The 13th World Construction Symposium - 2025

Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations

SYMPOSIUM

PROCEEDINGS

15th - 16th August 2025

COLOMBO
SRI LANKA



Organized by

CEYLON INSTITUTE OF BUILDERS
(CIOB) SRI LANKA

DEPARTMENT OF BUILDING ECONOMICS
UNIVERSITY OF MORATUWA

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PROCEEDINGS

of

THE 13TH WORLD CONSTRUCTION SYMPOSIUM 2025

ON

SUSTAINABLE FUTURES: SHAPING A REGENERATIVE BUILT ENVIRONMENT FOR FUTURE GENERATIONS

15-16 August 2025

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http://www.ciob.lk/

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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, Facilities Management, Project Management, Construction Law and Dispute Resolution and Occupational Safety and Health Management. 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

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

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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

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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/

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/

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

The University of Adelaide, Australia

The University of Adelaide is a well-regarded institution of higher learning and innovation located in Adelaide, Australia. It is a member of the prestigious Group of Eight, which consists of Australia's top research-intensive universities. The University of Adelaide has consistently received high ratings from respected international assessments, which is a testament to its commitment to academic excellence. It offers a range of undergraduate and graduate degree programs and has a strong emphasis on research. Students can choose from a variety of areas of study, including accounting and finance, agriculture, food and wine, allied health, animal and veterinary sciences, architecture, arts, biomedical science and biotechnology, and business. The university prides itself on being a future-maker for its state, nation, and the world. It has a strong commitment to creating meaningful change through contemporary educational and research excellence. The institution aims to meet the evolving needs of its local and global communities while applying proven values that celebrate its proud history.

https://www.adelaide.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

Dr. Bhanuben Nanavati College of Architecture, 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/

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 13th World Construction Symposium (WCS) under the theme "*Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations.*" This symposium marks the 13th 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: Western Sydney University, Australia; The University of Newcastle, Australia; Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Group Publishing; Colombo School of Construction Technology (CSCT), Sri Lanka; Deakin University, Australia; Massey University, New Zealand; The University of Adelaide, Australia; Indian Institute of Technology Madras (IIT Madras), India; and Dr. Bhanuben Nanavati College of Architecture, India.

We are especially thankful to all the authors who chose the 13th 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 13th iteration this year.

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, 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.

A special note of thanks goes to the panellists and moderators of the panel discussion on the theme "*2030 Step Ahead: Strategic Foresight for the Sri Lankan Construction Industry.*" The session brought together distinguished academics and industry leaders to discuss on sustainability-related challenges facing the Sri Lankan construction sector. The discussion emphasised the importance of strengthening collaboration between academia and industry, with key insights distilled into ten thematic summary areas that will guide the focus of the next World Construction Symposium.

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 13th World Construction Symposium 2025.

Editors

The 13th World Construction Symposium
Colombo, Sri Lanka
August 2025

PREFACE

The 13th World Construction Symposium (WCS 2025), 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 15th and 16th of August 2025. The symposium was organised in partnership with the Western Sydney University, Australia; The University of Newcastle, Australia; Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Group Publishing; Colombo School of Construction Technology (CSCT), Sri Lanka; Deakin University, Australia; Massey University, New Zealand; The University of Adelaide, Australia; Indian Institute of Technology Madras (IIT Madras), India; and Dr. Bhanuben Nanavati College of Architecture, India.

This year marks the 13th 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 *"Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations,"* envisioning a path towards sustainability and resilience for the industry.

The symposium attracted over 120 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.

Following this process, 108 papers were accepted for publication. Notably, authors of the selected papers represented countries including Australia, India, Indonesia, Sri Lanka, South Africa, the United Kingdom, and the UAE. Collectively, the papers address a broad spectrum of topics across ten subthemes: sustainable construction methods and processes for future generations; sustainable, resilient, and regenerative buildings; products and materials for a circular and sustainable future; socio-economic and cultural dimensions of built environment sustainability; innovation and smart technologies for sustainable futures; decision-support systems and assessment frameworks for a sustainable built environment; retrofitting and reuse of buildings for sustainable futures; solutions for modernizing and refurbishing existing buildings and adaptive reuse of buildings; awareness, education, training, and policy interventions for sustainable futures; and Artificial Intelligence (AI) for a sustainable built environment.

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.

