWalt & DeWalt, 2010). Particularly in architectural research, direct observation is considered an effective approach for understanding how users appropriate, adapt, and negotiate spaces after buildings become operational (Cross & Cross, 1995; DeWalt & DeWalt, 2010). The researchers conducted immersive observations within the market environment to investigate how architectural spaces were occupied and modified by users during daily market activities (Bertaud, 2024; Sinha & Choudhury, 2023). This approach aligns with the principles of post-occupancy evaluation, where buildings are assessed based on their actual performance and users' experiences rather than solely based on the original design intentions (Hay et al., 2018). Observation was conducted during the active operational period of the market,

from 4:00 a.m. to 3:30 p.m. on a weekday, allowing the study to capture variations in building performance throughout different stages of market activity, including peak operational hours. Field notes were recorded systematically to document observed behavioral patterns and environmental conditions.

### 2.1.3 Semi-structured Interviews

Semi-structured interviews were used to explore users' experiences and perceptions of the Manning Market Complex's functional performance (Bryman & Burgess, 1999). This method balances structure with flexibility, capturing subjective evaluations that physical observation cannot. The interview protocol focused on architectural performance aspects like spatial functionality, circulation, comfort, efficiency, adaptability, and maintenance (Zhang et al., 2023). Questions encouraged participants to reflect on their interactions, current issues, and how architecture supports daily activities, covering their roles, interaction durations, and building familiarity.

Interviews were conducted face-to-face at the market, linking responses to spatial features for validity. Participants were informed about the study's purpose, confidentiality, and consent was obtained. Sessions lasted 15–30 minutes, with open-ended questions to elicit honest responses. Data included audio recordings, notes, and reflections, later transcribed and analysed thematically.

## 2.2 DATA ANALYSIS

The data from multiple sources were analysed using a six-phase thematic approach (Braun & Clarke, 2006; Guest et al., 2023; Hoskyns, 2016). The process began with data identification and organisation, allowing systematic pattern recognition. Data from diverse sources and techniques were prepared independently. Familiarization involved reviewing and filtering non-textual data, with textual data including observation summaries, field notes, participant narratives, transcribed interviews, and chat extracts, while photos, images, diagrams, and sketches were categorised as non-textual. The second phase, generating initial codes, involved reviewing the entire data set, with the researcher coding and categorising data using colour codes. Subsequently, primary codes were examined, and meaningful codes were grouped into secondary codes. The third step in the thematic analysis, c) search for themes, involved synthesising and reviewing the primary and secondary codes. The fourth step, d) reviewing and refining the themes, was carried out by the researcher. The identified themes were then e) defined and appropriately titled based on the underlying meanings, constituting the final step of the thematic analysis. To reduce researcher bias and improve reliability, an intercoder analysis was used where two researchers independently coded interview transcripts with a developed coding framework. After independent coding, differences were discussed and refined until consensus was reached, enhancing data consistency and dependability. Researchers maintained reflexivity by reflecting their assumptions and distinguishing participant meanings from researcher interpretations, supported by multiple data sources.

The triangulation of multiple data sources further strengthened the validity of the findings. Interview data were compared with direct observations and visual documentation to confirm whether reported experiences corresponded with actual conditions within the building environment. For example, user perceptions regarding environmental discomfort, circulation difficulties, or waste management issues were examined alongside observed spatial conditions and photographic evidence.

### 2.3 LIMITATIONS OF THE STUDY

This study has methodological limitations, mainly in stakeholder representation, focused on end users, vendors, and buyers, whose experiences offered valuable insights into the building's performance. While this provided rich, contextual data, it centered on user perspectives. The study did not include interviews with the original designers or consultants of the Manning Market Complex, so insights into design intent, decision-making, spatial strategies, and technical constraints were missing. This limits comparison between intended outcomes and actual performance. Still, focusing on vendors and buyers is valuable, as they are the most frequent users, offering essential insights into operational performance. Future research should include architects, engineers, facility managers, and local authorities for a more comprehensive evaluation and better understanding of how design matches functional outcomes.

## 3. RESULTS

The thematic analysis identified eleven subcategories, six main categories, and five themes to address the research question. The results show the major influences on building performance caused by the architectural design. This theme captures the inconsistencies between the intended function of the Main Market building and its actual operational performance. Although the facility was designed to support commercial activities and improve market operations, stakeholders reported multiple contradictions between the physical infrastructure and the practical needs of users. The findings suggest that the building structure has failed to adequately respond to user requirements, operational workflows, and health and safety considerations. Consequently, stakeholders experience significant challenges in conducting their daily activities, indicating a mismatch between the built environment and its intended purpose (refer Figure 2).

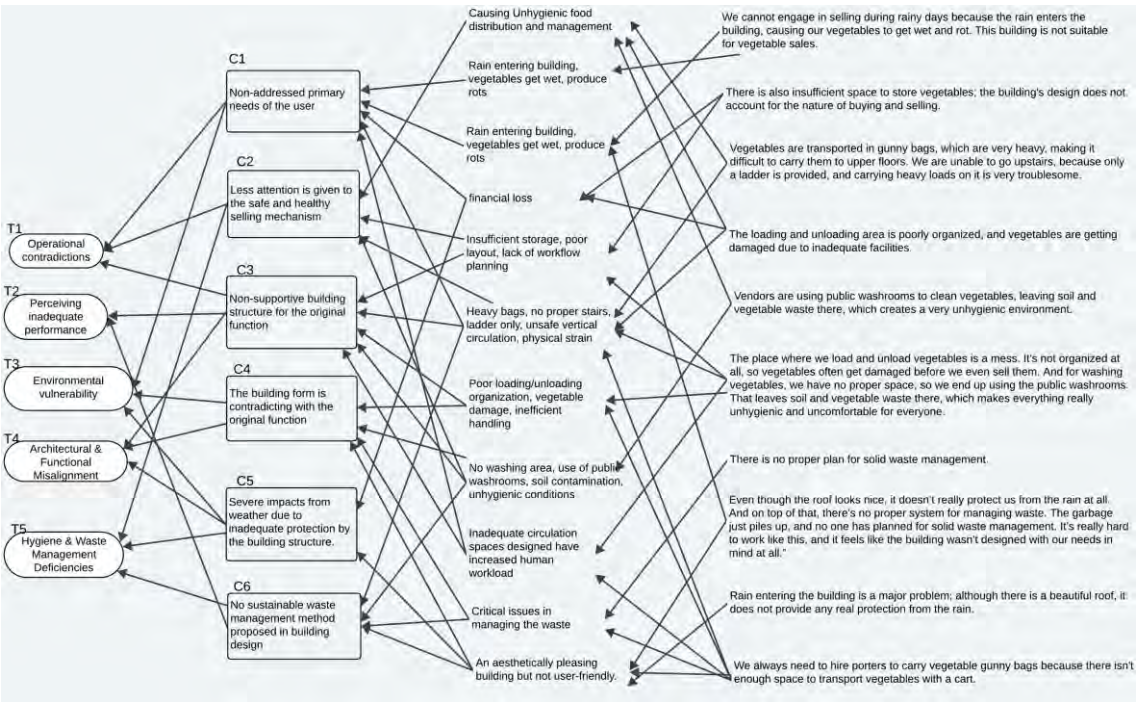



*Figure 2: Thematic map developed by the author*

Accordingly; C1: unattended primary needs of the user, C2: less attention given to safe and healthy selling mechanisms, C3: non-supportive building structure for the original function explains the architectural mismatch along with its original purpose. The results depict that the architectural design paid very little attention to the core business activities happening inside the building. The category one (C1) reflects the extent to which the fundamental needs of market users have been overlooked during the planning, design, and operational phases of the market facility. Participants reported that critical requirements necessary for the effective functioning of trading activities were insufficiently addressed within the building structure. These unmet needs included adequate circulation spaces, accessibility, loading and unloading facilities, storage provisions, customer interaction spaces, and environmental comfort conditions. The findings indicate that the building was developed with limited consideration of the everyday operational realities experienced by vendors and customers. As a result, stakeholders were compelled to adapt informally to structural inadequacies, often creating alternative arrangements to facilitate their business activities. Such adaptations reveal a significant disconnect between user requirements and the physical configuration of the market.

The architectural elements designed, such as the high roof and mezzanine floors that can only be accessed by ladders, have significantly impacted the building's daily operations. The primary function of buying and selling vegetables was not considered during the design process. In contrast, a high level of design solution was provided by hypothetically assuming that the actual users would fit into the given building structure. From a design perspective, the neglect of primary user needs represents a failure to incorporate stakeholder knowledge into the planning and design process, ultimately compromising the functionality and usability of the market environment.

However, instead of adapting the users to the proposed solution, they continued their usual routines within the building. The weight factors, loading and unloading factors, distribution of goods, and human circulation were not adequately considered during the design phase. The results showed a contradiction between actual usage and expected usage: “C4- the building form is contradicting with its original function.” This category captures stakeholder perceptions that the architectural form of the market building is fundamentally misaligned with its intended operational purpose. Participants indicated that while the building may possess a visually distinctive or architecturally significant form, its spatial configuration does not adequately facilitate the functional requirements of a public market environment. The findings suggest that the design process may have prioritized formal architectural expression over functional performance considerations. Stakeholders reported that certain spatial arrangements, circulation networks, and structural configurations create operational inefficiencies that hinder trading activities, customer movement, and service accessibility. Rather than supporting the dynamic interactions characteristic of market environments, the building form imposes physical constraints that disrupt daily operations.

Additionally, C5 highlights severe impacts caused by weather on the building's daily operations. The tropical climate of Sri Lanka experiences unpredictable and monsoon rains throughout certain periods of the year. During the rainy seasons, stormwater enters the building directly, and no weather protection was incorporated into the design to address these weather conditions at the initial planning stage. Sri Lanka's tropical climate requires building designs that respond effectively to environmental conditions through

appropriate shading systems, ventilation strategies, rainwater protection mechanisms, and thermal comfort considerations. However, stakeholders indicated that the existing structure demonstrates limited climatic responsiveness, resulting in operational disruptions during adverse weather conditions.

The findings suggest that insufficient environmental adaptation has reduced the building's capacity to maintain comfortable and functional conditions for vendors and customers. During periods of heavy rainfall, water ingress and circulation difficulties were reported, while excessive heat exposure affected both product quality and user well-being. These conditions negatively influence commercial performance and reduce the overall usability of the facility.

The C6 explains the issues caused by the unaddressed waste management system. Participants reported that waste generation associated with market operations, particularly organic and food-related waste, is not adequately managed through the existing infrastructure. The findings indicate that the building structure provides insufficient support for waste segregation, collection, storage, processing, and disposal activities. Consequently, waste accumulation has emerged as a persistent operational challenge affecting environmental quality, hygiene standards, and user experience. Stakeholders further emphasized that ineffective waste management contributes to unpleasant odours, pest infestations, sanitation issues, and environmental degradation. These conditions not only undermine the operational efficiency of the market yet negatively influence public perceptions of the facility. Furthermore, due to unaddressed weather protections, loading and unloading methods, and circulation problems, the daily production of solid waste is increasing. Many vegetables rot due to overexposure and lack of hygienic storage facilities, leading to an increase in solid waste.

The thematic analysis identified five themes that clearly explain the functional behaviour of the Manin Market Building. T1: Operational contradictions, T2: perceiving inadequate performances, T3: environmental vulnerability, T4: architectural and functional misalignment, T5: hygiene and waste management deficiencies are the themes that illustrate the building's functional performance over usability. Even though the market has been designed to cater to the retail and wholesale selling of fruits and vegetables, the building does not support its original function significantly.

## 3.1 OPERATIONAL CONTRADICTIONS

The theme one (T1) captures the inconsistencies between the intended operational objectives of the Main Market and its actual functional performance. Stakeholders consistently reported that the building structure fails to adequately support the everyday activities for which it was originally designed. Although the facility was established to facilitate efficient commercial transactions, circulation, product handling, and customer interactions, several structural and spatial characteristics impede these functions.

The findings reveal a significant mismatch between user requirements and building performance, resulting in operational inefficiencies that affect vendors, consumers, and service providers. These contradictions manifest through inadequate accommodation of user needs, inefficient spatial arrangements, poor circulation systems, and limited support for market-specific operational activities.

## 3.2 INADEQUATE PERFORMANCE OVER THE DEPICTED FUNCTION

The T2 shows stakeholders see the building as underperforming as a public market, citing issues with accessibility, usability, comfort, safety, convenience, and efficiency. Performance goes beyond construction quality, encompassing how well the facility meets user needs and supports activities. Stakeholders are dissatisfied because the building fails to meet basic functional and environmental standards. This distinguishes between technical completion and functional success; although structurally operational, users see significant shortcomings in supporting activities. Performance should be evaluated through user experiences and satisfaction. The building has caused disruptions and damage, with design conflicts such as storage on upper levels and unsafe ladders, contradicting its purpose. Unforeseen user needs early in design hinder performance assessment. Environmental vulnerabilities also impact functionality.

## 3.3 ENVIRONMENTAL VULNERABILITY

Theme three (T3) describes the market environment's susceptibility to adverse climatic and environmental conditions. Stakeholders reported that the building exhibits limited resilience against weather-related challenges, particularly excessive heat, rainfall, humidity, and inadequate environmental protection. Sri Lanka's tropical climatic context demands climate-responsive architectural solutions capable of mitigating environmental stressors while maintaining thermal comfort and operational continuity. However, participants indicated that the existing market structure provides insufficient protection against prevailing environmental conditions, resulting in discomfort, disruption of commercial activities, and deterioration of product quality.

The findings suggest that environmental considerations were inadequately integrated into the building design process. Consequently, the market demonstrates a heightened level of environmental vulnerability that compromises both user well-being and functional performance.

## 3.4 MISALIGNMENT OF THE ARCHITECTURE OF THE BUILDING AND THE FUNCTIONALITY

Theme 4 elucidates the discrepancy between the architectural design of the building and its functional requisites. The absence of adequate circulation spaces, unplanned retail areas, disorganised loading and unloading zones, high ceiling structures, and mezzanine levels with ladders collectively engender conflicts related to functionality. The building's actual operation encompasses the handling of substantial quantities of vegetables and fruits, which are sold in both retail and wholesale markets. On a daily basis, over 3000 visitors convene at this marketplace, necessitating more precise allocation of space. Nevertheless, the current market structure fails to provide additional support, enhancement, or meaningful contribution to the trading activities; rather, it introduces numerous daily operational challenges. It is imperative to estimate the volume of waste generated during actual operations during the design phase and to address this through effective design solutions. However, in the case of Manning Market, it has been demonstrated that the design team did not sufficiently consider the potential quantity of daily waste production. Furthermore, an appropriate design solution for solid waste management was not proposed.

### 3.5 WASTE MANAGEMENT DEFICIENCIES

The fifth theme highlights issues with hygiene management and waste handling at Manning Market Complex, showing a mismatch between the building's design and high-demand operations. The building lacks support for systematic waste processes, causing operational problems and environmental decline. A key problem is the absence of a well-planned loading system. The current layout hampers goods movement during busy times, creating conflicts with pedestrian flow and waste areas. Without defined service zones, loading spaces, or organised routes, handling is inefficient and disrupts daily activities.

The study found no integrated waste management in the building design, with no provisions for segregation, storage, collection, recycling, or disposal. Organic waste from vegetable and fruit trading accumulates, causing hygiene issues and environmental concerns. The absence of designated waste points and recycling shows limited consideration of the market's operational lifecycle. Architectural features do not support cleaning or maintenance effectively, lacking proper drainage, maintainable surfaces, cleaning zones, or accessible waste areas. As a result, cleaning depends mainly on manual effort instead of architectural solutions.

## 4. DISCUSSION

The architecture of a building influences residents' lifestyles, with architects capable of transforming living through innovative design. Architecture shapes human experience, and to create user-friendly solutions, architects must understand stakeholders' true needs. Rather than building first and fixing later, understanding functionality early is key. Elements such as configuration, circulation, responsiveness, materials, and function should be considered even in early design. Spatial hierarchy, accessibility, ergonomics, flexibility, and adaptability are vital, shaping architecture into a practical reality. When these factors align with human needs, architecture mediates between human desires and the environment. The findings show that a market building's success depends on both spatial provision and how architectural choices respond to user activities, environmental conditions, and operations. Hay (2018) argued that building performance must be assessed through actual use and user experience after occupancy, as design alone can't determine success. In Manning Market Complex, operational realities reveal that some architectural decisions conflict with the physical traits of the building and the functional needs of market activities.

Markets are dynamic with shifting spatial needs due to product movement, vendor activities, customer flow, loading, unloading, and storage. Bellentani (2021) states that built environments influence human behavior, but users adapt spaces for practical needs. Observations show users often modify spaces to address functional gaps, indicating designs don't fully support operational patterns. Successful design requires understanding user needs through observation, dialogue, and feedback. Empathy involves an in-depth inquiry into workflows, cultural practices, constraints, and aspirations, focusing on actual space use rather than assumptions. The findings suggest hygiene-related challenges are influenced by architectural planning decisions, not just management. Effective market design integrates functional zoning, service areas, circulation paths, and waste systems, supporting environmental design principles in which building performance results from interactions among spatial organisation, user behavior, and operational systems (Hay et al., 2018; Mustafa, 2017). Architecture should enable behavior, not impose it.

Environments should align with user needs, enhance capabilities, and promote sustainable living. When empathy guides innovation, architecture becomes a catalyst for meaningful everyday transformation.

## 5. CONCLUSIONS

This study analysed the performance of the Manning Market Complex using observed user behavior and interviews and identified five key themes: operational contradictions, perceived inadequate performance, environmental vulnerability, architectural and functional misalignment, and hygiene and waste management issues. Findings show a disconnect between design intent and actual support for retail and wholesale fruit and vegetable activities. Although meant to facilitate efficient operations, the building's spatial and environmental design falls short of operational needs, with issues like climate exposure, poor circulation, and waste management problems. This highlights the gap between architectural assumptions and post-occupancy performance in complex markets.

The study emphasizes the importance of post-occupancy evaluation for understanding building function in real life and suggests that market buildings, especially in tropical urban areas, need climate-responsive, user-centered, and integrated design strategies for lasting efficiency. Success should be measured beyond formal qualities, including environmental resilience and user experience.

Future research could compare different market types across climates to identify transferable design principles, using quantitative assessments including environmental monitoring and spatial analytics. Further studies might also examine governance, maintenance, and user adaptation in long-term performance. Ultimately, Manning Market shows that misalignment between design and function can cause underperformance, highlighting the need for performance-driven architectural approaches that consider environmental, spatial, and operational factors from the start through post-occupancy evaluation.

## 6. REFERENCES

Altomonte, S., Naves David Amorim, C., Campamà Pizarro, R., Carmon, D., Ciampi, G., Delvaeye, R., Garcia-Hansen, V., Gentile, N., Geisler-Moroder, D., Gkaintatzi Masouti, M., Hemphälä, H., Lindén, J., Osterhaus, W., Rodriguez, F., Pham, K., Pierson, C., Scorpio, M. & Sibilio, S. (2021). *Evaluating integrated lighting projects: A procedure to post-occupancy evaluation of daylight and electrical lighting integrated projects*. Solar Heating and Cooling Technology Collaboration Programme, International Energy Agency. https://doi.org/10.18777/ieashc-task61-2021-0006

Anabtawi, R., & Bleibleh, S. (2025). Assessing the resilience of public markets amidst the pandemic: A study on social sustainability through legibility and imageability. *Sustainable & Resilient Infrastructure*, *10*(6), 563–590. https://doi.org/10.1080/23789689.2025.2458411

Kanstrup, A.M. (2012). A small matter of design: An analysis of end users as designers. In K. Halskov, H. Winschiers-Theophilus, Y. Lee, J. Simonsen & K. Bodker (Eds.), *PDC '12: Proceedings of the 12th Participatory Design Conference: Research Papers* (Vol. 1, pp. 109-118). Association for Computing Machinery New York NY United States. https://doi.org/10.1145/2347635.2347651

Bellentani, F. (2021). *The Meanings of the Built Environment* (Vol. 24). De Gruyter Mouton. https://doi.org/10.1515/9783110617276

Bertaud, A. (2024). *Order without design: How markets shape cities*. UFS. Retrieved from https://www.researchgate.net/publication/360805383_Order_without_design_How_markets_shape_cities

Boissonneault, A., & Peters, T. (2025). The POE paradigm in architecture: Practices and perspectives of Canadian practitioners. *Building Research & Information*, *53*(5), 565–581. https://doi.org/10.1080/09613218.2025.2457940

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bryman, A., & Burgess, R. G. (Eds.). (1999). *Qualitative research [Methods of qualitative research]* (Vol. 2). SAGE.

Campo-Ruiz, I. (2025). Economic powers encompass the largest cultural buildings: Market, culture and equality in Stockholm, Sweden (1918–2023). *Archnet-IJAR*, *19*(1), 212–229. https://doi.org/10.1108/ARCH-06-2023-0160

Chen, L., Huang, C., & Xu, C. (2023). A farmers market architecture and ventilation design and its airflow analysis. *International Journal of Ventilation* *22*(3569), 1–21. https://doi.org/10.1080/14733315.2021.1943923

Comstock, G. (2013). *Research ethics: A philosophical guide to the responsible conduct of research.* Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511902703

Cross, N., & Clayburn Cross, A. (1995). Observations of teamwork and social processes in design. *Analysing Design Activity*, *16*(2), 143–170. https://doi.org/10.1016/0142-694X(94)00007-Z

Debrah, C., Chan, A. P. C., Darko, A., Akowuah, E., Amudjie, J., Asare, K. A. B. & Ghansah, F.A., (2025). A bibliometrix-based scientometric-systematic analysis and visualization of the global outlook on post-occupancy evaluation of green building. *Building Research & Information*, *41*(2). Retrieved from https://research-ebsco-com.ezp.sub.su.se/linkprocessor/plink?id=3797a6ce-9666-3782-8a12-a90e46133149

DeWalt, K.M., & DeWalt, B. R. (2010). *Participant observation: A guide for fieldworkers* (2nd ed.). Bloomsbury Publishing PLC. https://doi.org/10.5040/9798216409366

Francis, M., & Griffith, L. (2011). The meaning and design of farmers' markets as public space: An issue-based case study. *Landscape Journal*, *30*(2), 261–279. https://doi.org/10.3368/lj.30.2.261

Guest, G., MacQueen, M.K., & Namey, E.E. (2023). *Applied Thematic Analysis*. SAGE Publications, Inc. https://doi.org/10.4135/9781483384436

Hart, J., Albadra, D., Paszkiewicz, N., & Adeyeye, C., Kemi Alex. (2022). End user engagement in refugee shelter design: Contextualising participatory process. *Design Studies*, *80*, pp. 101107. https://doi.org/10.1016/j.destud.2022.101107

Hay, R., Samuel, F., Watson, K. J., & Bradbury, S. (2018). Post-occupancy evaluation in architecture: Experiences and perspectives from UK practice. *Building Research & Information*, *46*(6), 698–710. https://doi.org/10.1080/09613218.2017.1314692

Hoskyns, S. (2016). Thematic analysis. In B. Wheeler & K. Murphy (Eds.), *Music therapy research* (3rd ed. pp. 563-569). Dallas: Barcelona.

Kaminer, T. (2023). Non-Design: Architecture, Liberalism and the Market: by Anthony Fontenot, Chicago: University of Chicago Press, 2021, 376 pages. *Planning Perspectives*, *38(*2), 457–460. https://doi.org/10.1080/02665433.2023.2179262

Luck, R. (2007). Learning to talk to users in participatory design situations. *Participatory Design*, *28*(3), 217–242. https://doi.org/10.1016/j.destud.2007.02.002

Sinha, M., & Choudhury, D. (2023). Redevelopment and linkage of urban public markets: The case of Silchar town, India. *Urbanism. Arhitectura. Constructii*, *14*(2), 163–182. Retrieved from https://www.ceeol.com/search/article-detail?id=1090411

Mertens, D. M., & Ginsberg, P. E. (Eds.). (2009). *The handbook of social research ethics*. SAGE.

Mustafa, F. A. (2017). Performance assessment of buildings via post-occupancy evaluation: A case study of the building of the architecture and software engineering departments in Salahaddin University-Erbil, Iraq. *Frontiers of Architectural Research*, *6*(3), 412–429. https://doi.org/10.1016/j.foar.2017.06.004

Pervaiz, S., Tariq, F., Jamil, F., Khilat, F., Tariq, S., & Basheer, M. A. (2025). Placemaking for social cohesion and economic vitality: The role of urban design in transforming local markets in Pakistan. *Frontiers of Architectural Research*, *14*(4), 1035–1047. https://doi.org/10.1016/j.foar.2024.10.009

Ruiz De Gopegui Aramburu, M. (2024). *Urban public space and climate adaptation justice: Challenges and opportunities for project planning, design and evaluation* [Doctoral dissertation, Universitat Autònoma de Barcelona]. Tesis Doctorals en Xarxa. https://www.tdx.cat/handle/10803/693138

Salado Castillo, J. G., Bruneau, M., & Elhami-Khorasani, N. (2022). Functionality measures for quantification of building seismic resilience index. *Engineering Structures, 253*. https://doi.org/10.1016/j.engstruct.2021.113800

Simelane, N., Mewomo, M., & Okorafor, C. (2024). Barriers affecting the implementation of Post Occupancy Evaluation (POE) practices for RDP projects in Mpumalanga Province. In *2024 IEEE 5th International Conference on Electro-Computing Technologies for Humanity (NIGERCON)* (pp. 1-5). IEEE Xplore. https://doi.org/10.1109/NIGERCON62786.2024.10927239

Vischer, J. C. (2008). Towards an environmental psychology of workspace: How people are affected by environments for work. *Architectural Science Review*, *51*(2), 97. https://doi.org/10.3763/asre.2008.5114

Zhang, J., Yu, Z., Li, Y., & Wang, X. (2023). Uncovering bias in objective mapping and subjective perception of urban building functionality: A machine learning approach to urban spatial perception. *Land*, *12*(7). https://doi.org/10.3390/land12071322

Weerakoon, P.Y., Wijewickrama, M.K.C.S., Samaraweera, A. and Ochoa, J.J., 2026. Value creation in construction industry: A scoping review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1816-1828. DOI: https://doi.org/10.31705/WCS.2026.132. Available from: https://ciobwcs.com/papers/

# VALUE CREATION IN CONSTRUCTION INDUSTRY: A SCOPING REVIEW

**P.Y. Weerakoon[1], M.K.C.S. Wijewickrama[2] , A. Samaraweera[3] and J.J. Ochoa [4]**

## *ABSTRACT*

*Value creation (VC) in the construction industry supports the transition toward sustainable development and the achievement of sustainability goals; however, its practical implementation remains at an early stage, and the existing literature is fragmented. Based on this context, the research question of this study was formulated as "What are the existing themes and research gaps in this study domain?" Accordingly, the aim of the study is to identify and synthesise key themes and research gaps related to VC in the construction industry, providing a more holistic understanding of the concept. To achieve this aim, a scoping review methodology was adopted, and the PRISMA framework was used to systematically identify, screen, and select relevant studies, ensuring transparency and methodological rigor in the review process. The findings revealed several key themes that are prominently discussed in the literature, reflecting the diverse dimensions and perspectives through which VC has been explored in the construction context. These themes highlight the relationships between VC and areas such as supply chain management, corporate social responsibility, and procurement practices within the construction industry. Furthermore, the findings highlight that this research domain remains underdeveloped, with significant gaps in theory integration, practical application, and holistic understanding. Addressing these gaps presents an opportunity to generate considerable long-term benefits for the construction industry, particularly in enhancing sustainability outcomes and stakeholder value. Therefore, the study suggests directions for future research to bridge these gaps and advance the effective implementation of VC practices within the industry.*

***Keywords:*** *Construction Industry; Scoping Review; Value Creation (VC).*

## 1. INTRODUCTION

The construction industry can be recognised as a value creating system through the process of construction and it delivers extended benefits related to economic, social, and environmental aspects (Uusitalo et al., 2024). However, in the present context of the construction industry, value has been traditionally narrowed to the short-term project outcomes that are based on time, cost, and quality (Moshood et al., 2024; Schaltegger et al., 2016). This narrow interpretation of value has limited the industry's ability to deliver

[1] PhD Researcher, School of Civil Engineering and Construction Management, Adelaide University, Australia, panchali.weerakoon@adelaide.edu.au
[2] Lecturer, School of Civil Engineering and Construction Management, Adelaide University, Australia, chamitha.wijewickrama@adelaide.edu.au
[3] Senior Lecturer, School of Civil Engineering and Construction Management, Adelaide University, Australia, aparna.samaraweera@adelaide.edu.au
[4] Associate Professor, School of Civil Engineering and Construction Management, Adelaide University, Adelaide, Australia, jorge.ochoa@adelaide.edu.au

broader and long-term value across other industries and beyond. Hence, value creation (VC) has emerged as an important concept that extends beyond traditional project outcomes (Brozović et al., 2020).

VC can be defined as a process in which stakeholders interact by exchanging resources, resulting in benefits and enhance their overall well-being (Storbacka, 2019, p. 6). In the process of VC, both internal and external stakeholders engage to create value (Boruchowitch & Fritz, 2022). They can be identified as value actors and value beneficiaries as they not only create value but also capture value throughout the construction process (Malacina et al., 2022). Despite of the importance of VC, its practical incorporation within the construction industry is limited compared to other industries such as manufacturing (Badurdeen & Jawahir, 2017) and mining (Rathobei et al., 2024).

The existing studies within the construction context have discussed VC from different aspects. One of the major aspects is marketing and business (Marchowska-raza & Rowley, 2024; Varas et al., 2026). Another aspect of the existing studies is VC through innovation (Treptow et al., 2022). On the other hand, Liu et al. (2025) have focused on VC from a psychological aspect, examining participants' behaviours. The study conducted by Tampio and Haapasalo (2022) have focused on how value can be created through tools such as, Target value design, Last planner system, Big room and Smartsheet providing a comprehensive overview of the role of collaborative tools in enabling VC. However, none of these studies have focused on how value is created, how stakeholders are involved in the VC process and who capture the created value. Yet the existing studies on VC in the construction sector are in a fragmented nature which has refrained from understanding the practical enhancement of VC within the construction sector (Toukola et al., 2023).

There are several review studies conducted on VC in the construction industry. None of these review studies were able to provide a holistic understanding on theoretical foundations, and future research opportunities associated with VC in the construction industry. For instance, the recent study conducted by Liyanawatta and Teo (2026) focused on advancing circular practices through VC. Furthermore, the study carried out by Pigola and Fischer (2026) reviewed only on how social value can be created in business ecosystems. Moreover, several authors have reviewed how technology contributes to create value in the construction industry (Albalkhy, 2026; Pigola & Fischer, 2026). Hence, it is evident that the existing review studies on VC in the construction industry remain fragmented in nature.