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SYMPOSIUM INFORMATION

IMPORTANT: To ensure the proper execution of WCS 2025 hybrid symposium, please pay special attention to the instructions below. If you have any questions or difficulties following the guidelines, please contact the WCS 2025 Secretariat (info@ciobwcs.com) who will be happy to help.

• How will WCS 2025 Hybrid Symposium Work?

The conference is delivered physically at Sir Lanka Foundation Institute, Colombo 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 2025 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 2025 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 **before 14 August 2025** and the secretariat will manage the requests.

• Preparing for your Virtual Session - Instructions for Virtual Presenters:

Follow the instructions below when presenting your paper at WCS 2025 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 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 5.3.0 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. You can test your download speed here.
- 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 the 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 your 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 2025 Hybrid Symposium

To access the symposium virtually:

Join the 13th World Construction Symposium https://us05web.zoom.us/j/86918470014?pwd=OySQC8AVtfr3GmQXVRqVFalccEXaEi.1
Meeting ID: 869 1847 0014 Passcode: wcs2025

- Make sure to install Zoom on your computer or update it to the latest version (version 5.3.0 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 WCS2023 main meeting room).
- Parallel paper presentation sessions are held in breakout rooms within the main meeting room. Once, the breakout rooms are open, 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 5.3.0 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:
    - Click **Breakout Rooms** in your meeting controls.

      This will display the list of open breakout rooms (i.e. parallel sessions) created by the host.
    - Hover your pointer over the number to the right of breakout room you wish to join, click **Join**, then confirm by clicking Join.
    - Repeat as necessary to join other breakout rooms.
    - 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.
    - 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).
    - 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 standardise 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.
- Please click here for instructions on enabling virtual backgrounds on Zoom.

- ## Some other Useful Links

If you need more information on how to use Zoom:

How to join a Zoom meeting

How to configure your audio and video Participating in breakout rooms

- ## 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 the symposium virtually will receive the e-certificates in due course.

Disclaimer

Whilst every attempt be made to ensure that all aspects of the symposium mentioned in this announcement will take place as scheduled, the Organising 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 13th World Construction Symposium 2025



It is my honour and privilege to welcome you to the 13th World Construction Symposium, a flagship event in Sri Lanka's academic and professional calendar. Over the past thirteen 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, "*Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations*," 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 shaping a regenerative future that ensures 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 shape a more sustainable and regenerative built environment. Thank you for joining us at the 13th 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)



I take great pleasure in welcoming you to the 13th World Construction Symposium (WCS) 2025 on the theme "*Sustainable Futures: Shaping a regenerative Built Environment for future generations*" to be held on the 15th and 16th August 2025 in Colombo. CIOB's WCS is an exciting annual venture organized jointly with the Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics of the 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 will bring all like-minded individuals on a single platform to discuss new trends and challenges in the field of Sustainable Construction. During its proceedings, Sri Lankan academics, research scholars and practitioners will get the opportunity to interact with renowned experts from overseas on sustainable construction and new trends in global built environment.

The CIOB is honoured to have a distinguished team of academics and researchers to serve on the scientific committee, providing comprehensive reviews to the submissions. The extensive technical programme developed by the scientific committee, includes five concurrent sessions/presentation tracks. The event gives an opportunity for the professionals in the construction industry to achieve targets on their Continued Professional Development.

I wish the symposium to be a great success with your continued participation and the commitment of the University of Moratuwa and the generous support of all from the Sri Lankan Construction Industry.

MESSAGE FROM THE HON. SECRETARY, CIOB

Eng. Saliya Kaluarachchi

Hon. Secretary
The Ceylon Institute of Builders (CIOB)



I am pleased to welcome all the delegates to the 13th World Construction Symposium, 2025 held during the period 15th and 16th August 2025 in Colombo. It is with great pleasure I apprise you that our institute, the Ceylon Institute of Builders has been able to host the World Construction Symposium annually since 2012. The Symposium has become a popular event for both the academics and professionals in the Construction industry in Sri Lanka. I am sure that this Symposium will live up to their expectations and enable the participants to gain knowledge from the presentations and the discussion during its two-day proceedings.

The Building Economics and Management Research Unit (BEMRU) of the Department of Building Economics of the University of Moratuwa, Sri Lanka is the joint organizer of this Symposium along with the CIOB. I would like to express gratitude to them for their firm commitment and backing in making this a continued reality. I am also thankful to the Associate Partners of the Symposium which include leading academic and research institutions from a number of countries.

As in the previous years, this year also the Symposium has been greatly supported by the Construction industry stakeholders and professional institutions in organizing the event. I wish to record my special thanks to all of our Sponsors and well-wishers for their generous contribution to make this symposium a success.

My best wishes to all those who have joined this year's conference for gaining and spreading knowledge on sustainable built environment for sustainable futures.

MESSAGE FROM THE SYMPOSIUM CO-CHAIRPERSONS

Eng. Sagara Gunawardena

Dr. Kalana Alwis

Mr. Ranji Hewage







Co-Chairpersons
Organizing Committee
The 13th World Construction Symposium

We are pleased to welcome all distinguished delegates to the 13th World Construction Symposium 2025 (WCS 2025) to be held during 15th and 16th August 2025 in Colombo. This annual symposium has been jointly organized by the Ceylon Institute of Builders (CIOB) and the Department of Building Economics of the University of Moratuwa since the year 2012. The theme for this year's symposium is "*Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations*" which is timely in the context of the growing need to keep in line with the global trends and the sustainable goals in the construction industry.

During the past decade, the CIOB has taken a number of initiatives with the University of Moratuwa through this highly acknowledged event to play a leading role in the sustainable development process for the construction industry both in Sri Lanka and globally. 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 the researchers is a great motivating factor. Achievements by academic and professional bodies together are also a great encouragement for the industry and for further research.

We congratulate and appreciate the collective work done by all those stakeholders for the Construction Industry over the years and recognize the achievement of the Scopus indexed accomplishment as a significant achievement for the WCS by the University of Moratuwa.

We wish the WCS 2025 every success in its proceedings.

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

Prof. Anuradha Waidyasekara

Head of the Department
Department of Building Economics
University of Moratuwa



I extend my warmest wishes for the 13th World Construction Symposium 2025. 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 Western Sydney University, Australia; The University of Newcastle, Australia; Deakin University, Australia; Massey University, New Zealand; the University of Adelaide, Australia; Indian Institute of Technology Madras (IIT Madras), India; Dr. Bhanuben Nanavati College of Architecture, India; Built Environment Project and Asset Management (BEPAM) Journal, published by Emerald Group Publishing; Colombo School of Construction Technology (CSCT), Sri Lanka.

The global construction industries are transforming with sustainable futures, navigating through economic pressures, resource constraints, climate change, and trade wars. The 13th World Construction Symposium is themed "*Sustainable Futures: Shaping a Regenerative Built Environment for Future Generations*", reflecting its forward-looking and action-oriented approach.

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 13th World Construction Symposium 2025 every success and look forward to its continued contribution towards shaping a sustainable and innovative construction future.

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SYMPOSIUM PROGRAMME

FRIDAY, 15 AUGUST 2025 – DAY ONE	
08.30 am	Symposium Registration
09.00 am	Symposium Inauguration
09.10 am - 09.20 am	Welcome address by President, CIOB **Dr. Rohan Karunaratne**
09.20 am - 09.30 am	Address by Conference Chairperson **Prof. Chitra Weddikkara**
09.30 am - 09.40 am	Address by Deputy Vice Chancellor **Prof. D. P. Chandrasekara**
09.40 am -10.00 am	Address by the Chief Guest **Prof. Malik Ranasinghe**
10.00 am - 10.30am	Keynote Address 1 ***"Building Resilient Communities: Lessons from the UK Flood and Coastal Resilience Innovation Programme (FCRIP)"*** **Prof. David Proverbs**
10.30 am- 10.35 am	Sponsors Video
10.35 am- 10.55 am	Refreshments
10.55 am – 11.10 am	Address by Editor-in-Chief, Journal of Built Environment Project and Asset Management (BEPAM) **Prof. Mohan Kumaraswamy**
11.10 am – 11.40 am	Keynote Address 2 ***"Sustainability and Circularity through Digitalisation"*** **Prof. Srinath Perera**
11.40 am – 11. 50 am	Sponsors Video
11.50 am – 12.00 noon	Vote of Thanks by Hony. Secretary, CIOB **Eng. Saliya Kaluarachchi**
12.00 noon - 01.00 pm	Lunch Break
0 1.00 pm - 03.00 pm	**Parallel Sessions 1**
03.00 pm - 03.30 pm	Refreshments
03.30 pm - 05.30 pm	**Parallel Sessions 2**
05.30 pm	End of Day 1