This fragmented nature is associated with both empirical and review studies which highlights the urgent need for a review study from a holistic perspective synthesizing the existing research trends and future study gaps. Therefore, the research question of this study was established as: *"What are the existing themes and research gaps in value creation research within the construction industry?"*. In addressing this research question, this study aims to systematically identify and synthesise existing key themes and research gaps, providing a more holistic understanding of VC in the construction industry.

The remainder of this paper consist of the following sections; theoretical foundation of value creation, methodology, findings, discussion, and conclusions.

## 2. THEORETICAL FOUNDATION OF VALUE CREATION

The theory of VC is grounded on the Porter's value chain theory (Porter, 1985). At the time of the introduction of this theory, it focused only on company and customer relationship which is known as a dyadic approach (Aarikka-stenroos & Jaakkola, 2012). It discusses about providing the customer satisfaction exceeding their expectations while obtaining financial benefits. However, this theory has evolved over the years and now it has been reconceptualised as a multi-stakeholder approach, encompassing both internal and external stakeholders, in which value is co-created and captured throughout the process not limiting to the company and the customer (Grönroos, 2008; Vargo et al., 2008). Value-co creation has been defined by several authors in different fields. In the field of management research, value co-creation has been considered as a result of the collaborative and interactive efforts of multiple value actors (Alves et al., 2016; Pinho et al., 2014). In the service-dominant fields, value co-creation has been recognized as a provider beneficiary interaction between stakeholders (Makkonen et al., 2026; Vargo et al., 2008). Therefore, it can be concluded that, regardless of the field or context, stakeholders play a central role in influencing the VC process.

Despite these theoretical advancements, the application of VC within the construction context remains limited and conceptually underdeveloped (Fredriksson et al., 2025). Existing studies adopt fragmented perspectives and fail to provide a holistic understanding of how value is created, captured, and distributed across construction projects. This limitation underpins the need for the current study.

## 3. METHODOLOGY

The aim of this study is to systematically identify and synthesise key themes and research gaps, providing a more holistic understanding of VC in the construction industry (Gronstad, 2026). To achieve this, a scoping review approach adopted, as it helps to understand a specific domain in-depth in a broader spectrum (Pollock et al., 2024). To enhance the transparency of the results, the study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist for scoping reviews (Fernando et al., 2026). Figure 1 presents the PRISMA flow chart and it consist how the studies were filtered for the scoping review. Identification of the relevant studies for the review were obtained from Scopus and Web of Science databases with the use of search string "value creation" AND "construction industry". For this study, only these two databases were used as they cover a wide range of peer-reviewed articles (Ali & Phan, 2022).

Scopus database provided 186 studies and Web of Science provided 105 studies. After carefully comparing, duplicates were removed using EndNote 2025.3.1 version and altogether 109 duplicates were removed from the study. Duplicate records were identified both within the individual databases and between the databases. After screening 182 documents, several inclusion and exclusion criteria were applied. Only journal and conference papers which were published in English language were selected. Subsequently, a title and abstract screening process was conducted to further refine the studies, resulting in 109 studies being selected for full-text review. As a result of this step, 51 studies were removed due to their irrelevance to the research domain, as these studies primarily discussed VC within sectors other than construction. Finally, 58 studies were selected for the scoping review.

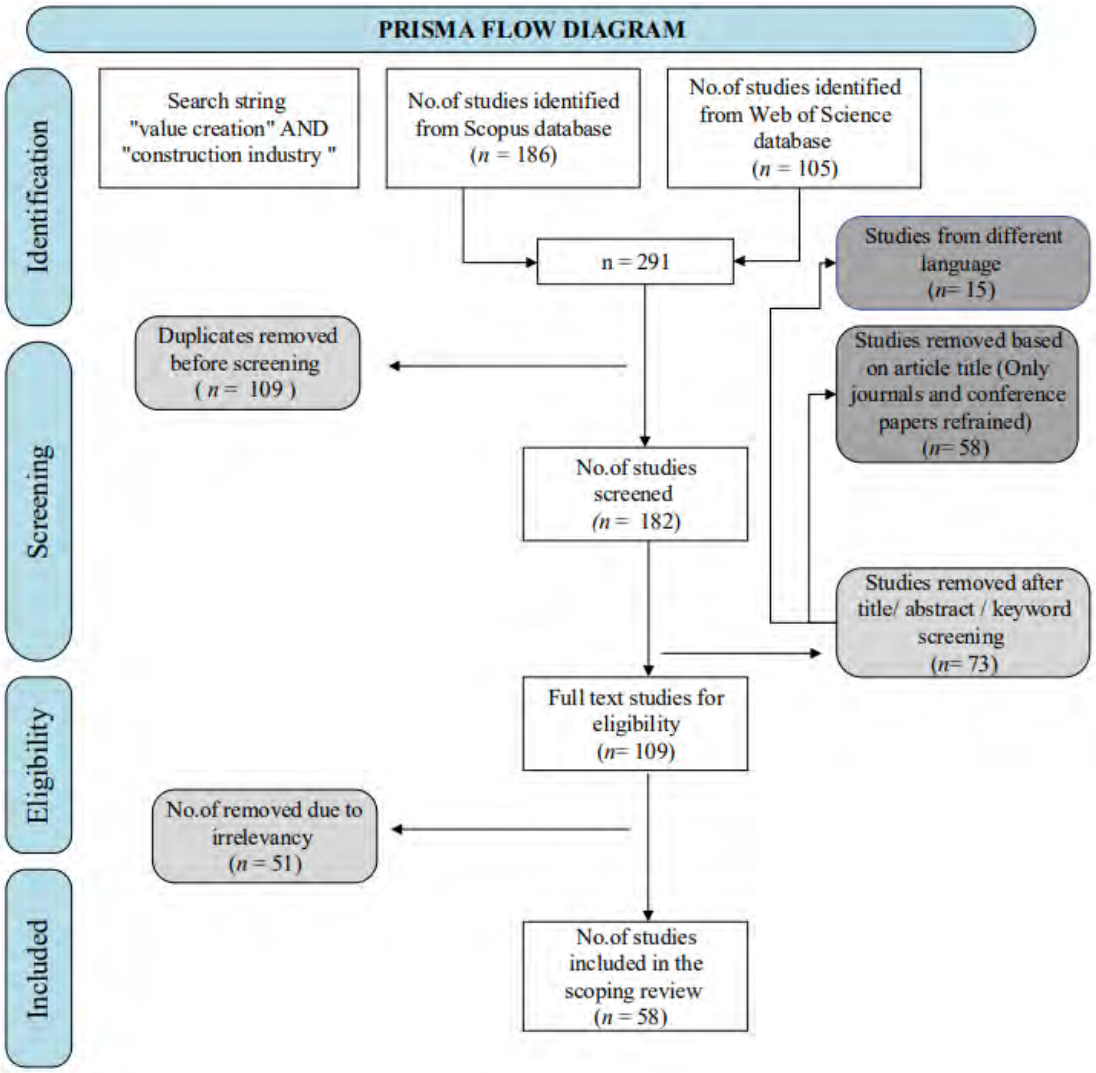



*Figure 1: PRISMA flow chart*

Upon identifying the relevant studies for the analysis based on the research string, the data extraction process was initiated. The extracted data were analysed using thematic analysis (Mak & Thomas, 2022), following an inductive approach. As the first step of the thematic analysis, an initial set of codes was generated and iteratively refined throughout the analysis process by the research team. Once the codes were generated, codes with conceptual similarities were merged to identify emerging patterns and themes. The thematic analysis was conducted manually using Microsoft Excel to facilitate systematic coding, categorisation, and theme development. To improve the reliability of the analysis, the coding structure and identified themes were continuously reviewed and discussed among the research team throughout the analysis process.

## 4. FINDINGS

This section presents the findings of the scoping review conducted.

### 4.1 VALUE CREATION AND SUSTAINABILITY

VC is an essential driver of sustainability in the field of construction management. It extends beyond traditional benefits limited to economic factors by incorporating environmental and social considerations, thereby contributing to long-term project performance and resilience. In this sense, sustainability is inherently embedded within the VC process, as projects are increasingly expected to deliver broader benefits beyond cost and time efficiency (Haddadi et al., 2016, 2017).

Upon recognising the severity of this longstanding problem, recent studies have increasingly shifted their attention towards the sustainability dimensions of VC within the construction industry. For instance, the study carried out by Jensen et al. (2019) examined how remanufacturing can achieve sustainability through VC. Further, Asiedu and Iddris (2022) highlighted that the relationship between VC and co-creation of values is important to maintain the sustainability in the construction projects. Furthermore, Putri et al. (2025) emphasised that value co-creation and sustainability are closely interconnected through collaborative stakeholder engagement, where small and medium-sized enterprises (SMEs) collaborate with value actors such as suppliers, customers, and regulators to jointly develop sustainable solutions, thereby enhancing environmental, economic, and social performance. However, the specific sustainability benefits that can be captured through VC within the construction industry remain unclear. Further, achieving sustainability benefits through VC has the potential to achieve sustainable development goals and to lead the whole construction industry towards sustainable development (Beck et al., 2023). Therefore, it is important to identify how these benefits can be achieved and disseminate knowledge among stakeholders about the benefits that they can capture through VC.

### 4.2 VALUE CREATION AND SUPPLY CHAIN MANAGEMENT IN CONSTRUCTION

Supply chain management (SCM) plays a critical role throughout the lifecycle of construction projects. Seuring et al. (2022) and Ludeke-Freund et al. (2016) highlighted SCM as a network of interconnected value actors and activities that can facilitate VC across organisations and beyond. Similarly, several other scholars have emphasised the importance of networks and stakeholder interactions in the VC process. For example, Zhou et al. (2025) proposed a platform-based model for value co-creation among small and medium-sized enterprises (SMEs) within supply chain networks. Further, Fredriksson et al. (2025) examined VC within logistics systems, which constitute an important component of SCM. Accordingly, VC can be effectively achieved through SCM, as it represents an integrated network that is not confined to a single project stage but continuously operates throughout the entire construction lifecycle (Chen et al., 2022).

### 4.3 VALUE CREATION AND CORPORATE SOCIAL RESPONSIBILITY (CSR)

The construction industry is responsible for maintaining the CSR of the industry. Construction industry's CSR is directly linked with the SCM, as it governs sourcing of materials, selection of suppliers, and coordination of project activities that significantly influence environmental, social, and economic outcomes (Hsu et al., 2022). Due to the close relationship between VC and sustainable SCM, VC serves as a critical link between SCM and CSR, enabling enhanced long-term benefits within the construction industry (Modak et al., 2020). Existing literature has not fully recovered how the construction

industry can enhance CSR through VC in SCM in a sustainable manner. Further, existing studies have not explicitly examined how VC itself can enhance CSR in the construction industry by extended sustainable value through economic, environmental, and social benefits.

### 4.4 VALUE CREATION AND PROCUREMENT IN CONSTRUCTION

Procurement process is a major activity in the SCM in construction. Procurement in construction supply chain can be defined as "acquiring goods and services for the construction activities". The main focus of construction procurement is to reduce costs proactively while managing risks and generate value by supporting product innovation and customer satisfaction (Parisi & Donyavi, 2025; Shishehgarkhaneh et al., 2024). Therefore, strategic procurement practices can contribute significantly to VC in construction projects by optimising resource utilisation, reducing project-related risks, and enhancing long-term stakeholder and customer value (Tumpa & Naeni, 2025). However, according to the study carried out by Lindfors and Jääskeläinen (2025), the existing procurement processes does not support VC in construction projects as expected. Yet, procurement is recognised as a foundational component of construction supply chain network which has a great potential of creating value (Boruchowitch & Fritz, 2022). Hence, there is a need of studying how value can be created throughout the procurement process in a construction project and the effects on procurement decision making.

### 4.5 VALUE CREATION AND STAKEHOLDER ENGAGEMENT

Even though VC was initially considered a firm centric concept, it has gradually evolved into a multi-stakeholder approach. Tommaso and Borini (2024) have discussed VC as a process where stakeholders exchange resources and obtain benefits from this exchange which improves their well-being. To enhance the incorporation of VC in any process, there should be a clear indication what activities create value and who are the stakeholders involved in this process (Boruchowitch & Fritz, 2022; Silva et al., 2026). Further, Biggemann and Williams (2014) highlighted that sustainability is built within multi-stakeholder participation, emphasizing the. the importance of the involvement of the stakeholders in the VC process. However, the existing literature remains a lack of clear understanding regarding which stakeholders are involved and who benefits from the VC process. Further, through understanding on the benefits that stakeholders can obtain through VC, will work as motivational factor for stakeholders for their proactive engagement in construction projects.

### 4.6 VALUE CREATION IN CONSTRUCTION BUSINESS MODELS

Construction companies have a significant responsibility to incorporate VC processes within their organizational objectives, as strategic-level alignment is essential for effective VC (Costa & Haftor, 2021). Without such integration, VC initiatives remain disconnected from core business priorities, thereby limiting their adoption and preventing their translation into project-level practices (Alsaadi et al., 2025). Consequently, there has been growing scholarly attention towards integrating VC into organisation-focused business models. For example, the recent study by Liyanawatta and Teo (2026) further highlights the increasing attention given to this area of research. Business models play a critical role in embedding VC within strategic organisational management by guiding how value is created, delivered, and captured across the organisation (Treptow et al.,

2022). However, existing business models in the construction industry continue to focus predominantly on traditional project performance measures, such as time, cost, and quality, with limited consideration of broader and more sustainable VC outcomes.

### 4.7 VALUE CREATION AND OTHER CONSTRUCTION METHODOLOGIES

Adopting a new construction methodology beyond the traditional construction methods has a great potential of enhancing VC and sustainability (Uddin et al., 2025). Modern methods of Construction (MMC) have been recognised as an innovative methodology to overcome the productivity and quality limitations associated with conventional construction methodologies (Saad et al., 2024). Further, several authors have highlighted the potential within MMC to create value while considering sustainable aspects (Josa & de la Fuente 2024). As discussed by Waqar et al. (2025) the implementation of MMC significantly support to overcome the existing sustainability challenges in traditional construction methodologies such as excessive construction waste, high emission of carbon dioxide, resource inefficiency and high energy consumption. Due to the strong link between MMC and sustainability, it is evident that a substantial value can be created within MMC-based construction projects. Proving this, the study carried out by Dang et al. (2024) extensively examined value mapping among stakeholders involved in pre-fabrication. However, the study overlooked several critical aspects of the VC domain, including who creates value, what types of value can be created, and who benefits from the created value within the projects implemented modern construction methodologies.

## 5. DISCUSSION

The concept of VC has not yet been comprehensively examined within the field of construction management, particularly in terms of how value is created, co-created, captured, and distributed among different stakeholders throughout the construction project lifecycle. VC can be mainly identified as a rigid pathway towards sustainable development (Brozović et al. 2020) of the construction industry but not fully exposed as to how it can be done. This study synthesized the existing studies on VC within the construction industry and identified the main themes which have been discussed. It can be clearly observed that existing studies in this domain are highly fragmented. This fragmentation may be one of the main reasons why the construction industry continues to struggle to achieve its sustainability goals.

Figure 2 presents the “framework for value creation in construction industry”, summarising the themes discussed in the existing literature, the identified research gaps, and potential directions for future studies. Even though the construction industry has a limited number of studies discussed on VC, in other fields like manufacturing and mining, VC has been widely discussed (Acosta-prado & Tafur-mendoza, 2022; Mohammadian et al., 2025). Further, these studies are focusing not only economical values but also focused on extended social and environmental values. Therefore, construction management studies should undertake in-depth investigations to understand how construction firms can create value within the context of construction projects.

Furthermore, future studies should focus on identifying who creates value and who captures value, along with the value-creating activities undertaken by different stakeholders at each stage of the construction project lifecycle. As shown in Figure 2, future studies should focus on quantifying the benefits of VC captured by stakeholders, as this would directly contribute to the overall development of the construction industry.

Studies should also focus on integrating VC into supply chain management and procurement practices within construction projects. Such understanding can serve as a critical basis for strategic decision-making among construction organisations worldwide, thereby supporting long-term business development. In this context, VC emphasises long-term benefits over short-term gains by integrating economic, environmental, and social considerations. It also promotes a safe, healthy, and equitable working environment for employees, enhancing worker well-being and overall organisational performance.

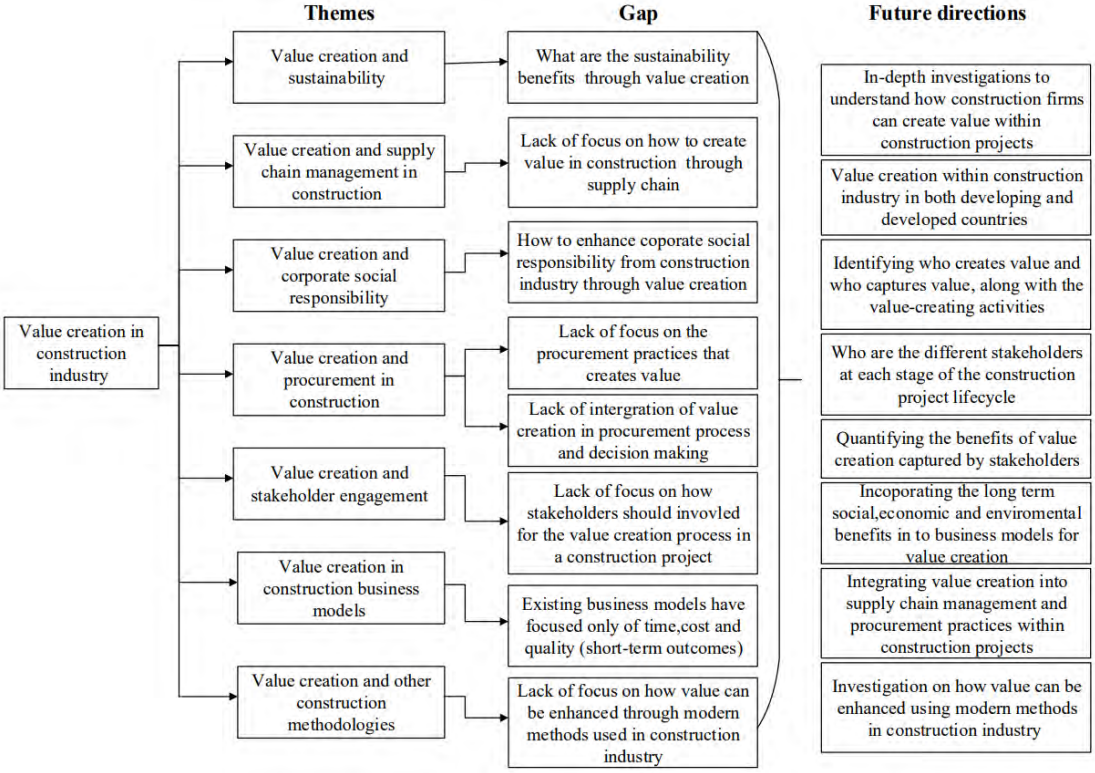



*Figure 2: Framework for value creation in the construction industry*

The development of the construction industry is strongly associated with the economic and social development of a country. Therefore, the initiatives that will be taken to create value in a developing and a developed country's construction industry are different. However, the existing studies have discussed about VC separately in developing and developed country context. For instance, the study carried out by Epede and Wang (2022) have discussed how VC acts in developing countries. They highlight that in developing countries, firm centric VC is important to address the local communities involved in the construction process. Further the study conducted by Ostos and Montoya-Ramírez (2025) highlights that VC in developing countries strongly shaped by technological influence adapted in firms. Which shows that, to enhance the VC, the initiation should be the firm. Moreover, the attention among developing countries focused studies on sustainability is considerably minimum. In developed countries, VC is mainly based on global sourcing, expertise in technology and high-value activities such as design and marketing (Kotabe and Mudambi, 2009). It is clear that the existing studies conducted on developed and developing countries are limited on specific areas, and this opens an avenue for future researchers. Therefore, it is necessary to study how the identified themes in this study can be applied in these two contexts separately and also to conduct a comparative study.

This study contributes to the existing body of knowledge by identifying key research gaps related to sustainability, stakeholder involvement, supply chain integration, CSR, procurement, business models and construction methodologies within the VC domain. The proposed future research directions can therefore serve as a foundation for advancing theoretical development and empirical investigations related to VC in construction management research. From a practical perspective, the findings of this study can assist industry practitioners, policymakers, and construction organisations in understanding how VC operates within the construction industry and how sustainable value can be incorporated into project delivery practices. The study also provides insights into the importance of stakeholder collaboration, supply chain integration, and sustainable business practices in enhancing long-term project performance and organisational development within the construction sector.

## 6. CONCLUSIONS

This study aimed to identify key themes and research gaps for VC in the construction industry. To achieve this aim, a scoping review was conducted, and the PRISMA guidelines were used to filter and select the relevant literature for the review. The selected studies were reviewed in depth, leading to the identification of seven themes within the existing literature.

VC has been largely overlooked in the construction industry. This has been one of the significant barriers for the construction industry to attain sustainable development. Sustainability can be achieved through enhancing value across the identified seven themes, as value enhancement mainly focuses on social, economic, and environmental aspects through a multi-stakeholder approach (Boruchowitch & Fritz, 2022) within these themes. Therefore, identifying relationships between these themes is important towards sustainable development of the total construction industry. This study can serve as a benchmark for future researchers to investigate the relationships among these themes and develop system-level syntheses, thereby contributing significantly to the theoretical advancement of this domain in the context of sustainable development.

This study was developed based on a well-structured methodology. To maintain the quality of the findings, only journal articles and conference papers considered for the study. However, relevant insights from grey literature were not included, which may limit the comprehensiveness of the findings (e.g., OCI Global and Orascom Construction, 2025). Future studies could incorporate such sources to provide a more comprehensive understanding of VC in the construction industry.

## 7. REFERENCES

Aarikka-stenroos, L., & Jaakkola, E. (2012). Industrial Marketing Management Value co-creation in knowledge intensive business services: A dyadic perspective on the joint problem-solving process. *Industrial Marketing Management*, *41*(1), 15–26. https://doi.org/10.1016/j.indmarman.2011.11.008

Acosta-prado, J. C., & Tafur-mendoza, A. A. (2022). Sustainable value creation and organizational performance in industrial manufacturing companies. *Measuring Business Excellence*, *27*(1), 143–156. https://doi.org/10.1108/MBE-12-2021-0151

Albalkhy, W. (2026). The integration between Lean Construction and the Internet of Things (IoT): A systematic literature review. *Smart and Sustainable Built Environment*, *15*(2), 649–679. https://doi.org/10.1108/SASBE-02-2024-0042

Ali, I., & Phan, H. M. (2022). Industry 4.0 technologies and sustainable warehousing: a systematic literature review and future research agenda. *The International Journal of Logistics Management*, *33*(2), 644–662. https://doi.org/10.1108/IJLM-05-2021-0277

Alsaadi, O., Alpkan, L., & Yildiz, B. (2025). International Journal of Innovation Studies Business model innovation as a mediator between construction 4.0 and firm performance: Evidence from Turkish construction companies. *International Journal of Innovation Studies*, *9*(1), 77–89. https://doi.org/10.1016/j.ijis.2024.12.002

Alves, H., Fernandes, C., & Raposo, M. (2016). Value co-creation: Concept and contexts of application and study. *Journal of Business Research*, *69*(5). https://doi.org/https://doi.org/10.1016/j.jbusres.2015.10.029

Asiedu, R., & Iddris, F. (2022). Value Co-Creation Approach to Management of Construction Project Stakeholders. *Journal of Construction in Developing Countries*, *27*, 1–23. https://doi.org/10.21315/jcdc2022.27.1.1

Badurdeen, F., & Jawahir, I. S. (2017). Strategies for Value Creation through Sustainable Manufacturing. *Procedia Manufacturing*, *8*, 20–27. https://doi.org/10.1016/j.promfg.2017.02.002

Beck, D., Ferasso, M., Storopoli, J., & Vigoda-Gadot, E. (2023). Achieving the sustainable development goals through stakeholder value creation: Building up smart sustainable cities and communities. *Journal of Cleaner Production*, *399*. https://doi.org/10.1016/j.jclepro.2023.136501

Biggemann, S., & Williams, M. (2014). Building in sustainability, social responsibility and value co-creation. *Journal of Business & Industrial Marketing*, *29*(4). https://doi.org/10.1108/JBIM-08-2013-0161

Boruchowitch, F., & Fritz, M. M. C. (2022). Who in the firm can create sustainable value and for whom? A single case-study on sustainable procurement and supply chain stakeholders. *Journal of Cleaner Production*, *363*. https://doi.org/10.1016/j.jclepro.2022.132619

Brozović, D., D'Auria, A., & Tregua, M. (2020). Value Creation and Sustainability: Lessons from Leading Sustainability Firms. *Sustainability*, 12(11), 4450. https://doi.org/10.3390/su12114450

Chen, Q., Feng, H. B., & de Soto, B. G. (2022). Revamping construction supply chain processes with circular economy strategies: A systematic literature review. *Journal of Cleaner Production* , *335*. https://doi.org/10.1016/j.jclepro.2021.130240

Costa, R., & Haftor, D. M. (2021). Value creation through the evolution of business model themes. *Journal of Business Research*, *122*, 353–361. https://doi.org/10.1016/j.jbusres.2020.09.007

Dang, P., Geng, L., Niu, Z., Chan, M., Yang, W., & Gao, S. (2024). A value-based network analysis for stakeholder engagement through prefabricated construction life cycle: evidence from China. *Journal of Civil Engineering and Management*, *30*(1), 49–66. https://doi.org/10.3846/jcem.2024.20726

Epede, M. B., & Wang, D. (2022). Global value chain linkages: An integrative review of the opportunities and challenges for SMEs in developing countries. *International Business Review*, *31*(5), 101993. https://doi.org/10.1016/j.ibusrev.2022.101993

Fernando, M. H., Hulathdoowage, N. D., & Perera, B. A. K. S. (2026). Unified Framework to Integrate Enterprise Resource Planning Systems, Electronic Tendering, and Smart Contracts in the Construction Industry. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *18*(2). https://doi.org/10.1061/jladah.ladr-1449

Fredriksson, A., Kjellsdotter Ivert, L., & Naz, F. (2025). Creating logistics service value in construction–a quest of coordinating modules in a loosely coupled system. *Construction Management and Economics*, *43*(6), 428–445. https://doi.org/10.1080/01446193.2025.2449996

Kotabe, M. and Mudambi, R. (2009), "Global sourcing and value creation: Opportunities and challenges", *Journal of International Management*, 15(2), 121–125, https://doi.org/ 10.1016/j.intman.2009.03.001.

Grönroos, C. (2008). Service logic revisited: Who creates value? And who co-creates? *European Business Review*, *20*(4), 298–314. https://doi.org/10.1108/09555340810886585

Gronstad, A. (2026). Scoping reviews vis-à-vis systematic reviews and integrative reviews in management research: guidelines for good practice. *Review of Managerial Science*, *20*(1), 221–250. https://doi.org/10.1007/s11846-025-00901-1

Haddadi, A., Hosseini, A., Johansen, A., & Olsson, N. (2017). Pursuing Value Creation in Construction by Research -A Study of Applied Methodologies. *Procedia Computer Science*, *121*, 1080–1087. https://doi.org/10.1016/j.procs.2017.11.138

Haddadi, A., Johansen, A., & Andersen, B. (2016). A Conceptual Framework to Enhance Value Creation in Construction Projects. *Procedia - Procedia Computer Science*, *100*(1877), 565–573. https://doi.org/10.1016/j.procs.2016.09.196

Hsu, B., Chen, Y., & Chen, L. L. (2022). Technological Forecasting & Social Change Corporate social responsibility and value added in the supply chain: Model and mechanism. *Technological Forecasting & Social Change*, *174*, 121302. https://doi.org/10.1016/j.techfore.2021.121302

Jensen, J., Prendeville, S., Bocken, N., & Peck, D. (2019). Creating sustainable value through remanufacturing: Three industry cases. *Journal of Cleaner Production*, *218*, 304–314. https://doi.org/10.1016/j.jclepro.2019.01.301

Josa, I., & de la Fuente, A. (2024). Traditional and modern methods of construction: Comparative study of the sustainability of single-family homes, *Structural Concrete*, 26(2), 2258–2276. https://doi.org/10.1002/suco.202400802

Lindfors, K., & Jääskeläinen, A. (2025). Creating value in infrastructure procurement: a practice-based view. *Journal of Public Procurement*, *25*(3), 321–354. https://doi.org/10.1108/JOPP-06-2024-0072

Liu, X., Geng, L., Liu, D., & Lin, S. (2025). Psychological Bonding Mechanisms and Value Creation in Construction Projects: Mediating Participants' Behaviors. *Journal of Construction Engineering and Management*, *151*(3), 1–13. https://doi.org/10.1061/JCEMD4.COENG-15484

Liyanawatta, T., & Teo, M. (2026). Stakeholder-Centred Value Creation Framework for Advancing Circular Economy Practices in the Construction Industry: A Systematic Review. *Buildings*, *16*(9), 1652. https://doi.org/10.3390/buildings16091652

Ludeke-Freund, F., Gold, S., & Bocken, N. (2016). Sustainable business model and supply chain conceptions: Towards an integrated perspective. In L. Bals & W. Tate (Eds.), *Implementing triple bottom line sustainability into global supply chains* (pp. 345–373). Greenleaf Publishing

Mak, S., & Thomas, A. (2022). Steps for Conducting a Scoping Review. *Journal of Graduate Medical Education*, *14*(5), 565–567. https://doi.org/10.4300/JGME-D-22-00621.1

Makkonen, H., Apsara, J., Gronroos, C., & Mantymaki, M. (2026). Advancing conceptual clarity in marketing science: Delineating process and systems perspectives on value co-creation. *Marketing Theory*, 1–24. https://doi.org/10.1177/14705931261430777

Marchowska-raza, M., & Rowley, J. (2024). Consumer and brand value formation, value creation and co-creation in social media brand communities. *Journal of Product & Brand Management*, *33*(4), 477–492. https://doi.org/10.1108/JPBM-01-2023-4299

Modak, N. M., Sinha, S., Raj, A., Panda, S., Merigó, J. M., & Jabbour, A. B. L. S. (2020). Corporate social responsibility and supply chain management: Framing and pushing forward the debate. *Journal of Cleaner Production*, 273, 122981. https://doi.org/10.1016/j.jclepro.2020.122981

Malacina, I., Karttunen, E., Jääskeläinen, A., Lintukangas, K., Heikkilä, J. and Kähkönen, A.-K. (2022), "Capturing the value creation in public procurement: A practice-based view", *Journal of Purchasing and Supply Management*, 28 (2), 100745, https://doi.org/10.1016/j.pursup.2021.100745

Mohammadian, B., Pishdar, M., & Matin, H. Z. (2025). Transition of mining industry toward sustainable value creation in. *International Journal of Quality & Reliability Management*, *43*(1), 277–294. https://doi.org/10.1108/IJQRM-04-2024-0127

Moshood, T. D., Rotimi, J. O., & Shahzad, W. (2024). Enhancing sustainability considerations in construction industry projects. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-04946-2

Putri, A. N. A., Hermawan, P., Mirzanti, I. R., Meadows, M., & Sadraei, R. (2025). Unpacking green growth in SMEs: A framework for dynamic capabilities, value co-creation, and sustainable performance. *Sustainable Futures*, 10, 100840. https://doi.org/10.1016/j.sftr.2025.100840

OCI Global. (2025, September 22). *OCI Global and Orascom Construction pursuing strategic combination to create a global infrastructure and investment platform*. OCI Global. www.oci-global.com.