SATURDAY, 16 AUGUST 2025 – DAY TWO	
08.00 am	Symposium Registration
08.30 am - 10.00 am	**Parallel Sessions 3**
10.00 am - 10.30 am	Refreshments
10.30 am - 12.00 noon	**Parallel Sessions 4**
12.00 noon - 01.30 pm	Lunch Break
01.30 pm - 03.15 pm	**Panel Discussion on:** **"2030 Step Ahead: Strategic Foresight for the Sri Lankan Construction Industry"** **Panel Members:** Prof. David Proverbs Prof. Srinath Perera Prof. Chitra Weddikkara Dr. Rohan Karunaratne Dr. Kalana Alwis **Panel Moderator:** Ch.QS. Lalith Ratnayake **Thematic Summary Contributor:** Dr. Suranga Jayasena
03.15 pm - 03.25 pm	Announcing the Award Winners **Prof. Mohan Kumaraswamy** **Prof. Anuradha Waidyasekara**
03.25 pm - 03.35 pm	Vote of Thanks by Scientific Committee Co-Chairperson **Dr. Indrani Wimalaratne**
03.35 pm - 04.00 pm	Refreshments
04.00 pm	End of Programme
06.30 pm Onwards	Awards Ceremony & Symposium Dinner at Hilton Colombo

SYMPOSIUM SESSION PLAN AT-A-GLANCE

Friday, 15th August 2025 – Day One					
08.30 am	**Symposium Registration**				
09.00 am - 12.00 noon	**Symposium Inauguration**				
12.00 noon - 01.00 pm	**Lunch Break**				
01.00 pm - 03.00 pm	**Session 1A**	**Session 1B**	**Session 1C**	**Session 1D**	**Session 1E**
	S17045	S17011	S17048	S17033	S17032
	S17052	S17129	S17068	S17034	S17056
	S17062	S17130	S17092	S17054	S17063
	S17074	S17131	S17105	S17110	S17100
	S17075	S17134	S17109	T17122	S17104
	T17125	Q&A	S17115	Q&A	S17107
	Q&A		Q&A		Q&A
03.00 pm - 03.30 pm	**Break**				
03.30 pm - 05.30 pm	**Session 2A**	**Session 2B**	**Session 2C**	**Session 2D**	**Session 2E**
	S17025	S17006	S17058	S17013	S17037
	S17072	S17007	S17023	S17039	S17042
	S17088	S17085	S17031	S17061	S17049
	S17097	S17090	S17043	S17098	S17071
	S17108	S17103	S17050	S17111	S17073
	S17132	Q&A	S17059	S17126	S17079
	Q&A		Q&A	Q&A	Q&A
05.30 pm	**End of Day 1**				
08.00 am	**Symposium Registration**				
Saturday, 16th August 2025 – Day Two					
08.30 am - 10.00 am	**Session 3A**	**Session 3B**	**Session 3C**	**Session 3D**	**Session 3E**
	S17080	S17004	S17001	S17028	S17027
	S17081	S17087	S17005	S17044	S17021
	S17089	S17113	T17008	S17095	S17076
	S17101	T17118	S17036	S17117	S17124
	S17102	S17135	S17128	S17136	S17047
	Q&A	Q&A	Q&A	Q&A	Q&A
10.00 am - 10.30 am	**Break**				
10.30 am - 12.00 noon	**Session 4A**	**Session 4B**	**Session 4C**	**Session 4D**	**Session 4E**
	S17012	S17010	S17009	S17041	S17026
	S17077	S17064	S17051	S17070	S17065
	S17086	S17067	S17055	S17091	S17066
	S17099	S17116	S17057	S17119	S17093
	S17120	S17123	S17096	S17121	T17106
	S17019	Q&A	Q&A	Q&A	Q&A
	Q&A				
12.00 noon - 01.30 pm	**Lunch Break**				
01.30 pm - 03.15 pm	**Panel Discussion**				
03.15 pm – 03.35 pm	**Symposium Sum-Up**				
03.35 pm - 04.00 pm	**Break**				
04.00 pm	**End of Programme**				
06.30 pm onwards	**Fellowship and Awards Night at Hilton, Colombo**				

DETAILED SESSION PLAN

FRIDAY, 15 AUGUST 2025

SESSION 1A

Theme	**Carbon Assessment in the Built Environment**
Session Chair	**A/Prof. Sepani Senaratne**
Venue/Time	**Room A - 01.00 PM - 03.00 PM**
Virtual	**Breakout Room - Session A**

Time	Paper ID, Title and Author(s)
01.00 PM - 01.15 PM	**S17045: Global Research Trends in Carbon Capture and Utilization Technologies for Cement Production: A Bibliometric Analysis** *H.H.A.P Hemantha, R.A.B.U.N. Perera, D.N.L.S. Uduwage*
01.15 PM - 01.30 PM	**S17052: Embodied Carbon Variability in Indian High-Rise Residential Buildings: A Case-Based Assessment** *K.G. Akshatha, Sivakumar Palaniappan, M.K. Pradeep Kumar Rao*
01.30 PM - 01.45 PM	**S17062: Carbon Financing in Construction: Review of Benefits and Barriers** *D.S.I. Wijayawardena, K.A.T.O. Ranadewa*
01.45 PM - 02.00 PM	**S17074: Learning from Nature: Biomimicry-Inspired Building Design for Carbon Reduction in Urban Living** *R.V.A.D. Rahubadda, Udayangani Kulatunga, A.P. Rathnasinghe*
02.00 PM - 02.15 PM	**S17075: Project Data Responsibilities for Carbon Assessment in Sri Lankan Construction Industry** *R.M.T.D. Rajapaksha, S.D. Gallage*
02.15 PM - 02.30 PM	**T17125: The Applicability of Carbon Emission Estimation with BIM Environment: Sri Lankan Context** *D.A.M.V. Perera, C. Allis, B.K.C. Perera, A. Lokuge*
02.30 PM - 03.00 PM	**Q&A**

Session Coordinator: Ch. QS Dilshan Akalanka

FRIDAY, 15 AUGUST 2025

SESSION 1B (Hybrid)

Theme	**Circular Economy Integration in Construction**
Session Chair	**Dr. Gayani Karunasena**
Venue/Time	**Room B - 01.00 PM - 03.00 PM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
01.00 PM - 01.15 PM	**S17011: Buildings Designed for Systemic Circularity: A Comprehensive Review of Methodological Taxonomies** *Prince Antwi-Afari, Daniel Oteng, S. Thomas Ng, Frank Ato Ghansah, Zhikang Bao*
01.15 PM - 01.30 PM	**S17129: Exploring Circular Building Material: Transforming Industrial and Agricultural Waste into 3D Printable Construction Material** *T. Takale, V. Anagal*
01.30 PM - 01.45 PM	**S17130: Mapping Circularity Parameters: A Literature Review of Policy Planning in the Built** *Environment* *R. Deshmukh, A. Garud, V. Anagal, S. Karve, M.* Siriwardena, A. Manewa
01.45 PM - 02.00 PM	**S17131: Investigating Business Models for Circular Economy Integration in Construction Sector** *S. Shah, A. Garud, V. Anagal, S. Karve, M. Siriwardena, A. Manewa*
02.00 PM - 02.15 PM	**S17134: From Policy Presence to Enforceability: Evaluating Water Circularity in the Indian Construction Frameworks** *N. Sakhardande, S. Karve, V. Anagal, A. Garud, A. Manewa, M. Siriwardena*
02.15 PM - 02.45 PM	**Q&A**

Session Coordinator: Mr. Lakshitha Bandaranayake

FRIDAY, 15 AUGUST 2025

SESSION 1C

Theme	**Enabling Digital Transformation in Sri Lankan Construction**
Session Chair	**Ch. QS Indunil Senevirathne**
Venue/Time	**Room C - 01.00 PM - 03.00 PM**
Virtual	**Breakout Room - Session C**