Ostos J, Montoya-Ramírez M. (2025). Factors that influence value creation and value capture in companies – evidence in an emerging market. *Journal of Economics, Finance and Administrative Science*, 30 (60), 282-297 https://doi.org/10.1108/JEFAS-08-2023-0223

Parisi, L., & Donyavi, S. (2025). Advancing materials procurement processes in construction: a framework for optimising technology integration in SMEs' construction supply chains. *International Journal of Construction Management*. 26 (7), 1365-1389. https://doi.org/10.1080/15623599.2025.2553610

Pigola, A., & Fischer, B. B. (2026). Building the bundle: a configurational review of social value creation in business ecosystems. *Cogent Business & Management*, *13*(1). https://doi.org/10.1080/23311975.2026.2612779

Pinho, N., Beir, G., Patrı, L., & Fisk, R. P. (2014). Understanding value co-creation in complex services with many actors. *Journal of Service Management*, *25*(4), 470–493. https://doi.org/10.1108/JOSM-02-2014-0055

Pollock, D., Evans, C., Menghao, R., Alexander, L., Pieper, D., Moraes, D., Peters, M. D. J., Tricco, A. C., Khalil, H., Godfrey, C. M., Saran, A., Campbell, F., & Munn, Z. (2024). '"How-to"': scoping review? *Journal of Clinical Epidemiology*, *176*. https://doi.org/10.1016/j.jclinepi.2024.111572

Porter, M. E. (1985). *The Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press.

Rathobei, K. E., Ranangen, H., & Lindman, A. (2024). The Extractive Industries and Society Exploring broad value creation in mining - Corporate social responsibility and stakeholder management in practice. *The Extractive Industries and Society*, *17*, 101412 https://doi.org/10.1016/j.exis.2024.101412

Saad, A. M., Dulaimi, M., & Arogundade, S. (2024). *Modern methods of construction (MMC) and innovation negativism in the UK public sector*. *14*(2), 147–163. https://doi.org/10.1108/BEPAM-06-2023-0108

Schaltegger, S., Lüdeke-freund, F., & Hansen, E. G. (2016). Business Models for Sustainability: A Co-Evolutionary Analysis of Sustainable Entrepreneurship, Innovation, and Transformation. *Organization & Environment*, *29*(3), 264–289. https://doi.org/10.1177/1086026616633272

Seuring, S., Aman, S., Hettiarachchi, B. D., Lima, F. A. De, Schilling, L., & Sudusinghe, J. I. (2022). Cleaner Logistics and Supply Chain Reflecting on theory development in sustainable supply chain management. *Cleaner Logistics and Supply Chain*, *3*,100016. https://doi.org/10.1016/j.clscn.2021.100016

Shishehgarkhaneh, M. B., Moehler, R. C., Fang, Y., Aboutorab, H., & Hijazi, A. A. (2024). Construction supply chain risk management. In *Automation in Construction*, 162. Elsevier B.V. https://doi.org/10.1016/j.autcon.2024.105396

Silva, M. De, Rossi, F., & Paunov, C. (2026). Managing multi-stakeholder co-creation to address grand challenges: The role of paradox management capabilities. *Research Policy*, *55*(2), 105408. https://doi.org/10.1016/j.respol.2025.105408

Storbacka, K. (2019). Actor engagement, value creation and market innovation. *Industrial Marketing Management*, *80*(4–10). https://doi.org/https://doi.org/10.1016/j.indmarman.2019.04.007

Tampio, K., & Haapasalo, H. (2022). Organising methods enabling integration for value creation in complex projects. *Construction Innovation*, *24*(7), 21–43. https://doi.org/10.1108/CI-11-2021-0223

Tommaso, N. De, & Borini, F. M. (2024). Stakeholder value creation system: understanding the process. *Sustainability Accounting, Management and Policy Journal*, *15*(4), 777–806. https://doi.org/10.1108/SAMPJ-09-2023-0701

Toukola, S., Ahola, T., Ståhle, M., & Anna, H. (2023). International Journal of Project Management The co-creation of value by public and private actors in the front end of urban development projects. *International Journal of Project Management*, *41*(8). https://doi.org/10.1016/j.ijproman.2023.102542.

Treptow, I. C., Kneipp, J. M., Gomes, C. M., Kruglianskas, I., Favarin, R. R., & Fernandez-Jardón, C. M. (2022). Business Model Innovation for Sustainable Value Creation in Construction Companies. *Sustainability (Switzerland)*, *14*(16). https://doi.org/10.3390/su141610101

Tumpa, R. J., & Naeni, L. (2025). Improving decision-making and stakeholder engagement at project governance using digital technology for sustainable infrastructure projects. *Smart and Sustainable Built Environment*, *14*(4), 1292–1329. https://doi.org/10.1108/SASBE-10-2024-0451

Uddin, A., Shahabuddin, M., Jameel, M., Rahman, M., Hosen, A., Alanazi, F., Abdelmongy, M., & El-kady, M. S. (2025). Sustainable construction practices in urban areas: innovative materials, technologies, and policies to address environmental challenges. *Energy & Buildings*, *3*, 115831. https://doi.org/10.1016/j.enbuild.2025.115831

Uusitalo, P., Peltokorpi, A., Seppänen, O., & Alhava, O. (2024). *Towards systemic transformation in the construction industry: a complex adaptive systems perspective*. *24*(7), 341–368. https://doi.org/10.1108/CI-01-2024-0015

Varas, G., Sabaj, O., Spinuzzi, C., Fuentes, M., Gerard, V., & Cabezas, P. (2026). Value Creation in Start-Up Discourse: Linking Pitch and Venture Through Logics of Justification. *International Journal of Business Communication*, *63*(1), 183–211. https://doi.org/10.1177/23294884221147020

Vargo, S. L., Maglio, P. P., & Archpru, M. (2008). On value and value co-creation: A service systems and service logic perspective. *European Management Journal*, *26*(3), 145–152. https://doi.org/10.1016/j.emj.2008.04.003

Waqar, A., Al, F., Danish, M., & Basit, M. (2025). Evaluating the influence of modern construction methods on sustainable construction success. *Cleaner and Responsible Consumption*, *19*, 100327. https://doi.org/10.1016/j.clrc.2025.100327

Zhou, S., She, J., Lu, C., & Xie, Y. (2025). The Evolutionary Path of Value Co-Creation Behavior in Construction Projects Under the Construction Supply Chain Finance Context. *Sustainability*, *17*(10), 4354. https://doi.org/10.3390/su17104354

Bookauram-Nahullah, S., Fernando, N.G., and Jowkar, M., 2026. What enables climate-responsive and resource-efficient office buildings in a small island developing state? A stakeholder-weighted readiness gap analysis. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1829-1842. DOI: https://doi.org/10.31705/WCS.2026.133. Available from: https://ciobwcs.com/papers/

# WHAT ENABLES CLIMATE-RESPONSIVE AND RESOURCE-EFFICIENT OFFICE BUILDINGS IN A SMALL ISLAND DEVELOPING STATE? A STAKEHOLDER-WEIGHTED READINESS GAP ANALYSIS

**S. Bookauram-Nahullah[1], N.G. Fernando[2] and M. Jowkar[3]**

## *ABSTRACT*

*Climate-responsive and resource-efficient office buildings, often described in practice as green office buildings, are increasingly promoted in Small Island Developing States (SIDS). However, there remains limited understanding of how policy, finance, skills, and supply conditions interact to constrain adoption, as the literature largely focuses on barriers and drivers rather than readiness as a systemic condition. This study aims to examine what enables such buildings in Mauritius through a systems-informed, stakeholder-weighted readiness gap analysis. A mixed-methods approach combined 33 survey responses with five expert interviews. Survey respondents were regrouped into four stakeholder clusters such as developer/owner, government/policy, commercial/advisory, and technical delivery. Weighted Likert-scale responses were normalised into four readiness domains: market and finance, technical and supply, policy and institutional, and collaboration and delivery. Interview evidence was coded into causal relationships to produce a qualitative system map and identify reinforcing adoption traps and leverage points. The largest weighted gaps were found in market and finance readiness (0.735), technical and supply readiness (0.666), and policy and institutional readiness (0.652), while collaboration and delivery showed a lower but still material deficit (0.449). By contrast, respondents expressed strong support for feasible implementation priorities, particularly flood resilience (0.860), life-cycle assessment (0.852), daylighting (0.843), rainwater harvesting (0.843), passive cooling and efficient air-conditioning (0.834), and digital technologies (0.831). The findings show that the main challenge is not the absence of technical pathways, but weak enabling conditions. The paper contributes a multi-stakeholder study and a practical readiness-to-action framework for scaling uptake in SIDS office building markets.*

***Keywords:*** *Climate-responsive office buildings; Mauritius; Readiness gap; Resource efficiency; Small Island Developing States.*

[1] MSc Graduate in Real Estate Management and Investment, School of Computing, Engineering & the Built Environment, Edinburgh Napier University, United Kingdom, 40644806@live.napier.ac.uk
[2] Associate Professor, School of Computing, Engineering & the Built Environment, Edinburgh Napier University, United Kingdom, N.Fernando@napier.ac.uk
[3] Lecturer, School of Computing, Engineering & the Built Environment, Edinburgh Napier University, United Kingdom, M.Jowkar@napier.ac.uk

# 1. INTRODUCTION

The building sector is a major focus of global decarbonisation and resource-efficiency agendas because design-stage decisions lock in long-term energy use, material demand and infrastructure burdens (Madadizadeh et al., 2024). This issue is particularly important in Small Island Developing States (SIDS), where construction is shaped by import dependence, climate risk, limited domestic markets and institutional capacity constraints (Salomon, 2024). In Mauritius, office development has strategic importance as the country positions itself as a regional business and services hub, yet the environmental performance of new commercial buildings remains uneven (Briguglio et al., 2020). Climate-responsive and resource-efficient office buildings are often framed around technical measures such as improved envelopes, renewable energy systems, efficient services, water management and waste reduction (World Green Building Council, 2019; Cheshire, 2016). This study adopts a broader interpretation that includes passive design, climate resilience, water efficiency and life-cycle resource performance. Although the questionnaire used the more familiar term "green office buildings", the analysis interprets the findings through the narrower climate-responsive and resource-efficient lens, supported by expert interviews. Existing evidence from Mauritius and comparable contexts shows that such strategies are recognised by professionals, but implementation remains inconsistent (Rana & Rughooputh, 2014; Joyram et al., 2024). The central problem is therefore not the absence of technical solutions, but the weak readiness conditions that prevent known measures from becoming routine practice. This paper addresses this issue by developing a stakeholder-weighted readiness gap analysis and a systems-oriented framework for identifying enabling deficits, leverage points and practical pathways for uptake in the Mauritian office-building sector. Accordingly, this paper is structured as follows. Section 2 presents the literature review. Section 3 outlines the research methodology. Section 4 presents the results, followed by a discussion in Section 5 and Section 6 concludes the paper.

# 2. LITERATURE REVIEW

## 2.1 FROM BARRIERS TO SYSTEMIC READINESS IN SUSTAINABLE BUILDINGS

The transition towards climate-responsive and resource-efficient buildings has often been examined through barriers and drivers, including high upfront costs, regulatory limitations, lack of technical expertise and low stakeholder awareness (Darko & Chan, 2017; Häkkinen & Belloni, 2011). Although useful, this approach can treat barriers as separate issues rather than interacting conditions. Recent studies suggest that sustainable-building adoption is better understood as part of a wider socio-technical system in which technological, institutional, economic and behavioural factors interact (Geels, 2011; Poorisat et al., 2024; Heinz et al., 2025; Hong et al., 2025; Dharmarathna et al., 2026). Readiness therefore provides a more integrative lens, as it captures whether markets, institutions and stakeholders are prepared to implement available low-carbon solutions (International Energy Agency [IEA], 2021; United Nations Environment Programme[UNEP], 2021).

## 2.2 CLIMATE-RESPONSIVE AND RESOURCE-EFFICIENT OFFICE BUILDINGS

Climate-responsive design uses passive strategies such as orientation, shading, natural ventilation and envelope optimisation to reduce reliance on mechanical systems, while

resource efficiency reduces energy, water and material use across the building life cycle (Xu et al., 2025; Poorisat et al., 2024; UNEP and Global Alliance for Buildings and Construction [Global ABC], 2025). These strategies are especially relevant to office buildings, where cooling demand, lighting, plug loads, dense occupancy and concentrated operating hours increase operational energy use (D. Hong et al., 2025; IEA, 2025). Buildings also offer major mitigation potential through passive and active strategies (Intergovernmental Panel on Climate Change [IPCC], 2022). However, the persistent gap between design intent and actual performance remains a concern and reflects not only technical issues but also misaligned incentives, fragmented responsibilities and limited user engagement (de Wilde, 2014).

## 2.3 THE SIDS CONTEXT: CONSTRAINTS AND VULNERABILITIES

Small Island Developing States (SIDS) face structural constraints that affect sustainable-building adoption, including geographic isolation, narrow resource bases, climate vulnerability and limited economies of scale (United Nations, 2024). These conditions shape readiness in several ways: import dependence can increase costs and reduce flexibility (Briguglio, 2016), limited institutional capacity can weaken enforcement (Robinson & Dornan, 2017), and small domestic markets can slow supply chain development. In such contexts, implementation is therefore better understood as a systemic readiness challenge than as a simple lack of technical knowledge.

## 2.4 MULTI-DIMENSIONAL ENABLERS AS READINESS COMPONENTS

Recent reviews show that sustainable-building uptake is shaped by financial and economic, policy and government, technological and technical, knowledge and training, and socio-cultural or stakeholder-related factors (Poorisat et al., 2024; Dharmarathna et al., 2026). In this study, these themes are consolidated into four operational readiness domains: market and finance readiness; technical and supply readiness; policy and institutional readiness; and collaboration and delivery readiness, as presented in Table 1. This classification reflects the view that building transition depends on investability, delivery capability, regulatory support and stakeholder collaboration working together rather than in isolation (Organisation for Economic Co-operation and Development [OECD], 2024; Vakeva-Baird et al., 2025).

*Table 1: Literature derived readiness domains and expected influence on adoption*

| Readiness domain | Constructs examined and influence on adoption | Source |
|---|---|---|
| Market and finance | High initial cost, ROI uncertainty and investment confidence shape whether green office specifications are viewed as investable | Darko & Chan, 2017; Madadizadeh et al., 2024; IFC, 2025 |
| Technical and supply | Expertise, training, technology availability and supplier capacity determine whether design intentions can be procured, installed and maintained | Häkkinen and Belloni, 2011; Poorisat et al., 2024; Dharmarathna et al., 2026 |
| Policy and institutional | Policy clarity, incentives, standards, enforcement and government leadership create the certainty needed for wider uptake | IEA, 2021; UNEP, 2021; OECD, 2024 |
| Collaboration and delivery | Early stakeholder involvement and interdisciplinary coordination reduce | de Wilde, 2014; Falana et al., 2025; Vakeva-Baird et al., 2025 |

| Readiness domain | Constructs examined and influence on adoption | Source |
|---|---|---|
| | fragmentation and help close the performance gap | |

### 2.5 STAKEHOLDER INFLUENCE AND THE WEIGHTED PERSPECTIVES

Office building delivery involves clients, designers, contractors, suppliers and policymakers, each influencing different stages of decision-making. Recent net-zero and sustainable-building research shows that interdisciplinary engagement is necessary but uneven, as actor roles differ across project stages and decision types (Falana et al., 2025; Vakeva-Baird et al., 2025). Clients and policymakers tend to shape strategic direction, regulation and investability, while designers, contractors and suppliers influence technical implementation. Treating stakeholder views as homogeneous may therefore understate how readiness deficits emerge, making analytical weighting necessary.

### 2.6 READINESS ASSESSMENT AND GAP ANALYSIS

Readiness assessment frameworks, including technology readiness levels, smart-readiness tools and adoption-readiness models, are used to evaluate preparedness for innovation adoption (Mankins, 1995; European Commission, 2026; U.S. Department of Energy, 2025). Gap-based diagnostic approaches similarly compare current and desired states to identify priorities for sustainability and organisational change (Klassen et al., 2025; Cambridge Institute for Sustainability Leadership, 2023). However, many frameworks remain linear and focus on single dimensions rather than interactions across technical, economic, political, social and behavioural conditions (Heinz et al., 2025; Anyanya et al., 2025). In the built environment, readiness applications remain fragmented across rating systems, smart-readiness tools and roadmaps, while SIDS literature continues to emphasise wider governance, finance and implementation constraints rather than integrated building-readiness models (Anyanya et al., 2025; World Green Building Council, 2025). Although low-carbon and net-zero building studies increasingly stress stakeholder engagement and partnership, these aspects are rarely embedded directly into readiness assessment (Vakeva-Baird et al., 2025; Falana et al., 2025). Three gaps therefore remain. First, empirical work on climate-responsive and resource-efficient office buildings in SIDS contexts such as Mauritius is still limited compared with the broader sustainable-building literature (Poorisat et al., 2024; Dharmarathna et al., 2026). Second, much of the literature continues to focus on barriers and drivers rather than readiness as a systemic condition (Poorisat et al., 2024; Heinz et al., 2025; Dharmarathna et al., 2026). Third, few studies integrate multi-dimensional readiness, stakeholder-weighted analysis and systems interpretation in the building sector. The present study addresses these gaps.

## 3. METHODOLOGY

This study adopts a mixed-method approach, combining a questionnaire survey with expert interviews to capture both breadth and depth of insight. Mixed-methods research is increasingly recognised as appropriate for addressing complex-built environment challenges that cannot be fully understood through a single method (Creswell and Plano Clark, 2018; Venkatesh et al., 2016; Johnson et al., 2007). Data collection was undertaken in two stages. First, a structured questionnaire was distributed purposively to 50 built-

environment professionals with experience relevant to office building delivery, sustainability, policy, commercial appraisal or technical implementation in Mauritius. The questionnaire covered respondent profile, perceived readiness barriers and enablers, and implementation priorities. Thirty-three complete and usable responses were retained for analysis. As Table 2 shows, the sample is experienced but unevenly distributed across job categories, which is analytically important for the weighting procedure.

*Table 2: Profile of the questionnaire survey respondents*

| **Job category** | **Number** | **Years of experience** | | |
|---|---|---|---|---|
| | | **5-10** | **11-15** | **15+** |
| Architect | 1 | | | 1 |
| Consultant | 18 | 7 | 4 | 7 |
| Contractor | 1 | 1 | | |
| Developer | 3 | 1 | 1 | 1 |
| Government | 3 | 3 | | |
| Project Manager | 4 | 3 | | 1 |
| Property Valuer | 1 | 1 | | |
| Sustainability Experts | 2 | | 2 | |
| **Total** | **33** | **16** | **7** | **10** |

Second, five semi-structured expert interviews were conducted to explain the survey patterns and explore mechanisms not captured through structured items. Interviewees were selected because of senior experience across property development, architecture, valuation, quantity surveying, project management and engineering consultancy, as presented in Table 3. The interviews focused on practical barriers, enabling conditions, actor roles, market confidence, supply-chain capacity and policy interventions. Given the exploratory nature of the study, depth of insight was prioritised over sample size (Patton, 2015; Saunders et al., 2019; Brinkmann, 2022). The integration of qualitative and quantitative data followed a triangulation logic to enhance interpretation (Patton, 2015; Venkatesh et al., 2024).

*Table 3: Profile of the expert interviewee*

| **Code** | **Position** | **Area of Expertise** | **Years of Experience** | **Organisation** |
|---|---|---|---|---|
| INT1 | Senior Executive Officer | Property Development; Facilities Management | 20+ | Government Insurance |
| INT2 | Director | Architecture | 20+ | Architectural Practice |
| INT3 | Director | Valuation | 20+ | Consultancy |
| INT4 | Executive Director; Quantity Surveyor | Project Management; Quantity Surveying | 20+ | Consultancy |
| INT5 | Business Development Manager | Structural Engineering Consultancy | 15+ | Consultancy |

The quantitative analysis used a stakeholder-weighted readiness gap analysis. This approach was developed by adapting established practices in Likert-scale survey analysis, composite-indicator construction, directional item recoding and relative-importance ranking (Norman, 2010; OECD, 2008; Vigil-Colet et al., 2020; Holt, 2014; Gündüz et al., 2013; Al Khatib et al., 2020). Because the survey responses were unevenly distributed across job categories, respondents were first grouped into four implementation-relevant stakeholder clusters: developer/owner, government/policy, commercial/advisory, and technical delivery. To prevent the largest respondent group from dominating the results,

each cluster was assigned equal analytical weight. Equal weighting and arithmetic aggregation are commonly used in composite-indicator construction where the purpose is to give comparable importance to predefined dimensions or groups (OECD, 2008).For each survey item, the mean score was first calculated within each stakeholder cluster:

$$\bar{x}_{ic} = \frac{1}{n_c}\sum_{j=1}^{n_c} x_{ijc} \qquad (01)$$

Where $\bar{x}_{ic}$is the mean score for item $i$ in stakeholder cluster $c$, $x_{ijc}$ is the score given by respondent $j$ in cluster $c$, and $n_c$ is the number of respondents in cluster $c$. The stakeholder-weighted mean scores were then normalised to a 0–1 readiness-gap scale. Normalisation is widely used in composite indicator construction to place variables on a common scale before aggregation (OECD, 2008). In this study, larger values indicate weaker readiness. Because the questionnaire contained both negatively framed barrier items and positively framed enabling items, item direction was standardised before aggregation. This follows the logic of reverse coding, where items are recoded so that all items have the same directional relationship with the construct being measured (Vigil-Colet et al., 2020). For negatively framed barrier items, stronger agreement indicates a larger readiness gap. The readiness gap was therefore calculated as:

$$G_i = \frac{\bar{x}_i^W - 1}{A - 1} \qquad (02)$$

Where $G_i$is the readiness-gap score for item $i$, $\bar{x}_i^W$is the stakeholder-weighted mean score for item $i$, and $A = 5$ is the highest possible score on the five-point Likert scale. For positively framed enabling items, weaker agreement indicates a larger readiness gap. The readiness gap was therefore calculated as:

$$G_i = \frac{A - \bar{x}_i^W}{A - 1} \qquad (03)$$

Where $G_i$is the readiness-gap score for item $i$, $\bar{x}_i^W$is the stakeholder-weighted mean score for item $i$, and $A = 5$ is the highest possible score on the five-point Likert scale. This standardisation ensured that all item scores were interpreted in the same direction, with larger values representing weaker readiness. Item level readiness gaps were then grouped into four composite readiness domains: market and finance readiness, technical and supply readiness, policy and institutional readiness, and collaboration and delivery readiness. For each domain, the overall score was calculated as the arithmetic mean of the item-level readiness gaps assigned to that domain:

$$D_d = \frac{1}{m_d}\sum_{i=1}^{m_d} G_i \qquad (04)$$

where $D_d$ is the readiness-gap score for domain $d$, $G_i$ is the readiness-gap score for item $i$, and $m_d$ is the number of items assigned to domain $d$. In addition to readiness-gap items, the questionnaire included potential implementation measures covering energy efficiency, water efficiency, climate resilience and resource management. Respondents rated the priority of each measure on a five-point Likert scale, where 1 indicated very low priority and 5 indicated very high priority. Priority ranking was calculated using a stakeholder-weighted Relative Importance Index (W-RII). The Relative Importance Index is widely used in construction management research to rank questionnaire items according to respondents perceived importance (Holt, 2014; Gündüz et al., 2013; Al

Khatib et al., 2020). First, an RII was computed for each item within each stakeholder cluster:

$$RII_{ic} = \frac{\sum_{j=1}^{n_c} w_{ijc}}{An_c} \qquad (05)$$

Where $RII_{ic}$ is the relative importance index for item $i$in stakeholder cluster $c$, $w_{ijc}$ is the priority rating assigned by respondent $j$in cluster $c$, $A = 5$ is the highest possible rating, and $n_c$ is the number of respondents in cluster $c$. The overall stakeholder-weighted priority score for each item was then calculated as the simple average of the four cluster-specific RII values:

$$W\text{-}RII_i = \frac{1}{C}\sum_{c=1}^{C} RI\,I_{ic} \qquad (06)$$

where $W\text{-}RII_i$ is the stakeholder-weighted relative importance index for item $i$, and $C = 4$ is the number of stakeholder clusters. Higher W-RII values indicate higher implementation priority. Items were ranked in descending order to identify the most strongly supported implementation measures.

Expert interviews were analysed to explain the survey findings and identify practical intervention points for improving uptake. Transcripts were thematically coded for recurring barriers, enabling conditions, proposed actions and actor roles, then grouped into higher-order themes and causal relationships, following established approaches to thematic analysis and qualitative data reduction (Braun & Clarke, 2006; Miles et al., 2014). These relationships were consolidated into a qualitative system map using causal-loop and systems-thinking principles (Sterman, 2000). Leverage points were identified where interviewees described interventions capable of disrupting reinforcing mechanisms and generating wider system change (Meadows, 1999). Finally, these leverage points were cross-checked against the stakeholder-weighted readiness gaps and implementation priorities to ensure consistency across the qualitative and quantitative findings.

# 4. FINDINGS

## 4.1 STAKEHOLDER-WEIGHTED READINESS GAPS

Table 4 presents the stakeholder-weighted readiness gap scores and item-to-domain mapping. The largest gap is market and finance readiness (0.735), showing that adoption is constrained mainly by high upfront costs and uncertain returns rather than by lack of awareness. Technical and supply readiness is also weak (0.666), reflecting concerns over expertise, training, supplier availability and implementation capacity. Policy and institutional readiness follow closely (0.652), particularly around incentives and enforcement. Collaboration and delivery show a lower but still relevant gap (0.449), suggesting that project coordination is stronger than the wider enabling environment. At item level, high initial cost is the largest deficit, with a stakeholder-weighted mean of 4.28/5. Other sizeable gaps include limited awareness, inadequate incentives, weak enforcement, constrained supplier availability, insufficient training and uncertain ROI. By contrast, early stakeholder involvement (3.42/5) and professional collaboration (3.34/5) are comparatively stronger. Overall, the sector appears able to coordinate projects once they proceed, but still lacks the enabling conditions needed to make climate-responsive and resource-efficient office buildings routine practice.

*Table 4: Stakeholder-weighted readiness gap scores by domain*

| Domain | Key items included | Gap score | Interpretation |
|---|---|---|---|
| Market & Finance | High initial cost; ROI uncertainty/investment confidence | 0.735 | Highest deficit: adoption is not yet investable at scale |
| Technical & Supply | Limited expertise; insufficient training; supplier/product availability | 0.666 | Skills and supply chains remain fragile |
| Policy & Institutional | Policy clarity; incentive adequacy; enforcement; government support | 0.652 | Rules and incentives are perceived as weak or inconsistent |
| Collaboration & Delivery | Stakeholder awareness; Early involvement; professional collaboration; government role | 0.449 | Project coordination exists, but enabling support is uneven |

## 4.2 STAKEHOLDER-WEIGHTED IMPLEMENTATION PRIORITIES

Table 5 shows the highest stakeholder-weighted implementation priorities. The readiness-gap results should not be interpreted as evidence that stakeholders lack preferred technical pathways.

*Table 5: Highest stakeholder-weighted implementation priorities*

| Category | Priority item | W-RII |
|---|---|---|
| Climate resilience | Flooding | 0.860 |
| Resource management | Lifecycle assessment of materials and systems | 0.852 |
| Energy efficiency | Optimisation of natural daylighting | 0.843 |
| Water efficiency | Rainwater harvesting | 0.843 |
| Energy efficiency | Adoption of passive cooling and efficient AC systems | 0.834 |
| Resource management | Use of digital technologies | 0.831 |
| Energy efficiency | Optimisation of building envelope | 0.824 |

The priority analysis shows the opposite. The strongest weighted priorities are flood resilience (0.860), life-cycle assessment of materials and systems (0.852), optimaisation of natural daylighting (0.843), rainwater harvesting (0.843), passive cooling and efficient air-conditioning (0.834), and digital technologies (0.831)and building-envelope optimisation (0.824).These values provide direct quantitative support for a feasible design agenda built around passive efficiency, climate resilience, water efficiency, life-cycle resource management and digital monitoring. A second pattern is that lower-complexity or design-integrated measures often outrank more capital-intensive or operationally demanding systems. Daylighting, passive cooling, envelope optimisation, and rainwater harvesting all score strongly. This suggests that stakeholders do not primarily resist climate-responsive and resource-efficient office buildings as an idea; rather, they resist uncertain investment conditions and implementation risks around them.

## 4.3 SYSTEMS INTERPRETATION AND LEVERAGE POINTS

The interview findings indicates that these gaps behave as an interacting system rather than a set of independent barriers. Figure 1 summarises the qualitative system map derived from the coded interviews and open-ended responses. Three reinforcing mechanisms are particularly important. The first is an investment-confidence trap, Weak public signalling, and limited incentives suppress project uptake; low project uptake produces few demonstrator projects and little performance evidence; and scarce evidence sustains ROI uncertainty and weak market confidence, which further suppress adoption. The second is a supply-chain trap. When adoption stays low, suppliers have little incentive to deepen stock, service capacity, or spare-parts availability. Import dependence remains high, maintenance risk remains visible, and costs stay elevated, which further discourages project uptake. The third is a capability trap. Low adoption reduces incentives for firms and institutions to invest in continuous professional development, shared knowledge platforms, and implementation support; this keeps technical confidence fragile and reinforces perceived delivery risk. The three loops interact: poor evidence feeds finance concerns, low market volume weakens suppliers, and shallow supplier capacity makes skills acquisition less attractive. Table 6 identifies the principal leverage points emerging from the systems analysis and shows how each intervention responds to a specific reinforcing mechanism.

*Table 6: Leverage points underpinning the proposed uptake framework*

| Enabling mechanism | Leverage point | System mechanism addressed | Sequencing implication |
|---|---|---|---|
| Signal | Permit-stage integration of minimum green criteria. | Strengthens public signalling and shifts green requirements from optional to expected | Near-term |
| Demonstrate | Public demonstrator projects plus performance disclosure | Turns projects into local evidence and weakens ROI uncertainty | Near-term |
| De-risk | Targeted fiscal de-risking; subsidies, tax breaks, concessional loans | Reduces upfront cost pressure and supports early market volume | Near- to medium-term |
| Standardise | Structured CPD and shared technical-support platform | Counters the capability trap and improves maintenance confidence | Medium-term |
| | Supplier standards, procurement support, and spare-parts availability | Deepens the market and reduces cost and maintenance risk | Medium-term |

The five leverage points were clustered into the four enabling mechanisms according to their dominant intervention logic: whether the action primarily signals expectations, demonstrates local evidence, de-risks investment or standardises repeatable delivery capability. CPD support and supplier standards were both grouped under Standardise because they convert one-off project learning into repeatable market capability.