Time	Paper ID, Title and Author(s)
01.00 PM - 01.15 PM	**S17048: Addressing Data Management Challenges in Sri Lankan Construction Industry through Blockchain Integration** *W.M.N.D. Wijesundara, M. Thayaparan, M.D.D. Costa*
01.15 PM - 01.30 PM	**S17068: Exploring The Potential of Blockchain Technology Adoption in the Sri Lankan Construction Industry: Opportunities and Barriers to Implementation** *D.W.J.W. Bandara, P.L.I. Wimalaratne, Udayangani Kulathunga, A. Wijayasiri*
01.30 PM - 01.45 PM	**S17092: Integrating BIM into Business Models of Consultancy Firms: Barriers and Enablers** *R.L. Samaraweera, D.N. Abeynayake, S. Sivanraj*
01.45 PM - 02.00 PM	**S17105: Barriers to Adopting Digital Twin Technology for Contract Administration in Sri Lankan Construction Sector** *M.K.L.I.C. Fernando, V. Lingasabeshan, P.L.I. Wimalaratne*
02.00 PM - 02.15 PM	**S17109: Applicability of Artificial Intelligence Models for Selection of ADR Methods to the Settlement of Contractor-Related Variation Disputes in Building Construction Projects in Sri Lanka** *Y.M.W.H.M.R.R.L.J.B. Kiridana, M.D.T.E. Abenayake*
02.15 PM - 02.30 PM	**S17115: Barriers and Solutions to Adopting Digital Twin in Sri Lankan Construction** *H.T.T.A. Indunil, R.P.H.S. Bandara, P.H.Y. Buddhini*
02.30 PM - 03.00 PM	**Q&A**

Session Coordinator: Ms. Dasuni Kodithuwakku

FRIDAY, 15 AUGUST 2025

SESSION 1D

Theme	**Technology-Driven Innovations for Safety and Productivity in Construction**
Session Chair	**Prof. Nayanthara De Silva**
Venue/Time	**Room D - 01.00 PM - 03.00 PM**
Virtual	**Breakout Room - Session D**

Time	Paper ID, Title and Author(s)
01.00 PM - 01.15 PM	**S17033: Detection of Mobile Phone Use by Labourers on Construction Sites using YOLOv11-s** *D.N.L.S. Uduwage, S. Sivanraj, K.G.A.S. Waidyasekara, R.K. Shiwakoti, M.Tripathi*
01.15 PM - 01.30 PM	**S17034: Comparison of Yolo Algorithms for PPE Compliance Monitoring at Construction Sites** *S. Sivanraj, D.N.L.S. Uduwage, M. Tripathi*
01.30 PM - 01.45 PM	**S17054: Examining Health and Safety Management among Foreign Contractors in Sri Lanka: Gaps, Barriers, and Improvement Strategies** *B.G. Wijayarathna, C. Allis, Y.K. Delpachitra*
01.45 PM - 02.00 PM	**S17110: Enhancing Labour Productivity in the Sri Lankan Construction Industry through Computer Vision** *E.M.K.K. Ekanayaka, B.A.I. Eranga*
02.00 PM - 02.15 PM	**T17122: IOT-Based Real-Time Monitoring Systems to Enhance Workers' Safety in High-Rise Construction Projects in Sri Lanka** *S.S. Jayasundara, B.A.I. Eranga*
02.15 PM - 02.45 PM	**Q&A**

Session Coordinator: Ms. Piumi Tennakoon

FRIDAY, 15 AUGUST 2025

SESSION 1E

Theme	**Lean Integration for Sustainable Construction**
Session Chair	**Dr. Mohan Siriwardena**
Venue/Time	**Room E - 01.00 PM - 03.00 PM**
Virtual	**Breakout Room - Session E**

Time	Paper ID, Title and Author(s)
01.00 PM - 01.15 PM	**S17032: BIM Implementation by Integrating Lean Construction and IDT (LCIDT)** *Rhijul Sood, Nandini Sharma, Boeing Laishram*
01.15 PM - 01.30 PM	**S17056: Client Satisfaction Model for Lean Implemented Construction SMEs: A Review** *K.G.P.N. Munasingha, K.A.T.O. Ranadewa, M.R.D.P. Wijerathna*
01.30 PM - 01.45 PM	**S17063: Lean Thinking for Green Building: Barriers for Lean Integrated Sustainable Construction** *S.J.L. Madhushani, K.A.T.O. Ranadewa, L.D.I.P. Seneviratne*
01.45 PM - 02.00 PM	**S17100: Lean Integrated Business Model for Construction - A Systematic Review on Current Practices and Future Directions** *P.W.A.H. Lawanga, Y.G. Sandanayake, K.A.T.O. Ranadewa*
02.00 PM - 02.15 PM	**S17104: Lean Integrated Circular Economy in the Sri Lankan Construction Industry: A Qualitative Delphi Study** *Hariis Vijayakumar, K.A.T.O. Ranadewa, Panchali Weerakoon, Agana Parameswaran, J.K.D.D.T. Jayanetti*
02.15 PM - 02.30 PM	**S17107: Integration of Lean Kaizen Model to Enhance Material Efficiency in Construction Projects: A Literature Review** *Sathursiya Selasteen, B.A.K.S. Perera, Anuki S. Kavirathna*
02.30 PM - 03.00 PM	**Q&A**