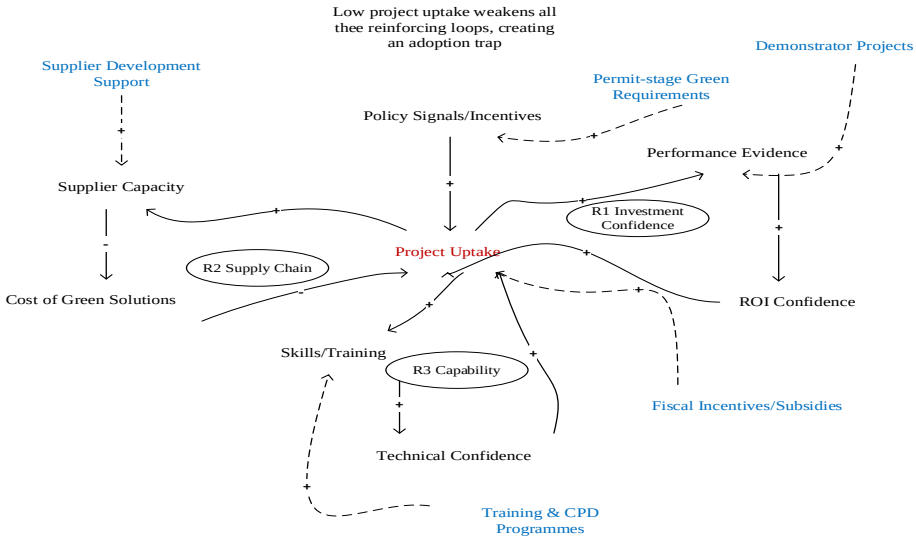



*Figure 1: Causal loop diagram of adoption dynamics for climate-responsive and resource efficient office building*

### 4.4 SYSTEMS-INFORMED FRAMEWORK FOR SCALING CLIMATE-RESPONSIVE AND RESOURCE-EFFICIENT OFFICE BUILDINGS

Building on the leverage points identified in Table 6, Figure 2 translates the readiness diagnosis and qualitative systems analysis into a structured readiness-to-action framework for Mauritius. The centre of the framework presents four cross-cutting enabling mechanisms: Signal, Demonstrate, De-risk and standardise. The mechanism labels were derived from the clustering logic reported in Table 6 and therefore describe broad types of systemic change, while the leverage points specify the concrete actions through which that change can be activated. Signal strengthens policy direction through permit-stage and procurement criteria.

Demonstrate builds local evidence through demonstrator projects and post-occupancy disclosure. De-risk reduces upfront cost and ROI uncertainty through subsidies, concessional finance, tax relief and valuation reform. Standardise supports repeatable delivery through CPD, supplier standards, technical support platforms, spare parts access and shared knowledge. Together, these mechanisms connect stakeholder priorities passive cooling and daylighting, rainwater harvesting, flood resilience, life-cycle assessment and digital monitoring to the conditions needed for scale; stronger project pipelines, market confidence, supplier ecosystems and maintenance confidence. The framework therefore links diagnosed readiness gaps to mainstream uptake in Mauritius rather than presenting a generic policy list.

## 5. DISCUSSION

The central empirical insight of this paper is that Mauritius does not mainly face a deficit of technical imagination in climate-responsive and resource-efficient office development. The priority results indicate a coherent implementation agenda because stakeholders rated passive and design-integrated measures highly: natural daylighting (0.843), passive cooling and efficient air-conditioning (0.834), and building-envelope optimisation (0.824). They also rated climate resilience and measurable resource performance highly, including flood resilience (0.860), rainwater harvesting (0.843), life-cycle assessment

(0.852) and digital technologies (0.831). What is missing are the system conditions that allow these measures to be financed, trusted, maintained and repeated across projects. This finding aligns with reviews arguing that sustainable building transitions depend less on a lack of design options than on the alignment of finance, policy, delivery capability and stakeholder coordination (Poorisat et al., 2024; Dharmarathna et al., 2026). The systems interpretation adds an important aspect to the readiness-gap results. High upfront cost, weak incentives, supplier fragility, limited training, and uncertain ROI should not be read as isolated variables. They function through feedback. Weak policy and limited public leadership reduce the number of demonstrator projects; low demonstrator volume reduces locally credible evidence; without evidence, valuation practices and tenant expectations do not change; without stronger commercial signals, private developers continue to see greener specifications as risky cost additions. In Repenning and Sterman's (2002) terms, parts of the Mauritian system resemble a capability trap: low volume justifies low investment in capability, and low capability in turn justifies low volume. This interaction is especially important in SIDS contexts. Thin markets and import dependence mean that even technically feasible solutions can remain commercially fragile for longer than in larger economies. A policy package that focuses only on codes may therefore underperform if it is not sequenced with demand creation, performance disclosure, skills support, and supplier development. Conversely, awareness campaigns without permit integration or financial de-risking are unlikely to move the system materially. This interpretation is consistent with recent policy and finance literature emphasising that building transition depends on coordinated regulatory signals, investability, and market development rather than isolated interventions (OECD, 2024; IFC, 2025).

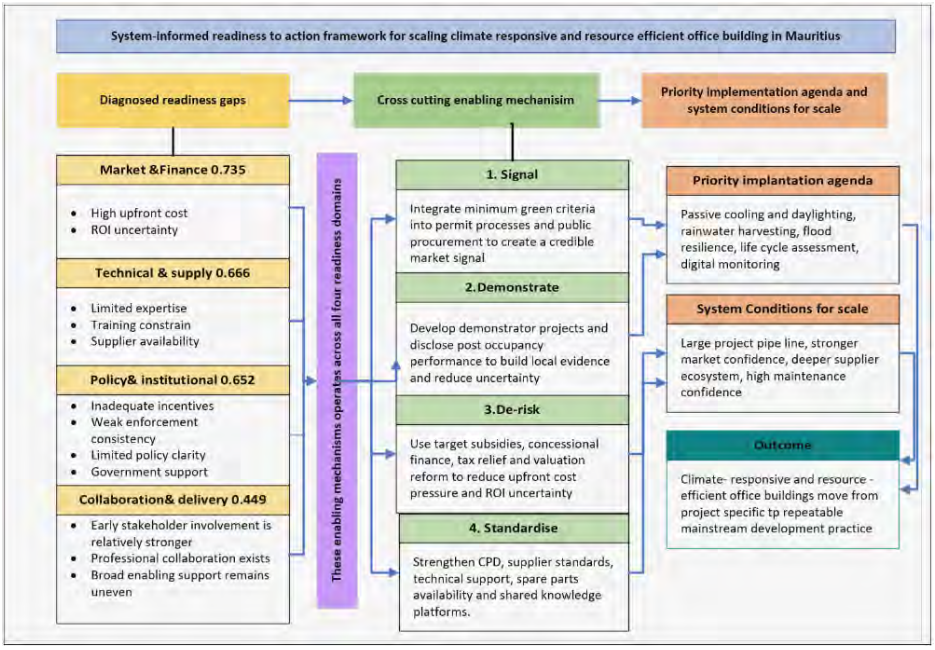



*Figure 2: Systems-informed readiness-to-action framework for scaling climate-responsive and resource-efficient office buildings in Mauritius*

## 6. CONCLUSIONS

This paper reframed the uptake of climate-responsive and resource-efficient office buildings in Mauritius as a readiness and systems challenge. The stakeholder-weighted

readiness gap analysis shows that the main constraints are market and finance readiness, technical and supply capacity, and inconsistent policy support, despite stakeholder agreement on feasible technical priorities. The implication is that Mauritius does not only need further promotion of sustainable design features; it needs an enabling environment that allows these measures to move from one-off projects to routine practice. The proposed framework suggests a transition sequence of signal, demonstrate, de-risk, and standardise. Public signalling, demonstrator projects, performance disclosure, financial de-risking, capability building, and supplier development should therefore be treated as connected interventions rather than separate actions. The study is limited by its small purposive sample, particularly the small developer/owner and government/policy clusters, meaning that individual responses may affect weighted scores. The qualitative system map is also based on expert interpretation rather than empirical validation of feedback dynamics. Future research should use larger samples, cross-SIDS comparison, sensitivity testing of weighted indicators, through simulation, longitudinal data and post-occupancy evidence to strengthen the readiness framework.

# 7. REFERENCES


Al Khatib, B., Poh, Y. S., & El-Shafie, A. (2020). Delay factors management and ranking for reconstruction and rehabilitation projects based on the relative importance index (RII). *Sustainability, 12*(15), 6171. https://doi.org/10.3390/su12156171

Anyanya, D., Paulillo, A., Fiorini, S., & Lettieri, P. (2025). Evaluating sustainable building assessment systems: A comparative analysis of GBRS and WBLCA. *Frontiers in Built Environment, 11*, 1550733. https://doi.org/10.3389/fbuil.2025.1550733

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Briguglio, L. P. (2016). Exposure to external shocks and economic resilience of countries: Evidence from global indicators. *Journal of Economic Studies, 43*(6), 1057–1078. https://doi.org/10.1108/JES-12-2014-0203

Briguglio, L., Byron, J., Moncada, S., & Veenendaal, W. (Eds.). (2020). *Handbook of governance in small states.* Routledge. https://doi.org/10.4324/9780429061356

Brinkmann, S. (2022). *Qualitative interviewing: Conversational knowledge through research interviews* (2nd ed.). Oxford University Press.

Cambridge Institute for Sustainability Leadership. (2023). *CISL's business transformation framework: Preliminary diagnostic*. University of Cambridge Institute for Sustainability Leadership. https://www.cisl.cam.ac.uk/news-and-resources/publications/cisls-business-transformation-framework-preliminary-diagnostic

Cheshire, D. (2016). *Building revolutions: Applying the circular economy to the built environment*. RIBA Publishing.

Creswell, J. W., & Plano Clark, V. L. (2018). *Designing and conducting mixed methods research* (3rd ed.). SAGE.

Darko, A., & Chan, A. P. C. (2017). Review of barriers to green building adoption. *Sustainable Development, 25*(3), 167–179. https://doi.org/10.1002/sd.1651

De Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction, 41*, 40–49. https://doi.org/10.1016/j.autcon.2014.02.009

Dharmarathna, D., Bunster, V., & Graham, P. (2026). Barriers and drivers of sustainable building adoption and influencing factor dynamics: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews, 226*, 116361. https://doi.org/10.1016/j.rser.2025.116361

European Commission. (2026). *Smart readiness indicator: Implementation tools*. https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/smart-readiness-indicator_en

Falana, J., Osei-Kyei, R., & Tam, V. W. Y. (2025). Critical barriers and success strategies to stakeholder partnership towards achieving net zero emissions building: A systematic literature review. *Cities, 163*, 106061. https://doi.org/10.1016/j.cities.2025.106061

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Gündüz, M., Nielsen, Y., & Özdemir, M. (2013). Quantification of delay factors using the relative importance index method for construction projects in Turkey. *Journal of Management in Engineering, 29*(2), 133–139. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000129

Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. *Building Research & Information, 39*(3), 239–255. https://doi.org/10.1080/09613218.2011.561948

Heinz, E., Sovacool, B. K., Kwan, T., & Petit, V. (2025). Reviewing the 95 sociotechnical barriers to the decarbonization of buildings. *Nature Communications, 16*, 9983. https://doi.org/10.1038/s41467-025-64923-9

Holt, G. D. (2014). Asking questions, analysing answers: Relative importance revisited. *Construction Innovation, 14*(1), 2–16. https://doi.org/10.1108/CI-06-2012-0035

Hong, D., Cheng, R., Lei, H., Zhou, X., Yang, L., Feng, C., & Gao, S. (2025). Comprehensive review on the impact of building envelopes on indoor thermal comfort in office buildings: Balancing occupant comfort and energy efficiency. *Building and Environment, 289*, 114018. https://doi.org/10.1016/j.buildenv.2025.114018

Hong, J., Chan, I., & Ma, P. (2025). Towards an integrated socio-ecological approach in green building transitions: A systematic literature review. *Sustainability, 17*(12), 5491. https://doi.org/10.3390/su17125491

International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. https://www.iea.org/reports/net-zero-by-2050

International Energy Agency. (2025). *Energy efficiency 2025*. https://www.iea.org/reports/energy-efficiency-2025

International Finance Corporation. (2025). *Sustainable buildings: Finance reference guide*. https://www.ifc.org/en/insights-reports/2025/sustainable-buildings-finance-reference-guide

Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (P. R. Shukla et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157926

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of Mixed Methods Research, 1*(2), 112–133. https://doi.org/10.1177/1558689806298224

Joyram, H., Govindan, K., & Nunkoo, R. (2024). Development of a novel psychological model to predict the eco-block building adoption in Mauritius. *Cleaner and Responsible Consumption, 12*, 100172. https://doi.org/10.1016/j.clrc.2024.100172

Klassen, M., Dobni, C. B., & Sheehan, N. T. (2025). Measure what matters: A blueprint for a sustainability culture diagnostic. *Business Horizons, 68*(6), 793–805. https://doi.org/10.1016/j.bushor.2025.07.004

Madadizadeh, A., Siddiqui, K., & Aliabadi, A. A. (2024). Review: The economics landscape for building decarbonization. *Sustainability, 16*(14), 6214. https://doi.org/10.3390/su16146214

Mankins, J. C. (1995). *Technology readiness levels: A white paper*. NASA Office of Space Access and Technology, Advanced Concepts Office.

Meadows, D. H. (1999). *Leverage points: Places to intervene in a system*. The Sustainability Institute. https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative data analysis: A methods sourcebook* (3rd ed.). SAGE.

Norman, G. (2010). Likert scales, levels of measurement and the "laws" of statistics. *Advances in Health Sciences Education, 15*, 625–632. https://doi.org/10.1007/s10459-010-9222-y

Organisation for Economic Co-operation and Development. (2024). *Global monitoring of policies for decarbonising buildings:A multi-level approach*. OECD Publishing. https://doi.org/10.1787/d662fdcb-en

Organisation for Economic Co-operation and Development, European Union, & European Commission, Joint Research Centre. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD Publishing. https://doi.org/10.1787/9789264043466-en

Patton, M. Q. (2015). *Qualitative research & evaluation methods: Integrating theory and practice* (4th ed.). SAGE.

Poorisat, T., Aigwi, I. E., Doan, D. T., & GhaffarianHoseini, A. (2024). Unlocking the potentials of sustainable building designs and practices: A systematic review. *Building and Environment, 266*, Article 112069. https://doi.org/10.1016/j.buildenv.2024.112069

Rana, J., & Rughooputh, R. (2014). The barriers and recommendations to implementing low carbon emission buildings in Mauritius. *GE-International Journal of Engineering Research, 2*(9), 168–177.

Repenning, N. P., & Sterman, J. D. (2002). Capability traps and self-confirming attribution errors in the dynamics of process improvement. *Administrative Science Quarterly, 47*(2), 265–295. https://doi.org/10.2307/3094806

Robinson, S.-A., & Dornan, M. (2017). International financing for climate change adaptation in small island developing states. *Regional Environmental Change, 17*(4), 1103–1115. https://doi.org/10.1007/s10113-016-1085-1

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modelling for a complex world*. McGraw-Hill.

U.S. Department of Energy, Office of Technology Commercialization. (2025). *Adoption readiness levels (ARL) framework*. https://www.energy.gov/technologycommercialization/adoption-readiness-levels-arl-framework

United Nations. (2024). *The Antigua and Barbuda Agenda for Small Island Developing States: A renewed declaration for resilient prosperity*. https://digitallibrary.un.org/record/4054465

United Nations Environment Programme. (2021). *2021 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*. https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction

United Nations Environment Programme & Global Alliance for Buildings and Construction. (2025). *Global status report for buildings and construction 2024/2025: Not just another brick in the wall*. https://www.unep.org/resources/report/global-status-report-buildings-and-construction-20242025

Vakeva-Baird, S., Tahmasebi, F., Williams, J.-J., & Mumovic, D. (2025). Effective interdisciplinary stakeholder engagement in net zero building design. *Buildings and Cities, 6*(1), 654–673. https://doi.org/10.5334/bc.510

Venkatesh, V., Brown, S. A., & Sullivan, Y. W. (2016). Guidelines for conducting mixed-methods research: An extension and illustration. *Journal of the Association for Information Systems, 17*(7), 435–495. https://doi.org/10.17705/1jais.00433

Venkatesh, V., Brown, S. A., & Sullivan, Y. W. (2024). *Conducting mixed-methods research: From classical social sciences to the age of big data and analytics*. Virginia Tech Publishing. https://doi.org/10.21061/conducting-mixed-methods-research

Vigil-Colet, A., Navarro-González, D., & Morales-Vives, F. (2020). To reverse or to not reverse Likert-type items: That is the question. *Psicothema, 32*(1), 108–114. https://doi.org/10.7334/psicothema2019.286

World Green Building Council. (2019). *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*. https://worldgbc.org/article/bringing-embodied-carbon-upfront/

World Green Building Council. (2025). *Zero carbon and climate resilience readiness framework*. https://worldgbc.org/zero-carbon-framework/

Xu, J., Gao, Y., & Yang, L. (2025). Climate-adaptive passive design strategies for near-zero-energy office buildings in central and southern Anhui, China. *Sustainability, 17*(14), 6535. https://doi.org/10.3390/su17146535

Sandaruwan, W.M.D.Y., Sandanayake, Y.G., Ekanayake, E.M.A.C. and Tennakoon, G.A., 2026. Withstanding supply chain vulnerabilities in off-site construction logistics: A narrative review and 3d visualisation. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1843-1856. DOI: https://doi.org/10.31705/WCS.2026.134. Available from: https://ciobwcs.com/papers/

# WITHSTANDING SUPPLY CHAIN VULNERABILITIES IN OFF-SITE CONSTRUCTION LOGISTICS: A NARRATIVE REVIEW AND 3D VISUALISATION

**W.M.D.Y. Sandaruwan[1], Y.G. Sandanayake[2], E.M.A.C. Ekanayake[3] and G.A. Tennakoon[4]**

## *ABSTRACT*

*Logistics operations challenges in Off-Site Construction (OSC) trigger Supply Chain Vulnerabilities (SCVs), highlighting the need for a better understanding of appropriate Withstanding Measures (WMs). Existing research often lacks an integrated mechanism to systematically map SCVs and WMs. This limits decision-makers' ability to understand interdependencies and prioritise responses effectively. As a result, there is a need for a visualisation model which also provides structured analysis of the relationships between SCVs and WMs. Therefore, this paper focused on developing a Three-Dimensional (3D) visualisation model to map SCVs and their corresponding WMs. Initially, a narrative literature review approach was employed to identify the SCVs in OSC and their relationships with WMs. A total of 30 papers were s selected through structured screening using predefined inclusion and exclusion criteria. Total of 73 SCVs and 98 WMs both across six thematic categories were identified. Based on the outcome of the literature review, the model was developed using CodeSandbox web development platform. The findings reveal that the integration of Geographic Information Systems (GIS) into Building Information Modelling (BIM) enables the mitigation of the highest number of SCVs. However, 61.64% of the identified SCVs are addressed by only a single WM, indicating limited exploration of WMs in these areas. Therefore, this study offers a novel contribution by developing a 3D visualisation model, addressing a critical gap in both relational mapping and visual decision-support in OSC Supply Chain (SC) logistics.*

***Keywords:*** *3D Model; Off-Site Construction; Supply Chain; Withstanding Measures.*

## 1. INTRODUCTION

The global construction industry, driven by rapid growth and increasing performance expectations, is progressively embracing OSC techniques as an alternative to

[1] Research Scholar, Department of Building Economics, University of Moratuwa, Sri Lanka, sandaruwanwmdy.26@uom.lk
[2] Professor, Department of Building Economics, University of Moratuwa, Sri Lanka, ysandanayake@uom.lk
[3] Senior Lecturer, Department of Architecture and Built Environment, Birmingham City University, United Kingdom, Anushika.mudiyanselage@bcu.ac.uk
[4] Senior Lecturer, Department of Building Economics, University of Moratuwa, Sri Lanka, anuradhat@uom.lk

conventional on-site methods (Sanjeepan, 2017). OSC represents a specialised form of industrialised construction in which building components, modules, or prefabricated sections are manufactured and pre-assembled within controlled factory environments (Dunton et al., 2024). Since OSC involves the processes of producing, storing, transporting, and assembling in a tightly synchronised sequence, logistics operations in OSC SCM play a decisive role in enhancing quality and time management, and strengthening overall project performance (Gunawardana & Wedage, 2020). Moreover, Dunton et al. (2024) highlighted that increasing logistics complexity turns small operational issues into larger system-wide risks and expensive delays, thereby increasing the vulnerability of OSC SCs. Similarly, Sanjeepan (2017) argued that supply SCVs in logistics operations, particularly in OSC, need to be properly managed, as they are highly interlinked among multiple stakeholders, and even minor neglect of SCVs, such as logistics availability, can affect overall project success. This makes it of paramount importance to understand SCVs in OSC logistics and their WMs to make the construction project successful.

Ekanayake et al. (2022) identified 37 SCVs in OSC that need to be addressed, and their findings emphasised the need for an action framework that addresses the vulnerabilities identified. A basic framework was developed by Ekanayake et al. (2019) to enhance Supply Chain Resilience (SCR) in industrialised construction by including both potential SCVs and WMs to mitigate these SCVs. Shemov et al. (2020) developed a blockchain-based model to perform construction SC threat analysis. Wang and Zhou (2024) proposed a complex network theory and the cascade failure model for vulnerability analysis in OSC SCs. However, Teymourifar (2026) pointed out that the existing frameworks and models often exhibit conceptual gaps and lack operational clarity, which further constrains their implementation in practice. This is further supported by Lou et al. (2020) who argued that frameworks and traditional models are too abstract and their practical application in real time decision making remains limited due to increasing complexity in information flow. Particularly in OSC SC, traditional linear frameworks and models fail due to dynamic logistics, high interdependencies and requirement for real time collaboration, whereas effective visualisation techniques can represent these aspects more comprehensively. Further, Lou et al. (2022) supported this by articulating that the absence of proper visualisation mechanisms exacerbates these challenges, as complex interrelationships among SC elements cannot be easily understood or communicated.

Visualisation enhances interpretability by transforming complex data into more understandable forms and reducing cognitive burden for decision-makers (Kurasova et al., 2024). However, despite being well-established theoretically by several authors and notwithstanding the growing recognition of complex multidimensional interactions within OSC SCs, the research focusing on visualisation-based analytical models that map SCVs and corresponding WMs remains limited. Similarly, the lack of suitable visualisation tools makes it challenging for practitioners and decision-makers to interpret the complex network of SCVs and WMs within OSC logistics operations. Without effective visualisation, understanding SCV–WM relationships are difficult. To address this gap, this paper focused on developing a 3D visualisation model to map SCV in OSC and their corresponding WMs, thereby enabling improved interpretation of complex interrelationships and supporting effective decision-making.

# 2. METHODOLOGY

This study is conducted in two phases. Phase I comprised a narrative literature review to identify SCVs and corresponding WMs, while phase II focused on the development of 3D visualisation model. Given the problem-oriented nature of the study, a pragmatic research philosophy which is to select methods based on their practical usefulness in addressing the research problem (Bacon, 2012) was adopted.

## 2.1 LITERATURE IDENTIFICATION AND DATA EXTRACTION

A narrative literature review approach which is suitable for establishing rationales for future research in areas with limited existing knowledge (Ferrari, 2015) was adopted to identify relevant studies related to OSC SCVs within logistics operations and their corresponding WMs. The literature search was conducted using the Google Scholar database. Keywords were developed under the four primary concept groups:

1. Off-site construction – off-site construction, modular construction, prefabrication
2. Supply chain – construction supply chain, supply chain management
3. Vulnerabilities – vulnerabilities, risk, disruption
4. Withstanding measures – resilience, withstanding measures, withstanding capabilities, mitigation measures, mitigation strategies.

These keywords were combined in different search strings to retrieve relevant publications. The search strings were designed to support a focused synthesis of relevant literature; therefore, the findings represent a structured interpretation of the available literature rather than a comprehensive census of all publications. Following the recommendations of Ferrari (2015), general inclusion and exclusion criteria were considered to maintain the relevance and quality of the selected literature. Priority was given to peer-reviewed journal articles and conference proceedings published in English between 2013 and 2025 to capture recent developments and emerging challenges related to SCR.

Studies that did not sufficiently address SCVs, risks, or WMs were omitted from the review. Similarly, non-academic sources and studies with limited methodological clarity or incomplete information were not considered. The search process initially identified 74 publications, from which the most relevant studies were selected through a review of titles, abstracts, and full texts. Ultimately, 30 papers were retained for detailed analysis and discussion.

From the final selected 30 papers, SCVs and their corresponding WMs were identified. Thematic categories for SCVs and WMs were derived based on recurring patterns, classifications, and terminology reported in the reviewed literature. Several prior studies were used as the basis for identifying common classification structures. For example, Ben-Daya et al. (2019) suggested SCVs related to warehouse, transportation, and inventory management and WMs related to IoT, while Ekanayake et al. (2019) proposed categories such as external environmental, technical, and financial vulnerabilities. Based on these recurring classifications, identified SCVs and WMs were manually grouped into relevant thematic categories according to their characteristics and contextual similarities. Furthermore, vulnerabilities and WMs that could not be directly assigned to the initially identified categories were comparatively analysed and grouped under newly developed relevant categories to maintain consistency in the classification process. Subsequently, each identified SCV and WM was manually assigned to the appropriate thematic category

based on its characteristics. In the same manner, relationships between SCVs and WMs were defined by linking each SCV to the WM as reported in the literature, thereby establishing SCV-WM relationship based on documented evidence.

## 2.2 VISUALISATION MODEL DEVELOPMENT

The visualisation model, developed from scratch, is a React-based 3D force-directed bipartite network defined here as an interactive 3D network in which elements are organised into two distinct groups and automatically positioned using a physics-based layout algorithm. The model was developed using JavaScript (React/JSX) within the CodeSandbox web development environment.

### 2.2.1 Network Structure

The model consists of a network structure which represents a directed mapping between SCVs and their corresponding WMs (refer Figure 2).

```
{
  id: "V2",
  code: "V2",
  type: "vuln",
  group: "Logistics & Infrastructure Risks",
  name: "Delivery schedule uncertainty / risk of delay",
  degree: 7,
  docsStr: "R7,R9,R26,R28,R19,R1",
```

```
{
  id: "S111",
  code: "S111",
  type: "sol",
  group: "Machine Learning",
  name: "ML-based subsystem simulation modeling",
  degree: 1,
  docsStr: null,
},
```

*Figure 1: Java Script code blocks which add the core data set to the model*

The network structure consists of two primary node sets: SCV nodes and WM nodes. Node set data which were initially stored in a Microsoft Excel file were transformed into JavaScript (React/JSX) format as depicted in Figure 1 using Microsoft Excel Visual Basic for Applications (VBA).

### 2.2.2 Node Size and Height

SCV node degree is defined as the number equal to the number of WMs connected to specific SCV. WM node degree is defined as the number equal to the number of SCVs connected to a specific WM (refer Figure 1). Then node geometry (radius and height) is scaled using node degree to visually represent connectivity importance, meaning larger nodes for highly connected SCVs and WMs. For that, the following formulas were used, where *d* denotes the node degree, *Number()* represents a numerical type conversion function, *r* denotes the computed node radius derived from the scaling function, *clamp()* is used to restrict values within predefined bounds to prevent nodes from becoming excessively small or large, *Math.sqrt()* denotes the square root scaling function, and *h* represents the node height.

*const d = Number (node.degree || 1)* (01)

*return clamp(1 + 6.25 * Math.sqrt(d), 2, 30)* (02)

*const h = clamp(4 + 18 * Math.sqrt(Number(node.degree || 1)), 10, 220)* (03)

Both radius and height dimensions apply square-root scaling to moderate size differences, ensuring that highly connected nodes appear larger and taller, thereby improving visual prominence and interpretability.

# 3. FINDINGS AND DISCUSSION

## 3.1 PHASE I – NARRATIVE LITERATURE REVIEW

This study aims to develop a 3D visualisation model to represent SCVs and their corresponding WMs within OSC logistics operations. To achieve the aim, during phase I, 30 selected targeted publications were analysed. 73 SCVs and 98 WMs were identified meanwhile 137 connections between SCVs and their corresponding WMs were examined which were taken directly to phase II to develop the visualisation model. 6 SCV thematic categories and 6 WM thematic categories were identified as described in the previous section. Identified SCVs, their corresponding WMs and groups were depicted in below Table 1. SCV thematic categories include warehouse management and infrastructure risk, financial and market Risks, strategic and organisational risks, information and digital risks, operational and technical risks, and external and environmental risks, while BIM, IoT, blockchain, machine learning, information systems and mathematical models were the 6 thematic categories identified to classify WMs.

## 3.2 PHASE II – 3D VISUALISATION MODEL

### 3.2.1 Unique Functionality of the Model

The developed 3D visualisation model and dedicated instructional video is publicly accessible through the following links.

- 3D Visualisation model: https://sc-vmodel3.vercel.app/
- Instructional Video: https://www.youtube.com/watch?v=wlCJsJzlN3c

As outlined in the instructional video, the main functionalities of the model are described in detail below:

- Integrated Legend

The model includes a legend toggle that provides interactive guidance and reference for both SCVs and WMs as depicted in Figure 2.

- Highlighted path

The highlighted path functionality enables users to trace the relationships of a selected SCV or WM. Selecting an SCV or WM from the legend highlights the chosen node, its connected nodes, and their linking edges, as shown in Figure 2.

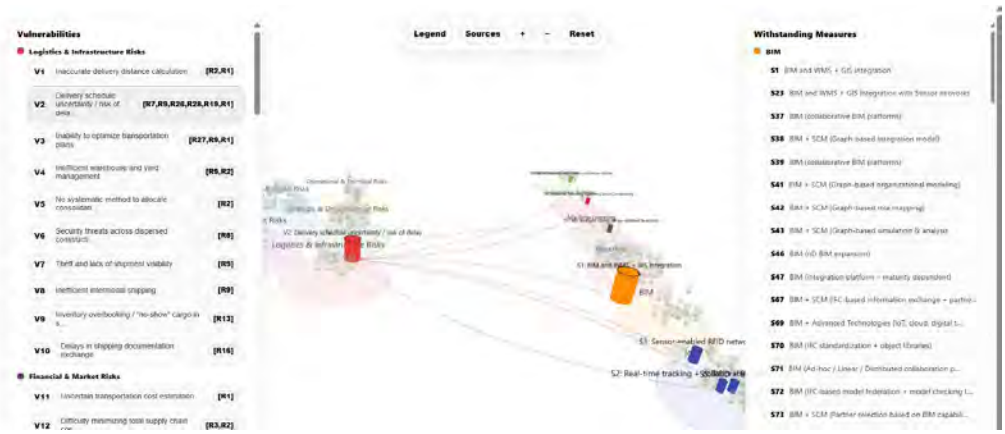



*Figure 2: Legend and highlighted path*

*Table 1: Core data set from narrative literature review - SCV and corresponding WMs*

| Document | Vulnerability | Withstanding Measure | Document | Vulnerability | Withstanding Measure |
|---|---|---|---|---|---|
| [R9] | Inefficient warehouse and yard management (VG1) | BIM and WMS + GIS integration (WG1)<br>Smart Things (WG4) | [R13], [R5] | Limited use of advanced technologies for SC integration (VG4) | Blockchain + Smart Contracts (WG3) |
| | | | [R5] | Lack of process, IT infrastructure standa rdisation (VG4) | BIM (IFC standardisation + object libraries) (WG1) |
| [R2] | No systematic method to allocate consolidation centers (VG1) | BIM and WMS + GIS integration (WG1) | [R6] | Lack of structured BIM collaboration among multiple firms (VG4) | BIM (Ad-hoc / Linear / Distributed collaboration patterns) (WG1) |
| [R8] | Security threats across dispersed construction sites/warehouse (VG1) | IoT (Security Monitoring & Identification Systems) (WG4) | [R6] | Redundancy and inefficiency in information exchange (VG4) | BIM (IFC-based model federation + model checking tools) (WG1) |
| [R8] | Security threats across dispersed construction sites/warehouse (VG1) | IoT (Face Detection & Surveillance) (WG4) | [R6] | Uneven BIM readiness among SC actors (VG4) | BIM + SCM (Partner selection based on BIM measure) (WG1) |
| [R9] | Inefficient intermodal shipping (VG1) | Smart containers (WG4) | [R12], [R13], [R14], | Lack of traceability of materials and components (VG4) | Blockchain (SC traceability + Proof of provenance) (WG3) |
| [R13] | Inventory overbooking (VG1) | Blockchain + Smart Contracts (WG3) | | | Blockchain + SCO-based Oracles (WG3) |
| [R1] | Uncertain transportation cost estimation (VG2) | BIM and WMS + GIS integration (WG1) | | | Blockchain (Immutable ledger + Provenance tracking) (WG3) |
| [R2] | Difficulty minimizing total SC cost (VG2) | BIM and WMS + GIS integration with Sensor networks (WG1) | | | Blockchain + Smart Contracts (WG3) |
| [R13], [R14], [R10] | Presence of intermediaries increasing transaction costs (VG2) | Blockchain (Peer-to-peer transactions) (WG3) | | | Blockchain (Product traceability systems) (WG3) |
| [R13], [R14], [R11] | Presence of intermediaries increasing transaction costs (VG2) | Blockchain + Smart Contracts (WG3) | [R10] | Low digital maturity and information resilience (VG4) | Blockchain-enabled decentralized common data environments (WG3) |
| [R13] | Illegal counterfeiting of products (VG2) | Blockchain + IoT (RFID / QR tracking + ledger) (WG3) | [R11] | Lack of reliable historical performance data (VG4) | Blockchain (Immutable transaction history / tracking) (WG3) |
| [R16] | Payment disputes in Letters of Credit (LC) (VG2) | Blockchain + Smart Contracts (WG3) | [R11] | Poor transparency of transaction records (VG4) | Blockchain (Tamperproof distributed ledger) (WG3) |
| [R16] | Financial and Banking risk (VG2) | Blockchain (Immutable data records) (WG3) | [R12] | Malicious or noisy sensor data in logistics tracking (VG4) | Blockchain + SCOs + Cross-reference Mechanism (WG3) |
| [R17] | inefficient profit distribution (VG2) | Machine Learning (DT, RF, KNN, DNN) (WG2) | [R12] | Inaccurate proof of location for prefabricated components (VG4) | SCOs (GPS Sensors) + Blockchain + Oracle Smart Contracts (WG3) |
| [R12] | Supplier and subcontractor payment issues (VG2) | Blockchain + Smart Contracts (WG3) | [R12] | Weak inter-organizational data verification (VG4) | Blockchain + Multi-stakeholder Consensus (PBFT) (WG3) |
| [R13] | Fraudulent/ forged/delayed documentation in logistics (VG3) | Blockchain (decentralised ledger (WG3) | [R13] | Poor integration between firms' ERP systems (VG4) | Blockchain + ERP integration platform (WG3) |
| [R2], [R1] | Difficulty in Supplier Selection (VG3) | BIM and WMS + GIS integration (WG1) | [R12], [R13] | Vulnerability of centralized data systems (VG4) | Blockchain (Decentralized P2P network) (WG3) |

| Document | Vulnerability | Withstanding Measure | Document | Vulnerability | Withstanding Measure |
|---|---|---|---|---|---|
| [R7], [R19], [R17] | Fragmented stakeholder decision-making (VG3) | BIM and WMS + GIS integration (WG1) | | | Blockchain + Decentralized SCO Oracle Sidechain (WG3) |
| | | Joint IPD governance structure (WG5) | | | Blockchain (Decentralized ledger architecture) (WG3) |
| | | Machine Learning (DT, RF, KNN, DNN) (WG2) | [R15], [R16] | Security vulnerabilities in intelligent transportation sys. (VG4) | Blockchain (Secure key management frameworks) (WG3) |
| [R16], [R2] | Lack of coordination between project site and suppliers (VG3) | BIM and WMS + GIS integration (WG1) | [R16] | Lack of transparency across multi-tier SCs (VG4) | Blockchain (Shared digital supply network) (WG3) |
| | | Blockchain (Integrated digital supply network) (WG3) | [R12], [R16] | Security vulnerabilities in centralized ERP systems (VG4) | Blockchain (Decentralized architecture) (WG3) |
| | | BIM (collaborative BIM platforms) (WG1) | | | Blockchain (Immutable ledger + PBFT consensus) (WG3) |
| [R5], [R4] | Lack of inter-organizational integration (VG3) | BIM + SCM (Graph-based integration model) (WG1) | [R12], [R3] | Limited quality control and field inspection integration (VG5) | BIM + SCOs + Blockchain (WG1) |
| | | BIM (collaborative BIM platforms) (WG1) | [R8], [R9], [R7] | Lack of Inventory Management (VG5) | IoT inventory alerts + coordinated procurement (WG4) |
| [R4] | Poor visibility of actor roles and interactions (VG3) | BIM + SCM (Graph-based integration model) (WG1) | | | IoT (RFID-based Inventory Replenishment & JIT Systems) (WG4) |
| [R18], [R4] | Mismatch between project duration (VG3) | BIM + SCM (Graph-based integration model) (WG1) | | | Smart things + multi-agent systems (WG4) |
| | | ML-driven predictive modeling (WG2) | [R9], [R7] | Quality issues (VG5) | Sensor-based monitoring + early stakeholder input (WG4) |
| | | ML-based classification and predictive modeling (WG2) | | | Time-Temperature Indicator wireless sensors (WG4) |
| [R5] | Limited flexibility to handle complex SC needs (VG3) | BIM (nD BIM expansion) (WG1) | | | Sensor-enabled RFID networks (WG4) |
| [R16], [R5] | Limited outsourcing and third-party logistics integration (VG3) | BIM (integration platform – maturity dependent) (WG1) | | | Smart packaging (WG4) |
| [R16], [R5] | Limited outsourcing and third-party logistics integration (VG3) | Blockchain (Distributed Ledger Technology) (WG3) | [R8], [R7] | Lack of real-time monitoring of construction equipment. (VG5) | IoT asset tracking (WG4) |
| [R8] | Inefficient remote site management (VG3) | IoT (Remote Operations & Monitoring Systems) (WG4) | | | IoT (Equipment Status Reports & Maintenance Sensors) (WG4) |
| [R15], [R11], [R13] | Lack of transparency and trust among SC actors (VG3) | Blockchain (Distributed Ledger Technology) (WG3) | | | IoT (Tracking Systems & Sensors) (WG4) |
| [R15], [R11], [R14] | among SC actors (VG3) | Blockchain (Immutable ledger + Decentralised validation) (WG3) | [R8] | High maintenance costs due to equipment failure (VG5) | IoT (Predictive Maintenance & Equipment Monitoring) (WG4) |
| [R15], [R11], [R15] | | Blockchain (Tracking + Distributed data sharing) (WG3) | [R9] | Long scanning and recording times (VG5) | RFID tags + Smartphones (WG4) |
| [R15], [R11], [R16] | | Blockchain (permission-based data platform) (WG3) | [R9] | Long processing times in joint ordering (VG5) | Smart things (WG4) |
| [R15], [R11], F68 | | Blockchain + Smart Contracts (WG3) | | | RFID tags + Temperature sensors (WG4) |

| Document | Vulnerability | Withstanding Measure | Document | Vulnerability | Withstanding Measure |
|---|---|---|---|---|---|
| [R15], [R11], F69 | | Blockchain (Peer-to-peer shipment tracking) (WG3) | [R13] | Product safety failures and difficulty in recalls (VG5) | Blockchain (Immutable shared ledger) (WG3) |
| [R15], [R11], F70 | | IoT (Increased SC Visibility Platforms) (WG4) | | | Blockchain + Smart Contracts (WG3) |
| [R14] | Opportunistic behaviour and information distortion (VG3) | Blockchain (Transparency + Distributed validation) (WG3) | [R17] | Delays in off-site production (VG5) | Predictive ML models + Data preprocessing (SMOTE, MinMaxScaler) (WG2) |
| [R17] | Manual or biased resource allocation decisions (VG3) | Data-driven classification models (DT & DNN) (WG2) | [R2], [R1] | Inaccurate delivery distance calculation (VG5) | BIM and WMS + GIS integration (WG1) |
| [R20]-[R24], [R26] | Lack of risk assessments models (VG3) | AHP–DEMATEL–ISM combined model, ,+ (WG6) | [R9], [R27], [R30], [R19], [R1] | Delivery schedule uncertainty / risk of delay (VG5) | BIM and WMS + GIS integration (WG1) |
| [R20]-[R24], F90 | | Fuzzy AHP + Simulation (Simphony.NET) (WG6) | [R9], [R27], [R30], [R19], [R2] | | Real-time tracking + collaborative scheduling (IOT + IPD) (WG4) |
| [R20]-[R24], [R27] | | Analytic Hierarchy Process (AHP) (WG6) | [R9], [R27], [R30], [R19], [R3] | | Sensor-enabled RFID networks (WG4) |
| [R20]-[R24], [R28] | | Risk Matrix (WG6) | [R9], [R27], [R30], [R19], [R4] | | Material Tracking System-Cloud Computing (WG5) |
| [R20]-[R24], F93 | | Monte Carlo Simulation (WG6) | [R9], [R27], [R30], [R19], [R5] | | RFID + Bar code (WG4) |
| [R20]-[R24], [R29] | Lack of risk assessments models (VG3) | Failure Mode and Effects Analysis (FMEA) (WG6) | [R9], [R27], [R30], [R19], [R6] | Delivery schedule uncertainty / risk of delay (VG5) | Re-Order Point (ROP) mathematical model (WG6) |
| [R3], [R1] | Weak coordination between material data and route planning (VG4) | BIM and WMS + GIS integration (WG1) | [R9], [R27], [R30], [R19], [F47] | Delivery schedule uncertainty / risk of delay (VG5) | ML analysis using delay-related features (WG2) |
| [R13], [R16], [R1] | Manual logistics documentation and reporting (VG4) | BIM and WMS + GIS integration (WG1) | [R28], [R9], [R1] | Inability to optimize transportation plans (VG5) | BIM and WMS + GIS integration (WG1) |
| | | Blockchain + Smart Contracts (WG3) | [R28], [R9], [R1] | | Smart things + sensors (WG4) |
| | | Blockchain (Distributed Ledger Technology) (WG3) | [R28] | | Probabilistic decision-support methodology (WG6) |
| [R9], [R2] | Lack of decision-support for logistics optimization (VG4) | BIM and WMS + GIS integration with Sensor networks (WG1) | [R28], [R9], [R1] | | Information fusion (WG5) |
| [R15], [R3] | Poor visibility of material flow across the SC (VG4) | BIM and WMS + GIS integration (WG1) | | | Cloud computing (WG5) |
| | | Blockchain (Distributed Ledger + Tracking Frameworks) (WG3) | [R9] | Theft and lack of shipment visibility (VG5) | Smart items (WG4) |
| | | Blockchain (Distributed Ledger Technology) (WG3) | | | Multi-agent systems (WG4) |
| [R8] | | Augmented reality (WG4) | | | RFID tags (WG4) |

| Document | Vulnerability | Withstanding Measure | Document | Vulnerability | Withstanding Measure |
|---|---|---|---|---|---|
| [R9] | | Smart things (WG4) | [R16] | Errors in compliance verification for trade documents (VG5) | Blockchain (Immutable shared ledger) (WG3) |
| [R15] | | Blockchain + Shipment tracking framework (WG3) | [R14], [R1] | Manual sustainability compliance checking (VG6) | BIM and WMS + GIS integration (WG1) |
| [R9], [R3] | Lack of real-time monitoring of delivery status (VG4) | BIM and WMS + GIS integration (WG1)<br>Smart things (WG4) | | | Blockchain + Smart Contracts (WG3)<br>Blockchain (Provenance tracking + Certification records) (WG3) |
| [R13], [R3] | Difficulty identifying supplier locations and availability (VG4) | GIS + Blockchain (Distributed network ledger) (WG3) | [R19], [R8] | Excessive $CO_2$ emissions (VG6) | IoT (Emission Monitoring & Control Sensors) (WG4) |
| [R3] | No automated warning system for delays (VG4) | BIM and WMS + GIS integration (WG1) | [R19] | | multi-agent simulation (MAS) with deep learning (WG2) |
| [R6], [R18], [R12] | Fragmented information flows (VG4) | BIM + SCM (WG1) | [R8] | High fuel and power consumption (VG6) | IoT (Power & Fuel Monitoring Systems) (WG4) |
| [R18], [R4], [R17] | | Machine Learning (DT, RF, KNN, DNN) (WG2) | [R13] | Low sustainability transparency in supply networks (VG6) | Blockchain (digital ledger - Provenance) (WG3) |
| [R13] | | Blockchain + Smart Contracts (WG3) | [R14] | Poor carbon footprint tracking (VG6) | Blockchain + IoT integration (SCEnAT 4.0) (WG3) |
| [R13] | High human errors due to manual processes (VG4) | Blockchain + Smart Contracts (WG3) | [R17] | Risk amplification due to subsystem perturbations (VG6) | ML-based subsystem simulation modeling (WG2) |
| [R13], [R5] | Limited use of advanced technologies for SC integration (VG4) | BIM + Advanced Technologies (IoT, cloud, digital tools) (WG1) | | | |

SCV Groups - VG1: Warehouse Management and Infrastructure risk, VG2: Financial & Market Risks, VG3: Strategic & Organizational Risks, VG4: Information & Digital Risks, VG5: Operational & Technical Risks, VG6: External & Environmental Risks.

WM Groups – WG1: BIM, WG2: Machine Learning, WG3: Blockchain, WG4: IoT, WG5: Information Systems, WG6: Mathematical Models.

Sources [R1]: (Chen & Nguyen, 2019), [R2]: (Deng et al., 2019), [R3]: (Irizarry et al., 2013), [R4]: (Papadonikolaki et al., 2015), [R5]: (Le et al., 2022), [R6]:(Papadonikolaki et al., 2016), [R7]: (Lotfi & Karakouzian, 2025), [R8]: (Ali et al., 2020), [R9]: (Ben-Daya et al., 2019), [R10]: (Tezel et al., 2020), [R11]: (Qian & Papadonikolaki, 2020), [R12]: (Lu et al., 2021), [R13]: (Cole et al., 2019), [R14]: (Saberi et al., 2019), [R15]: (Queiroz et al., 2019), [R16]: (Gurtu & Johny, 2019), [R17]: (Guo et al., 2025), [R18]: (Wu et al., 2025), [R19]: (Attajer et al., 2025), F81:(Golden et al., 2026), F82: (Qazi et al., 2021), [R20]: (Qiang et al., 2023), [R21]: (Li et al., 2013), [R22]: (Mei, 2023), [R23]: (Starczyk-Kołbyk & Jędras, 2025), [R24]: (Curkovic et al., 2013), [R26]: (Czajkowska & Ingaldi, 2025), [R27]: (Ko et al., 2016), [R28]: (Leontaris et al., 2019), F93: (Ismail, 2021), [R29]: (Rhodes et al., 2022), [R30]: (Panova & Hilletofth, 2018)

- Source identifier

The model includes a sources identifier function linked to the selected SCV. When a SCV is selected from the legend, a Sources button appear and when clicked it displays a table containing the document code according to Table 1, reference details according to the APA 7th style and the DOI.

- Statistical Module

Insights related to statistical measures as described in subsequent Section 3.2.2, can be analysed as shown in Figure 3 using the statistical module integrated in the visualisation model. Figure 3 further illustrates statistical measures related to SCVs only connected to single WM. In addition to that, users can generate customised graphs for each measure. According to the user requirement, the graph can be changed into "counter view" or "percentage view".

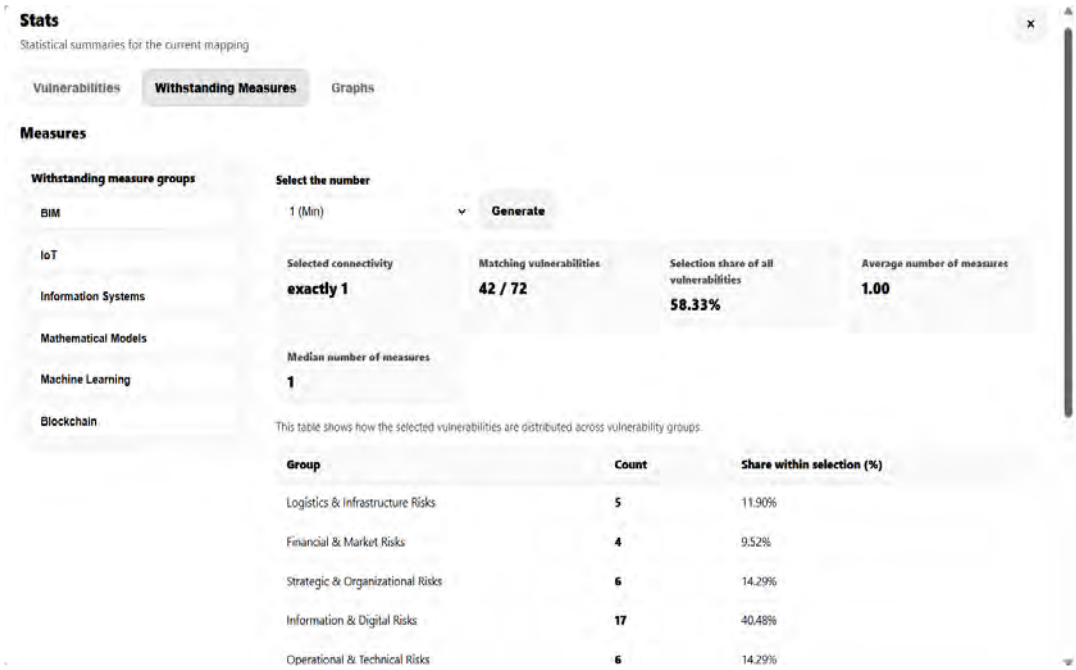



*Figure 3: Statistical module*

- Graph generation facility

Apart from the graph facility discussed in the previous section, the model provides another graph generation facility within Graph tab in the statistical module. There are two main types of graphs that can be generated using this facility. Type 1 shows each SCV against how many WMs connected them and type 2 displays each WM against how my SCVs are addressed by them.

### 3.2.2 Insights Derived from the Model

The analysis reveals that a majority of SCVs (61.64%) are associated with only a single WM, indicating that many vulnerabilities in OSC SCs are addressed through isolated and limited WMs. This finding highlights a structural limitation in current mitigation practices, where a lack of diversified strategies may reduce resilience against complex disruptions. Notably, vulnerabilities within the informational and digital risk category

show the highest concentration of such one-to-one relationships, suggesting that these areas remain underdeveloped in terms of comprehensive mitigation planning.

In contrast, 35.86% of SCVs are linked to multiple WMs, with vulnerabilities such as delivery schedule uncertainty and transportation optimisation challenges exhibiting the highest number of connections. These findings suggest that critical logistical issues tend to attract more diverse WMs, reflecting their complexity and importance within OSC SCs. This demonstrates that not all SCVs are treated equally, revealing an implicit prioritisation of certain types of vulnerabilities in existing practices.

Furthermore, the model identifies a small number of highly influential WMs, such as GIS integration within BIM, which address a wide range of SCVs across all categories. This highlights the potential of integrated digital solutions to serve as cross-cutting WMs, offering broader systemic benefits compared to isolated interventions. However, the finding that 89.80% of WMs address only a single SCV indicates a prevailing tendency toward fragmented, SCV-specific solutions, particularly within IoT-based approaches.

In relation to prior studies, Wang et al. (2019) also concluded through a literature review that BIM and RFID, which comes under the IoT class, are among the major methodologies adopted in existing research for SC withstanding capabilities. In addition, in line with the finding that 61.64% of the SCVs are addressed by only a single WM, Studer and De Brito Mello. (2021) mentioned that most studies focus on specific areas and reinforced the research gap by highlighting the clear need to present a total solution for SCM in the construction industry. Furthermore, the authors revealed that logistics is the second lowest subject area to be focused on by researchers in SCM domain. Moreover, Papadonikolaki et al. (2015) stated that graph-based approaches have already provided powerful visual and analytic tools for representing complex systems. Therefore, to educate researchers and industry practitioners that OSC logistics remains underexplored, as identified above, the visualisation approach used in this study can be considered highly convincing.

Overall, these findings contribute to knowledge by revealing the imbalance between isolated and integrative WMs in OSC SCs, and by identifying the critical role of multifunctional digital WMs in enhancing SCR.

# 4. CONCLUSIONS

OSC is rapidly transforming the construction industry due to its distinctive production and delivery characteristics. However, the process from the manufacturing yard to the construction site remains highly dependent on logistics operations, where SCVs can inevitably emerge. For successful project delivery, industry practitioners must develop a comprehensive understanding of these SCVs and the corresponding WMs. Nevertheless, a structured model that enables effective visualisation and analysis of these relationships remains limited. Therefore, this study developed a model to visualise and analyse SCV and their corresponding WMs within the logistics operations of OSC. The developed model facilitates the relationships between SCVs and WMs, provides reference sources for each identified relationship and valuable insights through statistical measures. Model enables researchers to analyse individual SCV and their corresponding WMs behaviour. Furthermore, both academic researchers and industry practitioners can utilise the insights generated to identify the most suitable WMs for addressing specific SCVs. However, the model is constrained by its dependence on a fixed pre identified dataset and simplified

representation of relationships, which may not fully reflect the dynamic and evolving nature of construction SCs. Future developments could focus on integrating real-time data sources, enhancing scalability across different project environments, and incorporating advanced analytics such as machine learning to enable predictive and decision-support measures.

## 5. ACKNOWLEDGEMENT

The authors would like to acknowledge the support received from the Senate Research Committee of University of Moratuwa, Sri Lanka under the Grant SRC/LT/2025/27.

## 6. REFERENCES

Ali, Y., Saad, T. B., & Rehman, O. U. (2020). Integration of IoT technologies in construction supply chain networks: CPEC a case in point. *Sustainable Operations and Computers*, *1*, 28–34. https://doi.org/10.1016/j.susoc.2020.12.003

Attajer, A., Mecheri, B., Hadbi, I., Amoo, S. N., & Bouchnita, A. (2025). Sustainable supply chain strategies for modular-integrated construction using a hybrid multi-agent–deep learning approach. *Sustainability*, *17*(12), 5434. https://doi.org/10.3390/su17125434

Bacon, M. (2012). *Pragmatism: An introduction.* Polity Press. Retrieved from https://books.google.lk/books?hl=en&lr=&id=XtX-O7wbn4EC&oi=fnd&pg=PR5&dq=Pragmatism:+An+Introduction&ots=fb50y77HNV&sig=r_NJWphh1V4qlcW4zrrSAFVsDrQ&redir_esc=y#v=onepage&q=Pragmatism%3A%20An%20Introduction&f=false

Ben-Daya, M., Hassini, E., & Bahroun, Z. (2019). Internet of things and supply chain management: A literature review. *International Journal of Production Research*, *57*(15–16), 4719–4742. https://doi.org/10.1080/00207543.2017.1402140

Chen, P.-H., & Nguyen, T. C. (2019). A BIM-WMS integrated decision support tool for supply chain management in construction. *Automation in Construction*, *98*, 289–301. https://doi.org/10.1016/j.autcon.2018.11.019

Cole, R., Stevenson, M., & Aitken, J. (2019). Blockchain technology: Implications for operations and supply chain management. *Supply Chain Management: An International Journal*, *24*(4), 469–483. https://doi.org/10.1108/SCM-09-2018-0309

Curkovic, S., Scannell, T., & Wagner, B. (2013). Using FMEA for supply chain risk management. *Modern Management Science & Engineering*, *1*(2). Retrieved from https://www.researchgate.net/profile/Sime-Curkovic-2/publication/263733916_Using_FMEA_for_Supply_Chain_Risk_Management/links/56d8433f08aebabdb408c424/Using-FMEA-for-Supply-Chain-Risk-Management.pdf

Czajkowska, A., & Ingaldi, M. (2025). Supply chain risk management in construction. *Advances in Science and Technology Research Journal*, *19*(8), 15–29. https://doi.org/10.12913/22998624/204013

Deng, Y., Gan, V. J. L., Das, M., Cheng, J. C. P., & Anumba, C. (2019). Integrating 4D BIM and GIS for construction supply chain management. *Journal of Construction Engineering and Management*, *145*(4), 04019016. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001633

Dunton, A. L. D., Martin, I., Delera, M., & Flickenschild, M. (2024). *Research note on offsite construction*. European Commission. Retrieved from https://build-up.ec.europa.eu/system/files/2025-01/RB385Rpj2z_29_01_2025_083227.pdf

Ekanayake, E. M. A. C., Shen, G. Q. P., & Kumaraswamy, M. M. (2019). Managing vulnerabilities and measures for supply chain resilience in industrialised construction. In C. Gorse, & C. J. Neilson (Eds.), *Proceedings of the 35th annual ARCOM conference* (pp. 811-820). Retrieved from https://www.researchgate.net/publication/335835307_Managing_Vulnerabilities_and_Measures_for_Supply_Chain_Resilience_in_Industrialised_Construction

Ekanayake, E. M. A. C., Shen, G. Q. P., Kumaraswamy, M. M., & Owusu, E. K. (2022). Identifying supply chain vulnerabilities in industrialized construction: An overview. *International Journal of Construction Management*, *22*(8), 1464–1477. https://doi.org/10.1080/15623599.2020.1728487

Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing*, *24*(4), 230–235. https://doi.org/10.1179/2047480615Z.000000000329

Golden, J., Mahdavisharif, M., Castelblanco, G., Mangano, G., & Ferrari, A. (2026). Disruptions and resilience in construction supply chains. *Automation in Construction*, *181*, 106577. https://doi.org/10.1016/j.autcon.2025.106577

Gunawardana, T. S. L. W., & Wedage, D. H. (2020). Supply chain management practices: Competitive advantage and organizational performance in Sri Lankan construction industry. *Sri Lanka Journal of Marketing*, *6*(2), 46–72. https://doi.org/10.4038/sljmuok.v6i2.42

Guo, Y., Zhao, Q., Li, X., & Liu, B. (2025). Research on profit distribution mechanism of green supply chain for precast buildings. *International Journal of Low-Carbon Technologies*, *20*, 990–1000. https://doi.org/10.1093/ijlct/ctae269

Gurtu, A., & Johny, J. (2019). Potential of blockchain technology in supply chain management: A literature review. *International Journal of Physical Distribution & Logistics Management*, *49*(9), 881–900. https://doi.org/10.1108/IJPDLM-11-2018-0371

Irizarry, J., Karan, E. P., & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*, *31*, 241–254. https://doi.org/10.1016/j.autcon.2012.12.005

Ismail, Z.-A. B. (2021). Hybrid intelligent vehicle system for managing construction supply chain in precast concrete building construction projects. *World Journal of Engineering*, *18*(4), 538–546. https://doi.org/10.1108/WJE-08-2020-0361

Ko, H. S., Azambuja, M., & Lee, H. F. (2016). Cloud-based materials tracking system prototype integrated with radio frequency identification tagging technology. *Automation in Construction*, *63*, 144–154. https://doi.org/10.1016/j.autcon.2015.12.011

Kurasova, O., Budžys, A., & Medvedev, V. (2024). Exploring multidimensional embeddings for decision support using advanced visualization techniques. *Informatics*, *11*(1), 11. https://doi.org/10.3390/informatics11010011

Le, P. L., Chaabane, A., & Dao, T.-M. (2022). BIM contributions to construction supply chain management trends: An exploratory study in Canada. *International Journal of Construction Management*, *22*(1), 66–84. https://doi.org/10.1080/15623599.2019.1639124

Leontaris, G., Morales-Nápoles, O., Dewan, A., & Wolfert, A. R. M. (2019). Decision support for offshore asset construction using expert judgments for supply disruptions risk. *Automation in Construction*, *107*, 102903. https://doi.org/10.1016/j.autcon.2019.102903

Li, H. X., Al-Hussein, M., Lei, Z., & Ajweh, Z. (2013). Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. *Canadian Journal of Civil Engineering*, *40*(12), 1184–1195. https://doi.org/10.1139/cjce-2013-0013

Lotfi, M., & Karakouzian, M. (2025). Integration of IPD and IoT on construction industry supply chain performance with a sustainable development approach. *Journal of Information Technology in Construction*, *30*, 496–523. https://doi.org/10.36680/j.itcon.2025.021

Lou, C. X., Bonti, A., Prokofieva, M., & Abdelrazek, M. (2022). Supply chain and decision making: What is next for visualisation? In B. Kovalerchuk, K. Nazemi, R. Andonie, N. Datia, & E. Banissi (Eds.), *Integrating artificial intelligence and visualization for visual knowledge discovery* (pp. 653–672). Springer International Publishing. https://doi.org/10.1007/978-3-030-93119-3_26

Lou, C. X., Bonti, A., Prokofieva, M., Abdelrazek, M., & Chowdary Kari, S. M. (2020). Literature review on visualization in supply chain & decision making. *2020 24th(International conference information visualisation (IV).* (746–750). https://doi.org/10.1109/IV51561.2020.00019

Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., & Yeh, A. G. O. (2021). Exploring smart construction objects as blockchain oracles in construction supply chain management. *Automation in Construction*, *129*, 103816. https://doi.org/10.1016/j.autcon.2021.103816

Mei, Y. (2023). Research on supply chain risk of prefabricated building based on AHP model. In S. H. B. D. M. Zailani, K. Yagapparaj, & N. Zakuan (Eds.), *Proceedings of the 2023 4th international conference on management science and engineering management (ICMSEM 2023)* (Vol. 259, pp. 1038–1046). Atlantis Press International BV. https://doi.org/10.2991/978-94-6463-256-9_102

Panova, Y., & Hilletofth, P. (2018). Managing supply chain risks and delays in construction project. *Industrial Management & Data Systems*, *118*(7), 1413–1431. https://doi.org/10.1108/IMDS-09-2017-0422

Papadonikolaki, E., Vrijhoef, R., & Wamelink, H. (2015). Supply chain integration with BIM: A graph-based model. *International Journal of Building Pathology and Adaptation*, *33*(3), 257–277. https://doi.org/10.1108/SS-01-2015-0001

Papadonikolaki, E., Vrijhoef, R., & Wamelink, H. (2016). The interdependences of BIM and supply chain partnering: Empirical explorations. *Architectural Engineering and Design Management*, *12*(6), 476–494. https://doi.org/10.1080/17452007.2016.1212693

Qazi, A., Shamayleh, A., El-Sayegh, S., & Formaneck, S. (2021). Prioritizing risks in sustainable construction projects using a risk matrix-based Monte Carlo simulation approach. *Sustainable Cities and Society*, *65*, 102576. https://doi.org/10.1016/j.scs.2020.102576

Qian, X., & Papadonikolaki, E. (2020). Shifting trust in construction supply chains through blockchain technology. *Engineering, Construction and Architectural Management*, *28*(2), 584–602. https://doi.org/10.1108/ECAM-12-2019-0676

Qiang, C., Yunchao, D., & Renxiang, W. (2023). Analysis on supply chain risk factors of prefabricated buildings using AHP-DEMATEL-ISM model. *Tehnicki Vjesnik*, *30*(5). https://doi.org/10.17559/TV-20230508000614

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2019). Blockchain and supply chain management integration: A systematic review of the literature. *Supply Chain Management: An International Journal*, *25*(2), 241–254. https://doi.org/10.1108/SCM-03-2018-0143

Rhodes, O., Rostami, A., Khodadadyan, A., & Dunne, S. (2022). Response strategies of UK construction contractors to COVID-19 in the consideration of new projects. *Buildings*, *12*(7), 946. https://doi.org/10.3390/buildings12070946

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *57*(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Sanjeepan, R. (2017). *Application of off-site construction in Sri Lanka.* Institutional Repository University of Moratuwa. http://dl.lib.mrt.ac.lk/handle/123/13207

Shemov, G., Garcia De Soto, B., & Alkhzaimi, H. (2020). Blockchain applied to the construction supply chain: A case study with threat model. *Frontiers of Engineering Management*, *7*, 564–577. https://doi.org/10.1007/s42524-020-0129-x

Starczyk-Kołbyk, A., & Jędras, I. (2025). Integrated risk assessment in construction contracts: Comparative evaluation of risk matrix and Monte Carlo simulation on a high-rise office building project. *Applied Sciences*, *15*(17), 9371. https://doi.org/10.3390/app15179371

Studer, W., & De Brito Mello, L. (2021). Core elements underlying supply chain management in the construction industry: A systematic literature review. *Buildings*, *11*(12), 569. https://doi.org/10.3390/buildings11120569

Teymourifar, A. (2026). A critical review of the SCOR Digital Standard (SCOR-DS): Conceptual implications for supply chain performance measurement. *Frontiers in Sustainability*, *7*, 1769304. https://doi.org/10.3389/frsus.2026.1769304

Tezel, A., Papadonikolaki, E., Yitmen, I., & Hilletofth, P. (2020). Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions. *Frontiers of Engineering Management*, *7*, 564–577. https://doi.org/10.1007/s42524-020-0110-8

Wang, H., & Zhou, Z. (2024). Identification of key risk nodes and invulnerability analysis of construction supply chain networks. *Buildings*, *14*(7), 1997. https://doi.org/10.3390/buildings14071997

Wang, Z., Hu, H., Gong, J., Ma, X., & Xiong, W. (2019). Precast supply chain management in off-site construction: A critical literature review. *Journal of Cleaner Production*, *232*, 1204–1217. https://doi.org/10.1016/j.jclepro.2019.05.229

Wu, L., Lu, W., Wang, X., Wang, B., & Dong, Z. (2025). An estimated Time of Arrival (ETA) model for achieving Just-in-Time (JIT) modular construction delivery in high-density cities. *Frontiers of Engineering Management*, *12*, 880–898. https://doi.org/10.1007/s42524-025-5112-0

Ranathunga, S.N., Dissanayake, P. and Sathsarani, W.N.K.B.N.A., 2026. Workplace design and Gen Z retention: A social sustainability perspective in Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1857-1870. DOI: https://doi.org/10.31705/WCS.2026.135. Available from: https://ciobwcs.com/papers/

# WORKPLACE DESIGN AND GEN Z RETENTION: A SOCIAL SUSTAINABILITY PERSPECTIVE IN SRI LANKA

**S.N. Ranathunga[1], P. Dissanayake[2] and W.N.K.B.N.A. Sathsarani[3]**

## *ABSTRACT*

*The Sri Lankan corporate sector is currently grappling with a significant talent retention crisis, particularly among Generation Z (Gen Z) employees who increasingly prioritize the quality of their physical work environment over traditional incentives. While workplace design is frequently evaluated for space efficiency and productivity, its role as a driver of "Social Sustainability" specifically through human capital retention remains under-investigated in the built environment literature. In this context, Job Embeddedness, which explains why employees remain in organizations through their perceived fit with the job, social links within the workplace, and the sacrifices associated with leaving, provides a useful theoretical lens for understanding employee retention. This paper proposed a conceptual framework to addressing the relationship between Workplace Design and Turnover Intention mediated by Job Embeddedness (JE) in gen Z employees working in Sri Lanka. The paper combines the Generational Cohort Theory and the JE Theory to come up with such important design dimensions as flexibility design, biophilic integration, relaxation areas design and technological resilience which creates such psychological aspects of the organization as "fit", "Link" and "sacrifice". The expected outcomes are anticipated to equip facility managers, architects and corporate stakeholders with evidence-based design strategies to convert office spaces into social anchors. Finally, the study will play a role in the development of built environments that can enhance the social sustainability and long-term stability of Sri Lankan workforce within the unstable economic environment.*

***Keywords:*** *Built Environment; Generation Z; Job Embeddedness; Turnover Intention; Workplace Design.*

## 1. INTRODUCTION

Retention of employees has become an extreme issue in modern organizations, especially when it comes to a multigenerational workforce (Chiwisa & Mpundu, 2024). In today's multigenerational workforce including generations of Baby Boomers, Generation X, Millennials and Gen Z differences in values, expectations and work orientations offer both opportunities as well as complexities in management (Dwivedula et al., 2019). Among these groups, Gen Z (born 1995-2012) is becoming increasingly prominent due

[1] Undergraduate, Department of Building Economics, University of Moratuwa, Sri Lanka, ranathungasn.21@uom.lk
[2] Senior Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, piumid@uom.lk
[3] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, amashas@uom.lk

to the influence of technological, economic instability, globalization, and political concerns (Magano et al., 2020; Seemiller & Grace, 2017). Gen Z prioritizes meaningful work, autonomy, flexibility, value congruence, and psychological well-being (Ali et al., 2024), which have a major impact on their turnover intentions expressed as the active desire to leave an organization (Makhdoom & Jamali, 2025). A high turnover intention is associated with real turnover, which has a number of adverse organizational consequences, particularly in competitive labor markets (Shoaib & Pathan, 2022). As a possible solution to these issues, the concept of social sustainability has attracted interest, with the well-being of the employees, employee engagement, and employee retention as key components of organizational resilience (Malik & Singh, 2024).

The JE theory, with dimensions of fit, links, and sacrifice provides a framework of studying employee retention (Yang et al., 2011). JE can mediate the positive correlation between workplace design factors and turnover intention in the case of Gen Z, in which workplace flexibility is the determining factors of retention (Kiazad et al., 2024). Although prior studies indicate relationships between workplace design, job embeddedness, and turnover intention, there is a limited integrated conceptual understanding of how these variables interact, particularly in the Sri Lankan context. This study addresses this gap by developing a conceptual framework to guide future empirical research. Therefore, the primary objective of this study is to develop a conceptual framework linking workplace design features, JE, and turnover intention among Gen Z employees working in corporate offices in Sri Lanka.

## 2. METHODOLOGY

The study explores the effects of the Workplace Design Features on Turnover Intention among Gen Z corporate office employees in Sri Lanka, with a focus on the mediating role of JE. Based on a narrative literature review, it will incorporate multidisciplinary insights of organizational behaviour, workplace design, and sustainability studies, filling in the gap of the intersectional nature of corporate built environments and the JE theory in this demographic. The methodology involved secondary data where the researcher has to gather data through peer-reviewed academic sources to obtain not only the recent relevance but also the theoretical basis. The synthesis exposes gaps in theory, discrepancies in current research and puts forward a specific conceptual model related to the corporate context in Sri Lanka. Finally, the research places workplace design as an instrument of social sustainability targeted at boosting the retention of Gen Z employees.

The process of literature selection to be used in the present study was systematic as demonstrated in Figure 1 and involved identification, screening, and inclusion phases. The relevant studies have been searched in the first stage in major academic databases, including ScienceDirect, ResearchGate, Emerald Insight, and Google Scholar, to find the required studies. The search was conducted using a combination of keywords such as “Workplace Design”, “Gen Z”, “Turnover Intention”, “Job Embeddedness”, “Flexible Work Arrangements”, and “Work-Life Balance”. The search string used was: (‘Workplace Design’ OR ‘Office Design’) AND (‘Generation Z’ OR ‘Gen Z’) AND (‘Turnover Intention’) AND (‘Job Embeddedness’) AND (‘Flexible Work’ OR ‘Work-Life Balance’). Initially, 120 publications were identified. After removing duplicates (11), irrelevant studies (20), and those lacking sufficient information (17), 72 publications remained for abstract screening. Following this, 68 studies were selected for full-text review, and finally, 65 articles were included in the analysis. Figure 1 presents the

PRISMA flow diagram detailing the study selection process from initial search to final inclusion.

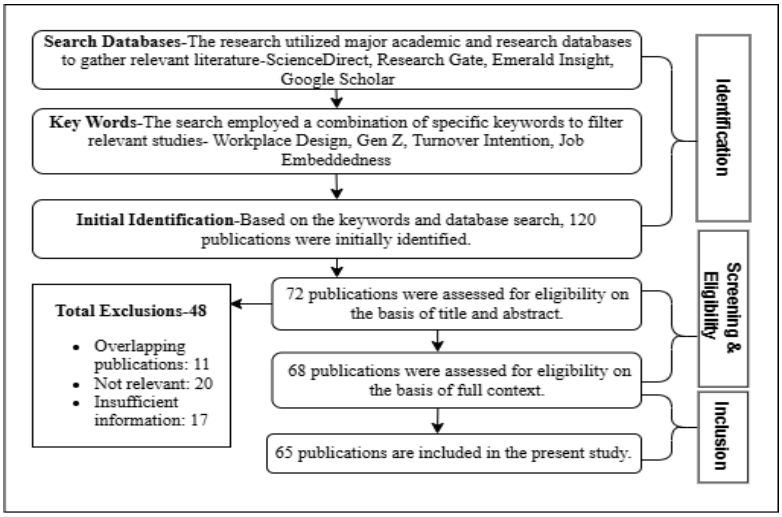



*Figure 1: PRISMA flow diagram of the literature selection process*

# 3. LITERATURE REVIEW

## 3.1 THEORETICAL BACKGROUND

### 3.1.1 Generational Cohort Theory (GCT)

Generational Cohort Theory (GCT) provides a framework for analysing generational differences in organizational behaviour, arguing that individuals born during the same socio-historical period develop diverse attitudes, values, and behaviours (D'Amato & Baruch, 2020) This theory proposes that such generational cohorts are shaped by distinct historical events, influencing work-related attitudes and behaviours in adulthood (D'Amato & Baruch, 2020) Notably, GCT enables the identification of both actual and perceived differences among generational cohorts in aspects like work values and job satisfaction (Lester et al., 2012). Specifically, Gen Z's need for diversity, innovation, and social responsibility stems from their cultural experiences and inspirations (Fernando & Umamaheswari, 2025). The theory explains the importance of accommodating Gen Z's preferences for diversity and personal growth in workplace design, emphasizing that organizational practices must align with their generational identity to enhance job satisfaction and reduce turnover (Zahra et al., 2025).

### 3.1.2 Gen Z and Turnover Intention

Gen Z, defined as people born between the mid-1990s to early 2010s (1997-2012), are digital natives who have constant access to social media and technology. They are distinguished by their digital savviness, adaptability, acceptance of diversity and individualism, as well as their analytical nature and desire to challenge societal norms (Naci Çoklar & Tatli, 2021) Furthermore, they are better educated, career-oriented, and prefer technology-enabled, authentic experiences compared to previous generations (Jayatissa, 2023). Organizations that foster inclusivity and provide offer flexible work arrangements have an upper hand in attracting and retaining Gen Z talent (Febriana & Mujib, 2024).

Turnover Intention (TI) refers to a worker's purposeful willingness to leave their organization, which differs from actual turnover since it can be influenced by external factors (Gaan & Shin, 2023) High TI can lead to increased recruitment and training costs, loss of institutional expertise, and disruption of team cohesion(Chen et al., 2023), which has detrimental impacts on service quality and business performance, especially as Gen Z becomes a major workforce segment in fields (Lee & Shin, 2025). To reduce TI, organizations can implement flexible work arrangements design, decent work conditions, and supportive leadership, all of which improve job satisfaction and self-efficacy (Berber et al., 2022). This is especially the case in Sri Lankan corporations where it is getting harder to retain young professionals. In Sri Lankan organizations brain drain and economic migration trends after the financial crisis have amplified Gen Z's turnover intentions (Jayakody et al., 2025). This suggests that life goals and work-life balance are important factors contributing to Sri Lankan Gen Z's high turnover, especially in the financial and IT industries (De Silva & Dhammika, 2022). Overall, TI in Gen Z is a sensitive indicator of organizational health, necessitating tailored retention strategies to address their unique needs and expectations (Wan & Duffy, 2022).

### 3.1.3 Job Embeddedness Theory (JE)

JE theory, introduced by (Mitchell et al., 2001), has evolved as a critical framework for understanding why employees stay with their organizations, diverging from traditional turnover models that mostly focus on job satisfaction and organizational commitment (Kiazad et al., 2024).This theory includes three essential dimensions- Links, Fit and Sacrifice, which can influence an employee's decision to stay or leave both on and off the job (Malalage & Perera, 2025).

The first dimension, “Fit” emphasizes the alignment between an employee's beliefs, career goals, and skills with the organizational culture and job requirements. This congruence fosters a sense of belonging, particularly among younger employees, like Gen Z, who prioritize meaningful work (Clinton et al., 2012). The second dimension, “Links” pertains to the relationships that employees develop within their organization and the surrounding community (Yang et al., 2011). The third dimension, “Sacrifice” refers to the estimated costs of leaving a job or community, including the loss of benefits, working conditions, and social networks (Setthakorn et al., 2024). Employee dissatisfaction can discourage those anticipating significant personal or professional losses from resigning. Sacrifice encompasses both tangible and intangible aspects (Yu et al., 2020).

When people are embedded in their job and community, JE helps them stay, but studies reveal a dark side when people feel trapped in poor conditions. When employees have high "Sacrifice" or "Links” but poor working conditions, JE reduces quitting but it is linked to worsening physical health, emotional exhaustion and sleep quality, meaning that employees do stay but suffer from these issues (Porter et al., 2024). Highly embedded employees in stressful or remote workplaces can face greater strain and exhaustion if these jobs are highly constrained or remote, demonstrating that JE is not a universal remedy for well-being (Schmidbauer et al., 2025). The inclusion of design features in this study's framework is specifically intended to mitigate these risks, ensuring that Gen Z employees are embedded through positive engagement rather than perceived constraints, thereby upholding the principles of long-term social sustainability. Table 1 presents the key dimensions of JE fit, links and sacrifice, which are the most important and the impact they make on TI. These dimensions describe the effects of the fit of employees to their

job, social relationships in the workplace, and the perceived cost of losing on organizational attachment to enhance the chances of staying longer in the organization.

*Table 1: JE dimensions and their impact on TI*

| Dimension | Definition | Key Findings on Turnover Intention | Citations |
|---|---|---|---|
| Links | Formal/informal connections to people, teams, and community | Stronger links reduce turnover intention via increased belonging | (Clinton et al., 2012) |
| Fit | Perceived compatibility with job, organization, and community | High fit lowers turnover intention by enhancing value congruence | (Yang et al., 2011) |
| Sacrifice | Perceived costs (tangible/intangible) of leaving job or community | Greater sacrifice most strongly predicts lower turnover intention | (Yu et al., 2020) |

## 3.2 WORKPLACE DESIGN AND EMPLOYEE EXPERIENCE

### 3.2.1 Workplace Design as a Stakeholder-Centred Strategy

A revolution in the design of a workplace towards a stakeholder-oriented approach highlights the experiences, needs, and expectations of the employees and shifts towards a place of focus on buildings and furniture (Shuaibu & Saleh, 2025). This type of strategic design improves the well-being, productivity, and retention of employees as well as showing respect to them (Van Simaeys et al., 2025). Including knowledge work, shows that involving employees in workplace design significantly improves satisfaction, work-life balance, and productivity, reinforcing the effectiveness of co-produced design solutions (Srivastava et al., 2024).

### 3.2.2 Relationship Between Physical Space and Employee Behavior

The connection between physical space and employee experience is massive and affects wellness, satisfaction, and organizational performance as indicated by studies (Dumitriu et al., 2025). Effective design spaces may contribute to better comfort and cognitive processes, and poorly designed spaces may cause dissatisfaction and health problems (Subarno et al., 2025). As an example, more partitions in open-plan offices can make people feel safer and minimize distractions, whereas such aesthetics as curved lines and biophilic design can make people pay more attention (Gath-Morad et al., 2024). In addition, physical environmental satisfaction is a strong predictor of job satisfaction and influences the connection between employee wellness and organizational commitment (Agha-Hossein et al., 2013).

### 3.2.3 Key Workplace Design Features Valued by Gen Z

Sustainability and eco-friendly design, particularly those including biophilic elements, have become pivotal in the workplace preferences of Gen Z, impacting their intentions to stay in the corporate setting (Wolf & Kluge, 2022). In part, this tendency is explained by the increased environmental consciousness of Gen Z that was promoted by the global climate discussion and access to information on the internet (Raman et al., 2024). Unlike earlier generations, Gen Z prefers employers who share their ideals of sustainability and

social responsibility values (Anjum, 2024). Exposure to social media has popularized green workplace trends, making environmentally friendly office designs desirable among young professionals (Tass & Malik, 2025) Organizations lacking sustainable design aspects risk being perceived as outdated, leading to increased turnover (Palomo et al., 2023). Flexible workspaces, incorporating collaborative zones (Mateescu et al., 2025), quiet areas (Kalmanovich-Cohen & Stanton, 2024), and breakout spaces (Davis et al., 2020), are increasingly essential for attracting and retaining Gen Z employees. The generation is more independent and flexible in their workplaces, and the space design has a significant impact on their work satisfaction and retention (Dieguez & Loureiro, 2025).

Relaxation areas, such as lounge spaces (Larsson et al., 2022), nap pods (Anand et al., 2025), on-site gyms and yoga studios (Singh et al., 2024), are essential in workplace design for retaining Gen Z employees, who prioritize work-life balance and well-being (Zivkovic et al., 2025). These areas promote a less stressful environment, reduce burnout, and enhance job satisfaction, fostering a sense of community and emotional support (Lazuardi et al., 2025). The implementation of advanced technology is essential for Gen Z, who view it as a basic expectation in the workplace (Pichler et al., 2021). Access to modern equipment, reliable wireless connectivity, and smart office setups significantly enhances job satisfaction and retention among Gen Z workers, as it supports their need for efficiency, autonomy, and innovation (Gupta et al., 2025). Studies in Sri Lanka indicate that flexible work arrangements are the most important human resource factor that increases job satisfaction and reduces turnover intention among Gen Z in industries such as telecommunication (Kodithuwakku et al., 2018). They also seek a workplace to support well-being and work-life balance, and a positive work environment has been found to enhance Gen Z productivity in other Asian studies (Hendratmoko & Mutiarawati, 2024). As illustrated in Figure 2, flexibility, technology integration, well-being focus, and sustainability represent the key workplace design features influencing Gen Z employees.

### 3.3 LINKING WORKPLACE DESIGN TO JOB EMBEDDEDNESS

An effective work environment is a major driver of JE particularly among Gen Z employees, since it enhances fit, link, and sacrifice each of which has a different effect in lowering turnover intention (Mitchell et al., 2001). The office design that combines lounge areas with small pods assists Gen Z employees achieve their desired balance between focused and collaborative work, fostering a sense of belonging (Berber et al., 2022). Incorporating sustainability features aligns with Gen Z's environmental beliefs and increases corporate attachment (Sengupta et al., 2024).

A well-designed workplace increases well-being by providing shared gyms, relaxation areas, and informal fostering of stronger social bonds among colleagues (Yu et al., 2020). Collaborative zones and community spaces are strategically created to encourage to promote good interactions and help develop professional networks, which is especially crucial for Gen Z in both social and career contexts (Davidescu et al., 2020). Technology integration and well-being amenities in the workplace raise the perceived cost of turnover for Gen Z employees, as they risk losing access to advanced tools, wellness centers, and premium lifestyle options (Rani & Suneja, 2025). As shown in Figure 2, workplace design features contribute to strengthening JE within organizations.

### 3.4 JOB EMBEDDEDNESS AND GEN Z RETENTION

To retain Gen Z employees, corporate offices must understand the importance of JE, which links workplace design to retention outcomes. Meta-analytic and cross-industry studies attest to the fact that a higher JE is a negative predictor of turnover intention among Gen Z (Setthakorn et al., 2024). For example, JE in both small and large corporate workplaces has a strong detrimental impact on turnover intention (Abdullah et al., 2025). Implementing flexible arrangements enhances JE and decreases TI (Larsson et al., 2022). In developing countries, Gen Z retention has become increasingly challenging, with a growing turnover intention driven by unmet expectations around the lack of flexibility, work-life balance, and meaningfulness. JE is important in this regard, as it lowers the intent to turnover of Gen Z employees (Rosita et al., 2024). Figure 2 further indicates that higher levels of JE reduce Gen Z employees' TI.

*Table 2: Key workplace features for Gen Z retention*

| Workplace Feature | Impact on Gen Z Embeddedness | Effect on TI | Citations |
|---|---|---|---|
| Flexible Work Arrangements | Increases fit and links | Reduces turnover | (Haapakangas et al., 2018) |
| Work-Life Balance | Enhances fit and sacrifice | Reduces turnover | (Tanoto & Tami, 2024) |
| Technology-Driven Workplaces | Increases fit | Reduces turnover | (Rani & Suneja, 2025) |

Table 2 presents the key workplace design features that influence Gen Z employee retention. It highlights how specific workplace features contribute to strengthening JE among Gen Z employees and subsequently affect their TI within corporate organizations.

### 3.5 JOB EMBEDDEDNESS AS A MEDIATING MECHANISM

The study underlines the significant influence of workplace design on turnover intention, particularly among Gen Z employees. It identifies JE as an important mediating factor. Switching to a mediating mechanism, high-quality workplace design makes JE stronger. Specifically, the "fit" dimension is strengthened when the design meets Gen Z's values, while "links" are promoted through communal and wellness spaces that build social ties (Yang et al., 2011). The "sacrifice" dimension is heightened by distinctive amenities and advanced technology, making the prospect of leaving cost-intensive for employees (Shah et al., 2020). As a result, firms that prioritize these designs can expect reduced turnover intentions, supported by a culture that promotes work-life balance and employee engagement. Figure 2 illustrates how JE mediates the interaction between workplace design.

### 3.6 IMPLICATIONS FOR SOCIAL SUSTAINABILITY

According to (Kazlauskaitė et al., 2023) JE is vital for keeping Gen Z employees and improving social sustainability in the built environment, since it connects organizational ties to favorable conditions for long-term wellbeing. Flexibility, supportive relationships, alignment with long-term sustainable human resource management that promotes employee well-being are key variables (Sypniewska et al., 2023). Office design has a substantial impact on social sustainability by improving comfort and health, resulting in

increased organizational attachment and reduced turnover (Dumitriu et al., 2025). Flexible work arrangements improve work-life balance and job satisfaction, appealing to Gen Z's preference for technology-driven flexibility (Davidescu et al., 2020). In Sri Lanka, green workplace adoption remains limited, with awareness, stakeholder pressure, and environmental commitment driving change. Strengthening these factors can support social sustainability and improve employee retention (Polgampola & Gunawardana, 2021). Investing in such surroundings can attract and retain Gen Z while advancing long-term health and sustainable employment relationships.

## 4. CONCEPTUAL FRAMEWORK

The conceptual framework given in Figure 2 is based on the effects of the features of workplace design on turnover intention among Gen Z employees, mediated by JE. The framework is based on the Generational Cohort Theory (GCT) and recognizes the individual workplace requirements of Gen Z, because they were raised in a digital environment and place importance on flexibility, well-being, and sustainability.

The key dimensions in this case are JE, Fit, Links and Sacrifice dimensions. The workplace that is built well promotes a powerful Fit with employee preferences, professional Links, and perceived Sacrifice in leaving, and thus leads to the improvement of JE and decrease of turnover intention. Finally, the framework makes JE a mediator, which means that workplace design has a key impact on turnover intention because it increases the embeddedness of employees in the organization by improving social sustainability and resulting in the provision of better retention, satisfaction, and engagement in corporate environments.

The novelty in this framework's theory is that it breaks away from conventional workplace models that emphasize physical comfort and ergonomic design. While earlier models have emphasized environmental comfort as a prime psychological factor for Job Embeddedness (JE), this framework uniquely considers Sustainability arrangement, flexible and well-being working areas, and Technology Integration as integral psychological factors impacting JE for Gen Z employees. Unlike previous studies in Facilities Management that view the office environment as a passive backdrop for work, this study highlights the built environment as a strategic element that supports "Links," "Fit" and "Sacrifice" to embed employees within an organization. Moreover, by situating the variables within the Sri Lankan corporate landscape, the model provides a niche approach to how social sustainability and the physical office are pillars of talent retention in a recovering economy a perspective largely absent from existing Western-centric literature. Through the connection of workplace variables and the psychological processes of JE, this research offers multi-disciplinary approach that integrates the built environment and organizational behavior

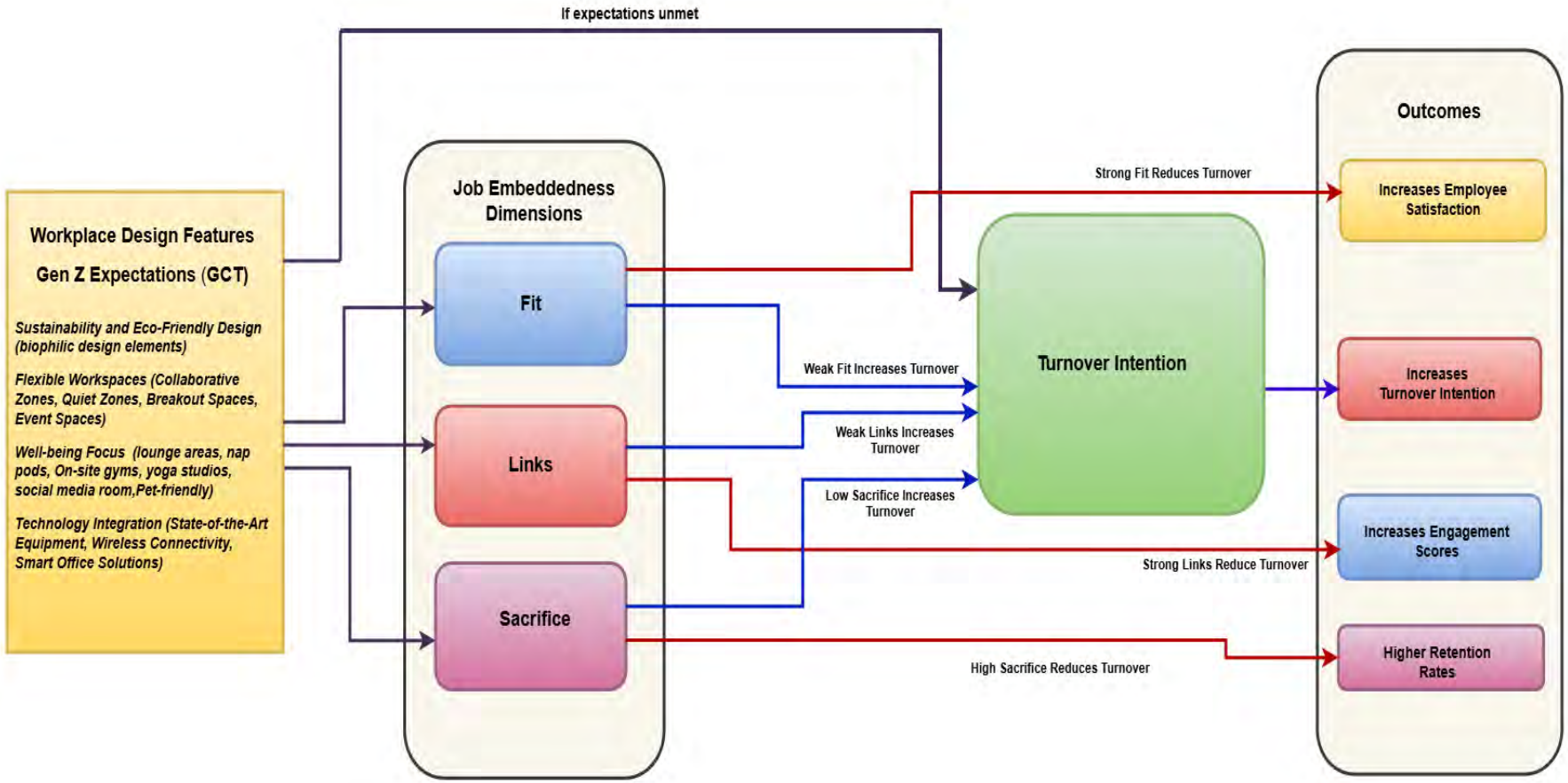



*Figure 2: Conceptual framework*

# 5. CONCLUSION

## 5.1 THEORETICAL CONTRIBUTIONS

This study contributes to the existing literature by proposing a conceptual model that connects workplace design elements to turnover intention via JE in the context of Sri Lankan workplaces. It connects the field of facilities management and organizational psychology by establishing workplace design as a precursor of JE. Moreover, the research enhances Generational Cohort Theory by placing Generation Z's expectations with a particular emphasis on their preference for sustainability and digitisation in the socio-economic context of Sri Lanka. This study adds a layer of complexity to previous studies that highlight the direct relationship between workplace design and retention, by suggesting that workplace design contributes to retention indirectly by physically and psychologically embedding employees into the organisation. In doing so, it highlights workplace design as a strategic factor for enhancing social sustainability through effective human capital retention.

## 5.2 PRACTICAL IMPLICATIONS

This framework necessitates a strategic shift in the Sri Lankan Built Environment from passive asset management to active workplace experience design. Organizations must prioritize flexible, tech-enabled, and well-being-oriented spaces to strengthen the "Fit" and "Links" of Job Embeddedness, effectively reducing Gen Z turnover. Professionals should reframe sustainability and well-being as a retention strategy rather than an operational cost, leading to an increased "Sacrifice" when employees consider leaving their jobs. In Sri Lanka's brain drain challenges, the office design takes on the vital role as a tool for Contextual Office Branding and local talent grounding. Ultimately, workplace investment must be viewed not as mere capital expenditure, but as a national strategy for workforce stability, transforming the office into a stakeholder-centred mechanism for sustaining the local talent pool.

## 5.3 FUTURE RESEARCH

Being a conceptual paper, one of the limitations is the lack of empirical evidence. Therefore, future research should test the proposed model using quantitative approaches, such as Partial Least Squares Structural Equation Modeling (PLS-SEM), to confirm the mediating effect of Job Embeddedness in the relationship between workplace design features and turnover intention. Future research could also undertake comparative studies between corporate workplaces in Sri Lanka and other South Asian countries to explore the role of workplace design factors in shaping Gen Z employees' perceptions of workplace fit.

Finally, this research positions the physical workplace as a key element in employee retention. For the Built Environment sector, the office needs to be transformed from a utilitarian solution to a 'Socially Sustainable' hub with digital connectivity and environmental considerations. Through these, employers provide the psychological and physical environment to embed Gen Z employees into the corporate structure. In the competitive Sri Lankan corporate landscape, this framework serves as a strategic blueprint for transforming office design into a powerful mechanism for long-term talent loyalty and organizational stability.

# 6. REFERENCES


Abdullah, W. J., Amarullah, D., Abdurrahman, Y. A., & Abdul, H. S. (2025). Determinants of turnover intention in the context of SMEs: Do generational differences matter? *Problems and Perspectives in Management*, *23*(3), 65–78. https://doi.org/10.21511/ppm.23(3).2025.06

Agha-Hossein, M. M., El-Jouzi, S., Elmualim, A. A., Ellis, J., & Williams, M. (2013). Post-occupancy studies of an office environment: Energy performance and occupants' satisfaction. *Building and Environment*, *69*, 121–130. https://doi.org/10.1016/j.buildenv.2013.08.003

Ali, H., Li, M., & Qiu, X. (2024). Examination of HRM practices in relation to the retention of Chinese Gen Z employees. *Humanities and Social Sciences Communications*, *11*(1), 24. https://doi.org/10.1057/s41599-023-02472-6

Anand, A., Tóth, R., Doll, J. L., & Singh, S. K. (2025). Wake up and get some sleep: Reviewing workplace napping and charting future directions. *European Management Journal*, *43*(4), 561–572. https://doi.org/10.1016/j.emj.2024.04.003

Anjum, S. (2024). Exploring job preferences among Gen Z: Trends and implications. *Journal of Research in Business and Management*,*12*(4),180-187. http://dx.doi.org/10.2139/ssrn.5352364

Berber, N., Gašić, D., Katić, I., & Borocki, J. (2022). The mediating role of job satisfaction in the relationship between FWAs and turnover intentions. *Sustainability*, *14*(8), 4502. https://doi.org/10.3390/su14084502

Chen, X., Al Mamun, A., Hoque, M. E., Wan Hussain, W. M.H., & Yang, Q. (2023). Work design, employee well-being, and retention intention: A case study of China's young workforce. *Heliyon*, *9*(5), e15742. https://doi.org/10.1016/j.heliyon.2023.e15742

Chiwisa, C., & Mpundu, M. (2024). Multigenerational workforce and organizational performance: A convergent analysis. *International Journal of Academe and Industry Research*, *5*(4), 23–52. https://doi.org/10.53378/ijair.353107

Clinton, M., Knight, T., & Guest, D. E. (2012). Job embeddedness: A new attitudinal measure. *International Journal of Selection and Assessment*, *20*(1), 111–117. https://doi.org/10.1111/j.1468-2389.2012.00584.x

D'Amato, A., & Baruch, Y. (2020). Cultural and generational predictors of learning goal orientation: A multilevel analysis of managers across 20 countries. *International Journal of Cross Cultural Management*, *20*(2), 159–179. https://doi.org/10.1177/1470595820926218

Davidescu, A. A., Apostu, S.-A., Paul, A., & Casuneanu, I. (2020). Work flexibility, job satisfaction, and job performance among Romanian employees—Implications for sustainable human resource management. *Sustainability*, *12*(15), 6086. https://doi.org/10.3390/su12156086

Davis, M. C., Leach, D. J., & Clegg, C. W. (2020). Breaking out of open-plan: Extending social interference theory through an evaluation of contemporary offices. *Environment and Behavior*, *52*(9), 945–978. https://doi.org/10.1177/0013916519878211

De Silva, L. N., & Dhammika, K. A. S. (2022). The impact of expectations on turnover intention among generation z employees in the financial sector in Sri Lanka. *Journal of Management, Social Sciences and Humanities*, *3*(1), 55–82. https://doi.org/10.4038/jmsh.v3i1.3

Dieguez, T., & Loureiro, P. (2025). The new workforce: Retention strategies for gen z engineers in a digital era. *International Journal of Future Engineering Innovations*, *2*(2), 83–86. https://doi.org/10.54660/IJFEI.2025.2.2.83-86

Dumitriu, S., Bocean, C. G., Vărzaru, A. A., Al-Floarei, A. T., Sperdea, N. M., Popescu, F. L., & Băloi, I.C. (2025). The role of the workplace environment in shaping employees' well-being. *Sustainability*, *17*(6), 2613. https://doi.org/10.3390/su17062613

Dwivedula, R., Singh, P., & Azaran, M. (2019). Gen Z: Where are we now, and future pathways. *Journal of Human Resource Management*, *22*(2), 28. https://www.jhrm.eu/wp-content/uploads/2019/12/HRM-02-2019-03-clanok.pdf

Febriana, A., & Mujib, M. (2024). Increasing productivity of Gen Z employees: The role of flexible work arrangements and participative style. *SA Journal of Human Resource Management*, *22*, a2489. https://doi.org/10.4102/sajhrm.v22i0.2489

Fernando, K. B., & Umamaheswari, S. (2025). A study on designing Gen Z friendly workplace culture in Kerry Indev logistics. *International Journal of Scientific Research in Engineering and Management, 9*(4), 1–9. https://doi.org/10.55041/IJSREM46021

Gaan, N., & Shin, Y. (2023). Generation Z software employees turnover intention. *Current Psychology, 42*, 27344–27359. https://doi.org/10.1007/s12144-022-03847-9

Gath-Morad, M., Egli, S., Grübel, J., Steemers, K., Hölscher, C., & Aguilar, L. (2024). Designing affective workplace environments: The impact of typology, contour, ceiling and partition height on cognitive and aesthetic appraisal. *Building and Environment, 265*, 111928. https://doi.org/10.1016/j.buildenv.2024.111928

Gupta, N. R., Singh, R., & Chauhan, N. (2025). Why Gen Z stays and leaves: Role of workplace flexibility, purpose-driven roles, and digital engagement tools on job retention. In T.K. Karlapudi & A. Ray (Eds.), *Contemporary Global Perspectives in Management Environment and Technology (CGPMET-2025)*, (pp. 59–81). International Economic Society Ltd. https://ijeponline.org/index.php/journal/article/view/918

Haapakangas, A., Hongisto, V., Varjo, J., & Lahtinen, M. (2018). Benefits of quiet workspaces in open-plan offices – Evidence from two office relocations. *Journal of Environmental Psychology, 56*, 63–75. https://doi.org/10.1016/j.jenvp.2018.03.003

Hendratmoko, & Mutiarawati, E. V. (2024). The significant impact of workplace environment on Gen Z performance in Indonesia. *Jurnal Manajemen, 13*(1), 28–41. https://doi.org/10.46806/jm.v13i1.1096

Jayakody, J. A. K. C., Manathunga, M. D. B. H., Gunathilaka, K. A. D. H. M., Ranasingha, R. A. N. C., Rajapakse, V., & Yapa, C. (2025). Psychosocial drivers of migration intentions: Exploring gender dynamics and workforce implications for generation z in Sri Lanka. *International Journal of Contemporary Business Research, 3*(2), 118–134. https://doi.org/10.4038/ijcbr.v3i2.17

Jayatissa, K. A. D. U. (2023). Gen Z – A new lifeline: A systematic literature review. *Sri Lanka Journal of Social Sciences and Humanities, 3*(2), 179–186. https://doi.org/10.4038/sljssh.v3i2.110

Kalmanovich-Cohen, H., & Stanton, S. J. (2024). Leveraging quiet: The power of choosing your workspace. *Industrial and Organizational Psychology, 17*(3), 371–374. https://doi.org/10.1017/iop.2024.23

Kazlauskaitė, R., Martinaitytė, I., Lyubovnikova, J., & Augutytė-Kvedaravičienė, I. (2022). The physical office work environment and employee wellbeing: Current state of research and future research agenda. *International Journal of Management Reviews, 25*(3), 413–442. https://doi.org/10.1111/ijmr.12315

Kiazad, K., Hom, P., Schwarz, G., Newman, A., & Holtom, B. (2024). High-performance work practices and job embeddedness: A comprehensive test. *Journal of Vocational Behavior, 155*, 104066. https://doi.org/10.1016/j.jvb.2024.104066

Kodithuwakku, M., Jusoh, M., & Chinna, K. (2018). Impact of human resource practices on intention to leave among generation z- The future workforce. *International Journal of Human Resource Studies, 8*(4), 267. https://doi.org/10.5296/ijhrs.v8i4.13845

Larsson, J., Vinberg, S., & Jahncke, H. (2022). Changing the office design to activity-based flexible offices: A longitudinal study of how managers' leadership behaviours are perceived. *International Journal of Environmental Research and Public Health, 19*(20), 13557. https://doi.org/10.3390/ijerph192013557

Lazuardi, M. A. L., Hasanudin, & Yakin, I. (2025). Work flexibility and rewards affect Gen Z employee retention through job satisfaction mediation. *International Journal of Economics, Business Management and Accounting (IJEBMA), 7*(2), 123–140. https://doi.org/10.59890/ijebma.v7i2.3057

Lee, M. S., & Shin, S. (2025). Factors affecting the turnover intention of newly graduated Generation Z nurses in Korea: Multilevel analysis. *Human Resources for Health, 23*(1), 36. https://doi.org/10.1186/s12960-025-01011-5

Lester, S. W., Standifer, R. L., Schultz, N. J., & Windsor, J. M. (2012). Actual versus perceived generational differences at work. *Journal of Leadership & Organizational Studies, 19*(3), 341–354. https://doi.org/10.1177/1548051812442747

Magano, J., Silva, C., Figueiredo, C., Vitória, A., Nogueira, T., & Dinis, M. A.P. (2020). Gen Z: fitting project management soft skills competencies—A mixed-method approach. *Education Sciences, 10*(7), 187. https://doi.org/10.3390/educsci10070187

Makhdoom, T. R., & Jamali, S. (2025). Measuring perceived effects of employee turnover: Development and validation of instrument for manufacturing organizations. *Sustainable Futures*, *9*, 100729. https://doi.org/10.1016/j.sftr.2025.100729

Malalage, G. S., & Perera, G. A. T. R. (2025). Exploring job embeddedness among local and international employees: A systematic review. *Cogent Business & Management*, *12*(1). https://doi.org/10.1080/23311975.2025.2486580

Malik, G., & Singh, P. (2024). Fostering social sustainability: Unveiling HR's power in enhancing employee resilience via social exchange and broaden-and-build theories. *Employee Relations: The International Journal*, *46*(3), 675–701. https://doi.org/10.1108/ER-08-2023-0427

Mateescu, M., Schulze, H., & Kauffeld, S. (2025). Choosing where to work: An empirical study of collaborative activities' impact on workspace choice behaviour. *Journal of Corporate Real Estate*, *27*(1), 47–68. https://doi.org/10.1108/JCRE-05-2024-0017

Mitchell, T. R., Holtom, B. C., Lee, T. W., Sablynski, C. J., & Erez, M. (2001). Why people stay: Using job embeddedness to predict voluntary turnover. *Academy of Management Journal*, *44*(6), 1102–1121. https://doi.org/10.2307/3069391

Naci Çoklar, A., & Tatli, A. (2021). Examining the digital nativity levels of digital generations: From generation x to generation z. *Shanlax International Journal of Education*, *9*(4), 433–434. https://doi.org/10.34293/education.v9i4.4224

Palomo-Dominguez, I., Elías-Zambrano, R., & Álvarez-Rodrigez, V. (2023). Gen Z's motivations towards sustainable fashion and eco-friendly brand attributes: the case of vinted. *Sustainability*, *15*(11), 8753. https://doi.org/10.3390/su15118753

Pathan, M.S.K. (2022). The Influence of Organizational Culture on Employee Commitment and Turnover Intentions. *International Research Journal of Management and Social Sciences*, *3*(4), 34–43. https://doi.org/10.5281/zenodo.10115346

Pichler, S., Kohli, C., & Granitz, N. (2021). DITTO for Gen Z: A framework for leveraging the uniqueness of the new generation. *Business Horizons*, *64*(5), 599–610. https://doi.org/10.1016/j.bushor.2021.02.021

Polgampola, D., & Gunawardana, K. D. (2021). A study on determinant factors of introducing a green office environment in sri lankan audit firms. *Journal of Contemporary Perspectives in Accounting and Digitalization*, *4*(1), 65–88. https://doi.org/10.4038/jcpad.v4i1.14

Porter, C. M., Peltokorpi, V., & Allen, D. G. (2024). On- and off-the-job embeddedness differentially shape stress-related reactions to job insecurity. *Applied Psychology*, *73*(4), 1916–1930. https://doi.org/10.1111/apps.12533

Raman, R., Das, P., Mandal, S., Vijayan, V., Amritesh, A.R., & Nedungadi, P. (2024). The impact of Gen Z's pro-environmental behaviour on sustainable development goals through tree planting. *Sustainable Futures*, *8*, 100251. https://doi.org/10.1016/j.sftr.2024.100251

Rani, S., & Suneja, A. (2025). Attracting talent: Understanding generation Z's expectations of technology-driven workplaces. *Vilakshan – XIMB Journal of Management*. https://doi.org/10.1108/XJM-08-2024-0129

Rosita, F., Noermijati, N., Setiwan, M., & Susilowati, C. (2024). The role of flexible work arrangement, job embeddedness, and work-life balance in reducing turnover intention: Study on millennials and generation z employees. *Journal of The Community Development in Asia*, *7*(2), 53–69. https://doi.org/10.32535/jcda.v7i2.2987

Schmidbauer, J., Niessen, C., Lubecki-Weschke, N., & Krupp, M. (2025). Staying in a stressful job? The role of job embeddedness for truck drivers' well-being and turnover intentions. *Journal of Business and Psychology*, *40*(5), 1189–1208. https://doi.org/10.1007/s10869-025-10011-0

Seemiller, C., & Grace, M. (2017). Gen Z: Educating and engaging the next generation of students. *About Campus: Enriching the Student Learning Experience*, *22*(3), 21–26. https://doi.org/10.1002/abc.21293

Sengupta, D., Mathews, M., Bridges, L., D'Costa, R., & Bastian, B. L. (2024). Sustainability orientation of Gen Z and its role in their choice of employer—A comparative qualitative inquiry of India and United States. *Administrative Sciences*, *14*(10), 249. https://doi.org/10.3390/admsci14100249

Setthakorn, K. P., Rostiani, R., & Schreier, C. (2024). A meta-analytic review of job embeddedness and turnover intention: Evidence from South-East Asia. *Sage Open*, *14*(2). https://doi.org/10.1177/21582440241260092

Shah, I. A., Csordas, T., Akram, U., Yadav, A., & Rasool, H. (2020). Multifaceted role of job embeddedness within organizations: Development of sustainable approach to reducing turnover intention. *Sage Open*, *10*(2). https://doi.org/10.1177/2158244020934876

Khan, M.S., & Pathan. (2022). The influence of organizational culture on employee commitment and turnover intentions. *International Research Journal of Management and Social Sciences*, *III*(4), 34-43. https://doi.org/10.5281/zenodo.10115346

Shuaibu, H., & Saleh, M. A. (2025). Impact of workplace design on employee well-being and productivity. *Frontiers in Management and Social Sciences*, *1*(1), 55–66. https://doi.org/10.63725/fmss.v1i1.05

Singh, V., Malhotra, R., Joshi, M., Tiwari, D. K., Joshi, N., & Pandey, P. (2024). Effect of yoga break on emotional intelligence of office workers of universities and colleges. *ShodhKosh: Journal of Visual and Performing Arts*, *5*(1). https://doi.org/10.29121/shodhkosh.v5.i1.2024.1954

Srivastava, C., Murnane, E. L., Billington, S. L., & Samuelson, H. W. (2024). Impact of workplace design on perceived work performance and well-being: Home versus office. *Journal of Environmental Psychology*, *95*, 102274. https://doi.org/10.1016/j.jenvp.2024.102274

Subarno, A., Indrawati, C. D. S., & Ninghardjanti, P. (2025). The influence of physical and non-physical factors on employee well-being in office spaces: A comprehensive study of the work environment. In *IOP Conference Series: Earth and Environmental Science* (pp. 012023). IOP Publishing. https://doi.org/10.1088/1755-1315/1462/1/012023

Sypniewska, B., Baran, M., & Kłos, M. (2023). Work engagement and employee satisfaction in the practice of sustainable human resource management – Based on the study of Polish employees. *International Entrepreneurship and Management Journal*, *19*(3), 1069–1100. https://doi.org/10.1007/s11365-023-00834-9

Tanoto, S. R., & Tami, E.G. (2024). Understanding Generation Z: work-life balance and job embeddedness in retention dynamics. *Binus Business Review*, *15*(3), 225–238. https://doi.org/10.21512/bbr.v15i3.11277

Tass, M. A., & Malik, I. A. (2025). Driving environmental change: the impact of social media on gen z's sustainability efforts. *South Eastern European Journal of Public Health*, *XXVI S1 2025*, 623-641. http://dx.doi.org/10.70135/seejph.vi.3639

Van Simaeys, H., Mannaerts, L., Serraes, B., & Clays, E. (2025). Evaluating the impact of a participatory organizational intervention on reducing occupational stress in an emergency department setting: A one group pretest-posttest design. BMC Public Health, 25(1), 2480. https://doi.org/10.1186/s12889-025-23540-3

Wan, W., & Duffy, R. D. (2022). Decent work and turnover intention among new generation employees: the mediating role of job satisfaction and the moderating role of job autonomy. *Sage Open*, *12*(2). https://doi.org/10.1177/21582440221094591

Wolf, M., & Kluge, A. (2022). Generation Z's opinion about sustainability of office buildings. *Art and Society*, *1*(2), 23–32. https://doi.org/10.56397/AS.2022.10.04

Yang, C., Ma, Q., & Hu, L. (2011). Job embeddedness: A new perspective to predict voluntary turnover. *Nankai Business Review International*, *2*(4), 418–446. https://doi.org/10.1108/20408741111178834

Yu, J., Ariza-Montes, A., Giorgi, G., Lee, A., & Han, H. (2020). Sustainable relationship development between hotel company and its employees: Linking job embeddedness, job satisfaction, self-efficacy, job performance, work engagement, and turnover. *Sustainability*, *12*(17), 7168. https://doi.org/10.3390/su12177168

Zahra, Y., Handoyo, S., & Fajrianthi, F. (2025). A comprehensive overview of Generation Z in the workplace: Insights from a scoping review. *SA Journal of Industrial Psychology*, *51*(a2263). https://doi.org/10.4102/sajip.v51i0.2263

Zivkovic, A., Adamek, A., & Brkić, A. (2025). Generation Z and the future of work: Expectations of a healthy workplace. In *Proceedings of the International Academic Conference on Management and Economics* (pp. 1–16). Diamond Scientific Publication. https://doi.org/10.33422/conferenceme.v3i1.1297

Abeydeera, L.H.U.W., Wadu Mesthrige, J., Maqsood, T. and Chandani, G.G.N., 2026. A scientometric analysis of construction value management research: A 25-year review. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1871-1884. DOI: https://doi.org/10.31705/WCS.2026.136. Available from: https://ciobwcs.com/papers/

# A SCIENTOMETRIC ANALYSIS OF CONSTRUCTION VALUE MANAGEMENT RESEARCH: A 25-YEAR REVIEW

**L.H.U.W. Abeydeera[1], J. Wadu Mesthrige[2], T. Maqsood[3] and G.G.N. Chandani[4]**

## *ABSTRACT*

*This study presents a Scientometric analysis of construction Value Management (VM) research to map the intellectual structure, knowledge evolution, and emerging trends within the field. Despite the growing body of VM literature, a comprehensive understanding of its development, influential contributors, and research directions remains limited. To address this gap, CiteSpace was employed to analyse 400 publications indexed in the Web of Science Core Collection between 2001 and 2026. The analysis incorporated document, author, and country co-citation techniques to identify influential publications, collaboration patterns, knowledge clusters, and thematic evolution within the construction VM domain. The findings reveal a substantial increase in research activity over the past decade, indicating the growing importance of value-based approaches in construction management. The knowledge domain is characterised by strong research clusters centred on project performance improvement, value optimisation, and implementation-related studies, while developed countries continue to dominate research output and influence. The results further indicate an emerging shift towards sustainability-oriented VM, digital technologies, and data-driven decision-making approaches. By providing a comprehensive knowledge map of construction VM research, this study contributes to a deeper understanding of the field's intellectual foundations and development trajectory. The findings offer valuable insights for researchers and practitioners and establish a foundation for future investigations into value-based approaches in the construction industry.*

***Keywords:*** *Knowledge Mapping; Literature Review; Scientometric; Value Management*

## 1. INTRODUCTION

Developed countries such as the United States and the United Kingdom have extensively implemented Value Management (VM) in construction projects (Perera et al., 2006). While VM is a well-established practice in these countries (Kelly et al., 2014), its adoption remains uneven globally. In many developing economies, including Malaysia, China, and several African nations, VM implementation is still limited due to factors such as low awareness, regulatory constraints, and contextual challenges (Jaapar et al., 2012;

[1] PhD Candidate, School of Property, Construction and Project Management, RMIT University, Australia, S3855817@student.rmit.edu.au
[2] Senior Lecturer, School of Property, Construction and Project Management, RMIT University, wadu.jayantha@rmit.edu.au
[3] Senior Lecturer, School of Property, Construction and Project Management, RMIT University, tayyab.maqsood@rmit.edu.au
[4] Lecturer, Department of Facilities Management, University of Moratuwa, Sri Lanka, navodag@uom.lk

Oke & Ogunsemi, 2011; Zhao & Moh, 2016). These disparities continue to influence the diffusion and maturity of VM practices across the construction sector (Alshehri, 2020).

Growing recognition of VM as a strategic approach for improving project value, stakeholder satisfaction, and resource efficiency has led to a substantial increase in research output over the past two decades. Consequently, the field has expanded to encompass diverse topics, including project performance, sustainability, stakeholder management, and digital technologies. However, existing reviews have primarily adopted narrative or systematic approaches, providing limited insights into the intellectual structure, evolution, and research networks of the field. To date, no comprehensive Scientometric study has mapped the development of construction VM research over the past 25 years. This gap limits understanding of how the field has evolved, where research influence is concentrated, and which topics are emerging as future research priorities. Therefore, this study employs CiteSpace-based Scientometric analysis to examine construction VM research published between 2001 and 2026. Specifically, the study aims to: (1) analyse publication trends; (2) identify the intellectual foundations of the field through document, author, and country co-citation analyses; and (3) reveal major research clusters, collaboration patterns, and emerging research directions. The findings provide a comprehensive knowledge map of construction VM research and offer insights for future scholarly and industry development.

## 2. METHODOLOGY

This study adopted a Scientometric research design to systematically map the intellectual structure, evolution, and emerging trends of construction VM research. Scientometric analysis is a quantitative literature analysis technique that enables the exploration of knowledge domains through citation relationships, collaboration networks, and thematic evolution patterns. Compared with conventional literature reviews, Scientometric methods provide a more objective and comprehensive understanding of the development of a research field by analysing large volumes of bibliographic data.

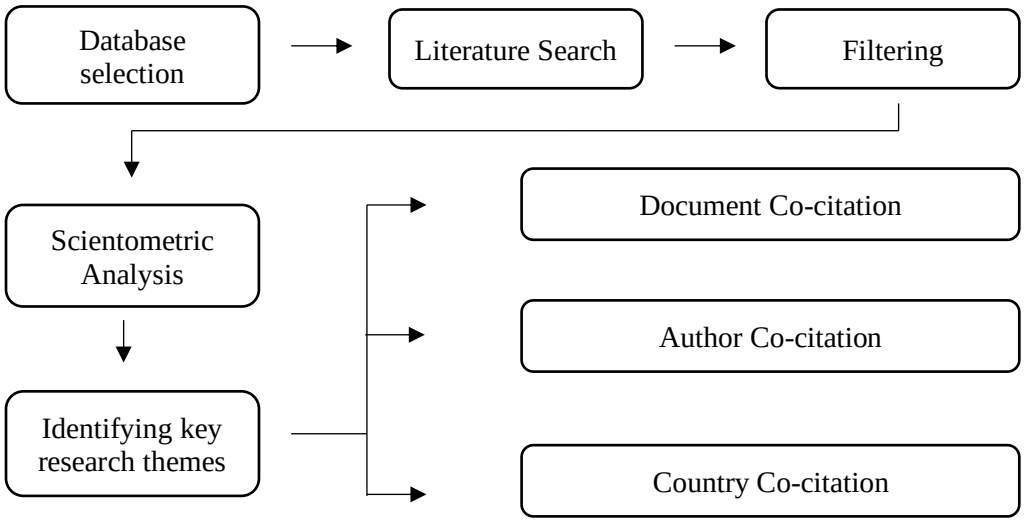



*Figure 1: Schematic diagram of research methodology*

CiteSpace (Version 6.3.R1) was employed as the primary analytical tool due to its strong capability in visualizing knowledge structures and detecting emerging research trends

(Chen, 2006). Previous studies have demonstrated that CiteSpace is particularly effective in identifying intellectual foundations, research hotspots, influential publications, and thematic evolution within scientific domains (Fang et al., 2018; Wei et al., 2015). Accordingly, the software was used to perform document co-citation, author co-citation, and country co-citation analyses to map the development of construction VM research. The overall research process adopted in this study is illustrated in Figure 1.

Prior to data collection, a comparison of major academic databases, including Web of Science (WoS), Scopus, and Engineering Village, was conducted. The Web of Science Core Collection was selected as the primary data source because of its comprehensive coverage of high-quality peer-reviewed journals, standardized citation information, and widespread use in Scientometric studies.

The literature search was conducted in March 2026 using the following search query:

**TS = ("value management" OR "value engineering") AND**

**TS = ("construction" OR "construction project*" OR "construction industry" OR "building project*" OR "built environment")**

**NOT**

**TS = ("earned value");**

where the topic field (TS) searches within the title, abstract, and keywords of publications. The search was restricted to publications published between 1 January 2001 and 1 March 2026. The exclusion of "earned value" was intentionally applied to minimise the retrieval of studies focusing exclusively on Earned Value Management (EVM), which represents a distinct project control methodology from Value Management and Value Engineering.

A multi-stage screening process was undertaken to ensure the relevance and quality of the dataset. The initial search returned 947 publications, which were subsequently filtered to include only English-language journal articles, reducing the dataset to 585 records. Further screening was conducted using relevant Web of Science categories, namely Construction and Building Technology, Civil Engineering, Industrial Engineering, Management, Business, and Multidisciplinary Engineering. A manual review of titles, abstracts, and keywords was then performed to exclude studies unrelated to construction value management, such as those focusing on manufacturing, product design, or healthcare applications. Following the screening process, a final dataset of 400 publications was obtained for Scientometric analysis.

The dataset was imported into CiteSpace, and document co-citation analysis (DCA) was employed to identify the intellectual foundations and knowledge structure of construction VM research. It should be noted that although studies containing the term “earned value” were excluded from the primary dataset, Earned Value Management (EVM) publications may still appear in the co-citation network because DCA analyses references cited by the selected publications rather than only the publications included in the dataset. Their presence therefore reflects their influence on the intellectual development of the field rather than their inclusion in the primary dataset.

Citation networks were generated using annual time slices, with the top 50 cited references selected from each year. The analysis incorporated document co-citation, author co-citation, country co-citation, and citation burst analyses to identify influential publications, key contributors, geographical research patterns, and emerging research

trends. Network quality was assessed using Modularity Q and Silhouette scores, which measure cluster separation and homogeneity, respectively (Chen, 2013). The resulting visualisations and Scientometric indicators were subsequently interpreted to identify major research themes, intellectual foundations, collaboration patterns, and emerging trends within the construction VM domain.

# 3. RESEARCH FINDINGS

This research analyses the construction VM research studies starting from 2001 to 2026. It was discovered that in the early 2000s and before, the yearly productivity of pertinent articles remained low. This could be explained by the fact that at the time few people were aware of the broad applicability of VM, despite ongoing efforts to increase awareness of it (Perera et al., 2006). The annual publication trend indicates a clear growth in research on construction value management between 2001 and 2026. In the early years (2002–2013), publication output remained relatively low, generally below 15 publications per year, reflecting the limited research attention given to the topic during that period. However, a steady increase in research publications is evident after 2015, with publications rising significantly from 23 studies in 2019 to a peak of 41 studies in 2021, which represents the highest contribution (10.25%) within the dataset. Although slight fluctuations are observed in subsequent years, the consistently high outputs in 2024 and 2025 (38 publications each) demonstrate sustained scholarly interest in the field. The lower number recorded for 2026 (8 publications) can be attributed to the ongoing nature of the year at the time of data collection. Overall, the trend highlights a rapid expansion of research interest in construction VM, particularly in the last decade, indicating the growing importance of value-based approaches in construction management research.

## 3.1 DOCUMENT CO-CITATION ANALYSIS

The core data set of VM under construction from 2001 to 2026, which is the development era of the knowledge domain, was used in the study to conduct a document co-citation analysis. The timeline was broken up by CiteSpace into a series of time slices, each of which represented a year, according to the analysis. Each time slice's top 50 citations were considered for the analysis. The co-citation network with 463 nodes and 1489 links, which is the detailed result of CiteSpace's document co-citation analysis, is shown in Figure *2*. The network is logically separated into densely connected clusters, as indicated by the findings' modularity Q, which is equal to 0.7937. The fair homogeneity of the clusters is indicated by the mean silhouette value, which is 0.9304. Figure 2 provides a graphical representation of the clusters identified through the CiteSpace analysis. Several clusters were identified by the software which indicated that construction VM is a popular topic amongst the research community. The high number of links indicate that VM research community relies on and uses peer research articles to strengthen the new research studies. From a broader perspective, similar patterns have been observed in global VM research. Studies such as Ekanayake et al. (2019) and He et al. (2017) demonstrate that construction management domains tend to evolve into clearly defined thematic clusters over time, often centred around key areas such as value optimisation, project performance, decision-making frameworks, and sustainability integration. The presence of densely connected clusters in this study similarly suggests that VM research has moved beyond fragmented early explorations toward more consolidated and specialised research streams.

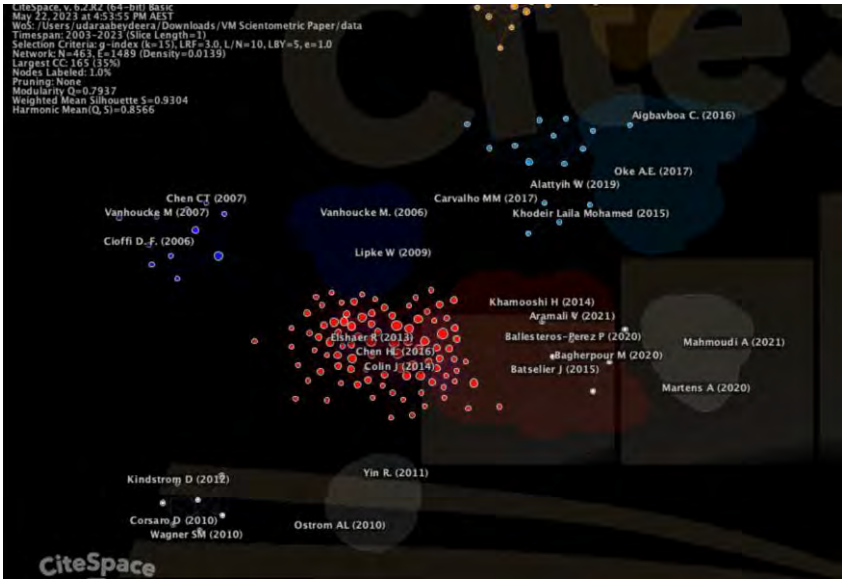



*Figure 2: Document co-citation analysis of construction VM research from 2001 to 2026*

Table 1 provides the details of the top 9 highly co-cited documents of this research domain. These 9 research studies belong to a single cluster, cluster #0 of the figure 2. The other notable fact is that all these studies were conducted after 2012. Two studies, EDM: Earned Duration Management, a new approach to schedule performance management and measurement by Khamooshi and Golafshani (2014) and Evaluation of deterministic state-of-the-art forecasting approaches for project duration based on earned value management by Batselier and Vanhoucke (2015) reported a co-citation count of 18 while the others studies also followed closely ranging a co-citation count of 14-17. All these studies mainly focused on one significant theme: enhancing the project performance by using VM. This has been the common motive of construction stakeholders when VM is integrated to construction projects.

VM is distinct from other management metrics in that its goal is to increase value by controlling function and cost (Value/ Function/Cost). Typically, a project's value is increased while expenditures are decreased, and the needed project functions are met or improved (Cheah & Ting, 2005). The improvement of project function is the intended result, which will raise the value of the final building product overall. VM can be used for virtually any project or product (Adnan et al., 2018). VM is therefore more than just a straightforward way to minimise costs. Because VM involves a systemic technique and applies a systematic VM task plan to increase project value, it varies from related methodologies like cost cutting, constructability, and reengineering.

*Table 1: Top 9 publications with the highest citation count*

| Research Article | Author (Year) | Citation count |
|---|---|---|
| EDM: Earned Duration Management, a new approach to schedule performance management and measurement | Khamooshi and Golafshani (2014) | 18 |
| Evaluation of deterministic state-of-the-art forecasting approaches for project duration based on earned value management | Batselier and Vanhoucke (2015) | 18 |

| Research Article | Author (Year) | Citation count |
|---|---|---|
| Impact of sensitivity information on the prediction of project's duration using earned schedule method | Elshaer (2013) | 17 |
| Setting tolerance limits for statistical project control using earned value management | Colin and Vanhoucke (2014) | 16 |
| Improving project forecast accuracy by integrating earned value management with exponential smoothing and reference class forecasting | Batselier and Vanhoucke (2015) | 16 |
| Earned value project management: Improving the predictive power of planned value | Chen et al. (2015) | 16 |
| A comparison of the performance of various project control methods using earned value management systems | Colin and Vanhoucke (2014) | 15 |
| Classification of articles and journals on project control and earned value management | Willems and Vanhoucke (2015) | 14 |
| A multivariate approach for top-down project control using earned value management | Colin et al. (2015) | 14 |

A citation burst indicates a highly active research field. A citation burst is the detection of a burst event that can last for more than one year. A citation burst indicates that a specific publication is associated with an increase in citations. In other words, the publication has evidently garnered a great deal of interest from the scientific community. Moreover, if a cluster contains numerous nodes with significant citation surges, the cluster as a whole represents an active area of research or a developing trend.

## 3.2 AUTHOR CO-CITATION ANALYSIS

By measuring the number of times any author's work is co-cited with the work of another author in the references of citing documents, author co-citation analysis, or ACA, is used to identify, track, and visualise the intellectual structure of an academic subject (Bayer et al., 1990). The basic objective of the ACA is to pinpoint the conceptual organisation of a scientific knowledge area in terms of the clusters created by collected co-citation trails in the literature. Figure 3 provides a visualization of the author co-citation analysis results of construction VM research. The results revealed 460 nodes with 1521 links and a mean silhouette of 0.9115. The modularity Q of the results received was 0.7776 which is an indication of the fair homogeneity of the clusters. There were twelve main clusters in the co-author analysis results. The largest cluster (#0) has 90 members and a silhouette value of 0.994. It is labelled as top-down project control by LLR, value management by LSI, and signal quality (1.35) by MI. The major citing article of the cluster is: Batselier and Vanhoucke (2015) Empirical evaluation of earned value management forecasting accuracy for time and cost. The most cited members in this cluster are: 100 Lipke, 80 Vanhoucke and 74 Anbari.

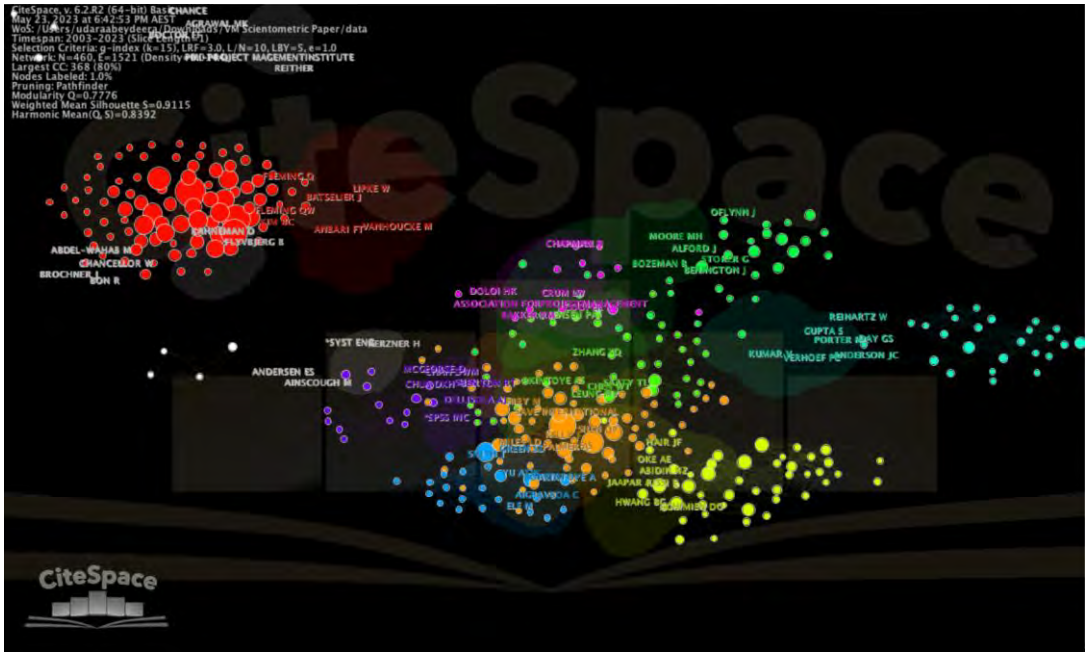



*Figure 3: Author co-citations of construction VM research 2001-2026*

The second largest cluster (#1) has 70 members and a silhouette value of 0.785. It is labelled as value management studies by both LLR and LSI, and as knowledge management system (1.01) by MI. The major citing article of the cluster is: Aghimien et al. (2018) Barriers to the adoption of value management in developing countries. The most cited members in this cluster are: 76 KELLY J, 48 MALE S, and 25 SHEN QP. The third largest cluster (#2) has 46 members and a silhouette value of 0.907. It is labelled as structural equation modelling approach by LLR, value management by LSI, and stationary barrier (0.24) by MI. The major citing article of the cluster is: Kineber et al. (2021) Impact of value management on building projects success: structural equation modelling approach. The most cited members in this cluster are: 18 Oke A.E., 18 Hair J.F., and 18 Jaapar A.

The citation burst analysis, as indicated in Figure 4, reveals how scholarly attention within the field has shifted over time, highlighting authors whose work significantly shaped the development of value management research in construction. Citation burst strength reflects the intensity of scholarly interest in a particular author's work, while burst duration indicates how long that influence remained prominent within the literature. Early citation bursts were driven by foundational contributors such as Dell'Isola (1997), whose work played a critical role in establishing the theoretical and methodological foundations of value management in the construction industry. As the field matured, citation bursts between 2015 and 2020 became associated with authors such as Colin, Batselier, and Khamooshi, reflecting a growing research emphasis on project performance monitoring and the application of earned value management techniques. More recent bursts from 2021 onwards, particularly those linked to Aghimien, Oke, Jaapar, and Kissi, suggest a shift toward practical implementation issues and the integration of value management with broader concerns such as sustainability and contemporary construction management practices. Overall, the pattern of citation bursts illustrates the evolving intellectual trajectory of the field, moving from foundational theoretical development toward

performance-oriented methodologies and, more recently, toward implementation-driven and sustainability-focused research directions.

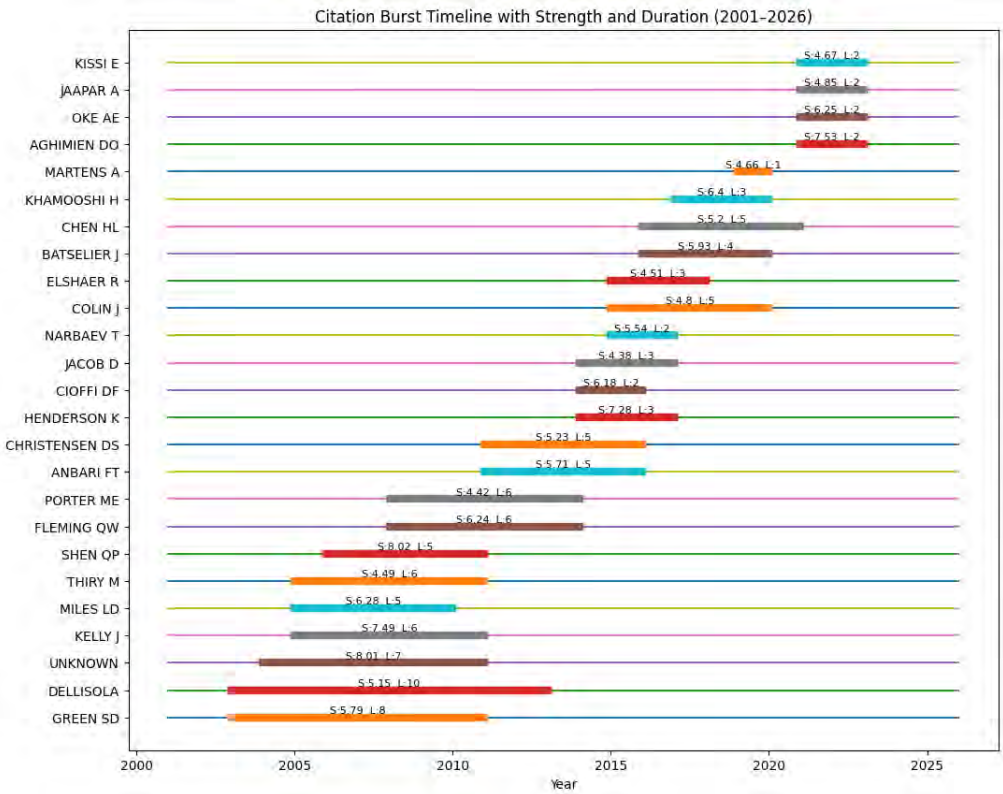



*Figure 4: Top 25 author citation bursts of construction VM research 2001-2026*

## 3.3 COUNTRY CO-CITATION ANALYSIS

The country co-citation network provides an insight on how the construction VM research studies span around the world. Figure *5* provides a visual of the most prominent countries in this research domain. The results indicate 70 nodes with 126 links with a mean silhouette of 0.8793. The results also indicated a low modularity Q of 0.4535 suggesting that community structure in construction VM research is not strong. The top ranked item by citation counts is USA (2003), with citation counts of 84. The second one is ENGLAND (2005), with citation counts of 70. The third is PEOPLES R CHINA (2003), with citation counts of 67. The 4th is AUSTRALIA (2005), with citation counts of 38. The 5th is MALAYSIA (2008), with citation counts of 26. The 6th is BELGIUM (2011), with citation counts of 26. The 7th is IRAN (2007), with citation counts of 26. The 8th is SOUTH KOREA (2006), with citation counts of 26. The 9th is SPAIN (2005), with citation counts of 21. The 10th is SOUTH AFRICA (2006), with citation counts of 19. These results are also in line with the common argument that construction VM research is majorly limited to the developed countries.

Several authors note the application of VM outside of the United States, including Australia, Indonesia, and Korea (Jay & Bowen, 2015); Europe, Australia, Hong Kong, and Japan; and France, Germany, Japan, and Australia (Kelly et al., 2014). These researchers discovered that the primary reason for adopting value management was cost reduction. China provides an example of an adoption path; the concept was sparked in

1978 by academic research (Liu & Shen, 2005). The subsequent collaboration with Japanese firms led to significant cost savings (Liu et al., 2004). In most countries, a value study is conducted over a brief "time box" period of hours or days. However, in China, a study may be conducted over a substantially extended period and may involve the identification and quantification of value opportunities in great detail (Shen & Liu, 2004).

VM research domain has become popular among the academia in the recent years thus resulting an increase in the research output. The country co-citation analysis further affirms this result and indicates that the research domain is gradually gaining its popularity in the developing countries. The cluster is included with countries such as Malaysia, Indonesia, Saudi Arabia and Taiwan which is a clear indication that over the past years, developing countries have also stepped up in the construction VM research sector. The use of VM in various construction projects was said to be in its infancy in numerous countries. More research on the existing use and lack of VM in various building projects, notably infrastructural and industrial projects, should be conducted. Furthermore, more research is suggested to discover and assess aspects that have a substantial impact on VM in different building projects, such as risk factors encountered during VM (Lin et al., 2022). Considering limited VM research on individual construction projects has been undertaken in most parts of Africa, new studies are suggested to assist the wider application of VM throughout the continent. Furthermore, further studies that employ appropriate and multiple research methodologies to provide credible results are strongly encouraged (Lin et al., 2022). It is intended that research findings would be published in a wider range of journals, helping to publicise and promote the method in other construction projects.

*Figure 5: Country co-citations of construction VM research 2001-2026*

# 4. DISCUSSION

## 4.1 EVOLUTION OF CONSTRUCTION VALUE MANAGEMENT RESEARCH

The publication trend analysis demonstrates that construction value management research has evolved from a relatively niche research area in the early 2000s into an increasingly established field of scholarly inquiry. The limited publication output observed between 2001 and 2013 suggests that VM was primarily viewed as a specialist project

management technique rather than a broader strategic management approach. However, the substantial growth in publications after 2015 indicates increasing recognition of VM's role in improving project performance, enhancing stakeholder value, and supporting organisational decision-making. This trend coincides with the growing complexity of construction projects, increasing client expectations, and the industry's shift towards value-driven project delivery approaches. The sustained publication growth observed during the last decade also suggests that researchers are increasingly exploring VM beyond its traditional cost optimisation focus. Contemporary studies have expanded the scope of VM to include project success, stakeholder satisfaction, sustainability considerations, risk management, and strategic decision-making. This evolution reflects the broader transformation of the construction industry from a cost-centric paradigm toward a value-centric paradigm.

## 4.2 INTELLECTUAL STRUCTURE OF THE CONSTRUCTION VM KNOWLEDGE DOMAIN

The document co-citation analysis revealed a highly interconnected knowledge network characterised by several well-defined clusters. The high modularity and silhouette values suggest that construction VM research has matured into a structured and specialised knowledge domain rather than remaining a fragmented collection of isolated studies. One of the most significant findings is the dominance of publications related to project performance measurement and forecasting within the most highly cited cluster. Although the primary dataset excluded studies explicitly focused on Earned Value Management (EVM), EVM-related publications emerged prominently within the co-citation network because they are frequently cited by VM researchers. This indicates that project performance measurement has become an important intellectual foundation supporting contemporary VM research.

The prominence of these studies suggests that researchers increasingly view value creation and project performance as interconnected concepts. While traditional VM research focused primarily on function-cost relationships, recent studies demonstrate a broader concern with measuring, monitoring, and predicting project outcomes. This shift reflects the industry's growing demand for evidence-based decision-making and performance-oriented management practices. Furthermore, the dense connectivity observed within the co-citation network indicates a high degree of knowledge accumulation and intellectual convergence. Researchers are increasingly building upon established theoretical foundations rather than conducting isolated investigations, suggesting that the field has entered a stage of academic maturity.

## 4.3 EVOLUTION OF RESEARCH THEMES AND SCHOLARLY INFLUENCE

The author co-citation analysis provides valuable insights into the intellectual evolution of construction VM research. The largest author cluster was associated with project control and performance measurement, highlighting the growing importance of evaluating value delivery throughout the project lifecycle. The prominence of authors such as Vanhoucke, Lipke, and Anbari demonstrates the influence of project performance management literature on the broader VM knowledge domain. The second cluster, dominated by authors such as Kelly, Male, and Graham reflects the foundational body of work that established VM principles, methodologies, and implementation frameworks. These authors have played a critical role in defining the conceptual boundaries of VM

and promoting its application within construction projects. The emergence of more recent clusters focusing on implementation barriers, organisational adoption, and structural equation modelling indicates a gradual shift from theoretical development toward empirical validation and practical implementation. Researchers are increasingly investigating factors influencing VM adoption, organisational readiness, and the measurable benefits of VM implementation in different project contexts. The citation burst analysis further illustrates the intellectual progression of the field. Early citation bursts were associated with foundational VM theorists, whereas more recent bursts highlight researchers investigating implementation challenges, project success factors, and sustainability-related applications. This pattern suggests that VM research has progressed from establishing conceptual foundations toward addressing contemporary industry challenges.

## 4.4 GLOBAL RESEARCH DISTRIBUTION AND KNOWLEDGE DIFFUSION

The country co-citation analysis demonstrates that construction VM research remains concentrated within a relatively small group of countries, particularly the United States, the United Kingdom, China, and Australia. These countries have historically been early adopters of VM and continue to serve as major centres of knowledge production. The dominance of developed economies may be attributed to stronger institutional support, established professional frameworks, greater research funding, and wider industry adoption of VM practices. The findings therefore reinforce previous observations that VM has achieved greater maturity in developed construction markets. However, the emergence of countries such as Malaysia, Saudi Arabia, South Africa, Iran, and Taiwan within the co-citation network suggests that the geographical distribution of VM research is gradually expanding. This pattern indicates increasing recognition of VM's potential benefits in developing economies, particularly in addressing cost efficiency, project performance, and resource optimisation challenges. The growing participation of developing countries also reflects the globalisation of construction knowledge and the increasing transfer of management practices across national boundaries. Nevertheless, substantial disparities remain, indicating opportunities for future research examining VM implementation within underrepresented regions, particularly Africa, South Asia, and Latin America.

## 4.5 EMERGING RESEARCH DIRECTIONS

The findings suggest that construction VM research is entering a new phase characterised by greater integration with contemporary construction management challenges. While traditional studies focused primarily on value optimisation and cost reduction, recent research trends indicate increasing interest in sustainability, digitalisation, and project performance enhancement.

Several emerging directions can be identified from the evolution of citation patterns and recent scholarly contributions:

- Integration of VM with sustainable construction and life-cycle value assessment.
- Carbon value management and environmental performance evaluation.
- Application of Building Information Modelling (BIM) to support VM workshops and decision-making.
- Artificial intelligence and machine learning techniques for value optimisation and decision support.

- Digital twins and data-driven approaches for real-time value assessment.
- Integration of VM with risk management and resilience frameworks.

These emerging areas demonstrate that the future development of VM is likely to extend beyond traditional cost-function optimisation toward supporting broader sustainability, digital transformation, and strategic project management objectives.

# 5. CONCLUSIONS

This study presents a Scientometric analysis of construction VM research based on 400 publications published between 2001 and 2026. The findings reveal a significant increase in research interest over the past decade, highlighting the growing importance of value-based approaches in construction management. The analysis identified project performance improvement, value optimisation, and implementation-related studies as the dominant research themes, while developed countries such as the United States, the United Kingdom, China, and Australia continue to play a leading role in shaping the field.

This study contributes to the literature by mapping the intellectual structure, influential contributors, and evolution of construction VM research over a 25-year period. The findings provide researchers and practitioners with valuable insights into current research priorities and emerging directions. In particular, sustainability, carbon value assessment, BIM, artificial intelligence, machine learning, and digital technologies appear to be promising areas for future investigation.

The study is limited by its reliance on English-language publications indexed in the Web of Science database and citation-based Scientometric techniques. Future research could incorporate additional databases and complementary review methods to provide broader thematic insights. Overall, this study offers a comprehensive overview of the development and emerging directions of construction VM research and provides a foundation for future value-based construction research.

# 6. REFERENCES

Adnan, T. M., Hasan, S., Rahman, M. S., & Das, A. (2018). An analytical way to reduce cost of a product through value engineering employment (case study: Walton). *International Journal of Scientific Engineering and Research, 9*(2), 527–533. https://doi.org/10.14299/ijser.2018.02.011

Aghimien, D. O., Oke, A. E., & Aigbavboa, C. O. (2018). Barriers to the adoption of value management in developing countries. *Engineering, Construction and Architectural Management, 25*(7), 818–834. https://doi.org/10.1108/ecam-04-2017-0070

Alshehri, A. (2020). Value management practices in construction industry: An analytical review. *The Open Civil Engineering Journal, 14*(1), 44–52. https://doi.org/10.2174/1874149502014010044

Batselier, J., & Vanhoucke, M. (2015). Empirical evaluation of earned value management forecasting accuracy for time and cost. *Journal of Construction Engineering and Management, 141*(11), Article 05015010. https://doi.org/10.1061/(asce)co.1943-7862.0001008

Bayer, A. E., Smart, J. C., & McLaughlin, G. W. (1990). Mapping intellectual structure of a scientific subfield through author cocitations. *Journal of the American Society for Information Science, 41*(6), 444–452. https://doi.org/10.1002/(SICI)1097-4571(199009)41:6<444:AID-ASI7>3.0.CO;2-9

Cheah, C. Y., & Ting, S. K. (2005). Appraisal of value engineering in construction in Southeast Asia. *International Journal of Project Management, 23*(2), 151–158. https://doi.org/10.1016/j.ijproman.2004.07.008

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology, 57*(3), 359–377. https://doi.org/10.1002/asi.20317

Chen, C. (2013). *Information visualisation and virtual environments*. Springer Science & Business Media.

Chen, H. L., Chen, W. T., & Lin, Y. L. (2015). Earned value project management: Improving the predictive power of planned value. *International Journal of Project Management, 34*(1), 22–29. https://doi.org/10.1016/j.ijproman.2015.09.008

Colin, J., Martens, A., Vanhoucke, M., & Wauters, M. (2015). A multivariate approach for top-down project control using earned value management. *Decision Support Systems, 79*, 65–76. https://doi.org/10.1016/j.dss.2015.08.002

Colin, J., & Vanhoucke, M. (2014). Setting tolerance limits for statistical project control using earned value management. *Omega, 49*, 107–122. https://doi.org/10.1016/j.omega.2014.06.001

Dell'Isola, A. (1997). *Value engineering: Practical applications for design, construction, maintenance and operations* (Vol. 35). John Wiley & Sons.

Ekanayake, E. M. A. C., Shen, G. Q. P., & Kumaraswamy, M. M. (2019). Mapping the knowledge domains of value management: A bibliometric approach. *Engineering, Construction and Architectural Management, 26*(3), 499–514. https://doi.org/10.1108/ECAM-07-2017-0154

Elshaer, R. (2013). Impact of sensitivity information on the prediction of project's duration using earned schedule method. *International Journal of Project Management, 31*(4), 579–588. https://doi.org/10.1016/j.ijproman.2012.10.006

Fang, Y., Yin, J., & Wu, B. (2018). Climate change and tourism: A scientometric analysis using CiteSpace. *Journal of Sustainable Tourism, 26*(1), 108–126. https://doi.org/10.1080/09669582.2017.1329310

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International Journal of Project Management, 35*(4), 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001

Jaapar, A., Zawawi, M., Bari, N. A. A., & Ahmad, N. (2012). Value management in the Malaysian construction industry: Addressing a theory and practice gap. *Procedia - Social and Behavioral Sciences, 35*, 757–763. https://doi.org/10.1016/j.sbspro.2012.02.153

Jay, C., & Bowen, P. (2015). Value management and innovation: A historical perspective and review of the evidence. *Journal of Engineering, Design and Technology, 13*(1), 123–143. https://doi.org/10.1108/JEDT-05-2013-0034

Kelly, J., Male, S., & Graham, D. (2014). *Value management of construction projects* (2nd ed.). Wiley-Blackwell.

Khamooshi, H., & Golafshani, H. (2014). EDM: Earned duration management, a new approach to schedule performance management and measurement. *International Journal of Project Management, 32*(6), 1019–1041. https://doi.org/10.1016/j.ijproman.2013.11.002

Kineber, A. F., Othman, I., Oke, A. E., & Buniya, M. K. (2021). Value management activities in building projects in developing countries. In *Advances in civil engineering materials: Proceedings of the International Conference on Architecture and Civil Engineering (ICACE 2020)* (pp. 63–70). Springer.

Lin, X., Mazlan, A. N., Ismail, S., Hu, L., Kasiman, E. H. B., & Yahya, K. (2022). Status of value management studies in construction projects: A systematic review. *Ain Shams Engineering Journal, 13*(6), Article 101820. https://doi.org/10.1016/j.asej.2022.101820

Liu, G., & Shen, Q. (2005). Value management in China: Current state and future prospect. *Management Decision, 43*(4), 603–610. https://doi.org/10.1108/00251740510593554

Liu, G., Shen, Q., Li, H., & Shen, L. (2004). Factors constraining the development of professional project management in China's construction industry. *International Journal of Project Management, 22*(3), 203–211. https://doi.org/10.1016/S0263-7863(03)00044-7

Oke, A. E., & Ogunsemi, D. R. (2011). Value management in the Nigerian construction industry: Militating factors and perceived benefits. In *Proceedings of the Second International Conference on Advances in Engineering and Technology* (pp. 353–359). Makerere University. https://ghanatrade.com.gh/old/file/Developing%20the%20Construction%20Industry%20in%20Ghana%20BUILDING.pdf

Perera, S., Karunasena, G., & Selvadurai, K. (2006). Application of value management in construction. *Built-Environment Sri Lanka, 4*(1), 3–12. https://doi.org/10.4038/besl.v4i1.7647

Shen, Q., & Liu, G. (2004). Applications of value management in the construction industry in China. *Engineering, Construction and Architectural Management, 11*(1), 9–19. https://doi.org/10.1108/09699980410512636

Wei, F., Grubesic, T. H., & Bishop, B. W. (2015). Exploring the GIS knowledge domain using CiteSpace. *The Professional Geographer, 67*(3), 374–384. https://doi.org/10.1080/00330124.2014.983588

Willems, L. L., & Vanhoucke, M. (2015). Classification of articles and journals on project control and earned value management. *International Journal of Project Management, 33*(7), 1610–1634. https://doi.org/10.1016/j.ijproman.2015.06.003

Zhao, R., & Moh, W. H. (2016). Value management practices on major construction projects and green building. *Frontiers of Engineering Management, 3*(2), 147–157. https://doi.org/10.15302/J-FEM-2016021

# The 14th World Construction Symposium - 2026

*Towards a Regenerative Built Environment: From Foresight to Action*

SYMPOSIUM

# PROCEEDINGS

## ORGANIZED BY

CEYLON INSTITUTE OF BUILDERS (CIOB) SRI LANKA

DEPARTMENT OF BUILDING ECONOMICS
UNIVERSITY OF MORATUWA

## ENDORSED BY

MINISTRY OF HOUSING, CONSTRUCTION AND WATER SUPPLY
MINISTRY OF ENERGY
MINISTRY OF TRANSPORT, HIGHWAYS AND URBAN DEVELOPMENT

Gold Partner

TOKYO CEMENT GROUP

Official Partners

HOME LANDS
LUMOS
INSEE CEMENT
ALUMEX
SIGN-TECH
invitations.lk
WONMA

Associate Partners

CSCT CAMPUS
WESTERN SYDNEY UNIVERSITY
DEAKIN UNIVERSITY
Adelaide University
MASSEY UNIVERSITY
BNCA

Event Concept & Managed by

Saga Group
www.sagagroup.lk

Official Magazine

Arzede Magazine

Electronic Media Partners

Print Media Partners

DAILY MIRROR
Daily FT

**CELYLON INSTITUTE OF BUILDERS**

No.80/1, Fife Road, Colombo 05.

Tel : +94 (0) 112 508 139 | Email : info@ciob.lk

www.ciobwcs.com