Session Coordinator: Ms. Dewmini Wijerathne

FRIDAY, 15 AUGUST 2025

SESSION 2A

Theme	**Advancing Circular Economy Practices and Policy in the Built Environment**
Session Chair	**Dr. Dilani Abeynayake**
Venue/Time	**Room A - 03.30 PM - 05.30 PM**
Virtual	**Breakout Room - Session A**

Time	Paper ID, Title and Author(s)
03.30 PM - 03.45 PM	**S17025: Private Sector Role as a Key Stakeholder Towards the Circular Economy in the Construction Industry in Sri Lanka** *N.V.J. Chathurya, K.A.N. Gunarathna, Kavini Guruge*
03.45 PM - 04.00 PM	**S17072: Moving from Linear to Circular Apparel Economy in Sri Lanka: PRISMA-Based Analysis of Circular Economy and Supply Chain Interactions** *C.H. Kumara, Harshini Mallawaarachchi, J.A.D.K.S. Jayakodi*
04.00 PM - 04.15 PM	**S17088: Competencies of Construction Professionals to Perform Circular Economy Practices: A Systematic Review** *D.S.I. Wijayawardena, Iresha Gamage, Sepani Senaratne, B.A.K.S. Perera*
04.15 PM - 04.30 PM	**S17097: A Review on Circular Economy and its Synergy with Industrial Symbiosis** *Angel Lokuge, Gihan Anuradha Tennakoon, Udayangani Kulatunga*
04.30 PM - 04.45 PM	**S17108: Comparison of Legislation of UK and Sri Lanka for Better Implementation of Circular Economy in Sri Lankan Construction Industry** *M.D.T.E. Abeynayake, B.A.K.S. Perera*
04.45 PM – 05.00 PM	**S17132: Review of Circularity Assessment Tools in the Built Environment** *S. Shende, V. Anagal, A. Manewa, S. Karve, A. Garud, M. Siriwardena*
05.00 PM - 05.30 PM	**Q&A**

Session Coordinator: Ms. Nimaya Perera

FRIDAY, 15 AUGUST 2025

SESSION 2B (Hybrid)

Theme	**Digital Transformation and Technology Adoption in Construction**
Session Chair	**Dr. Navodana Rodrigo**
Venue/Time	**Room B - 03.30 PM - 05.15 PM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
03.30 PM - 03.45 PM	**S17006: Assessing Organisational Readiness for Digital Transformation: Key Attributes for Indigenous South African Construction Firms** *Mayowa Adedapo Ogungbe, Matthew Ikuabe, Clinton Ohis Aigbavboa*
03.45 PM - 04.00 PM	**S17007: Defining Green Building Criteria for Building Information Modeling-Based Rating Systems** *Mustika Sari, Mohammed Ali Berawi, Rahmadi Surya, Gunawan Saroji, Nunik Madyaningarum, Siti Rahma Utami, Rafly Muzady*
04.00 PM - 04.15 PM	**S17085: Towards a Computerised Maintenance Management System for Healthcare Facilities in South Africa** *Matthew Ikuabe, Clinton Aigbavboa, Bankole Awuzie, Mayowa Ogungbe*
04.15 PM - 04.30 PM	**S17090: Barriers to Adoption of Automation in Indian Construction Projects** *Mohammed Akberuddin Adnan, Santhosh Loganathan*
04.30 PM - 04.45 PM	**S17103: A Review of Procurement and Management of Building Services Systems: Complexities and Technology Adoption** *Sachindra Hewavitharana, Srinath Perera, Xiaohua Jin, Krisanthi Seneviratne, Keivan Bamdad*
04.45 PM – 05.15 PM	**Q&A**

Session Coordinator: Mr. Lakshitha Bandaranayake

FRIDAY, 15 AUGUST 2025

SESSION 2C

Theme	**Sustainable Construction and Circular Economy Strategies**
Session Chair	**Prof. Lalith De Silva**
Venue/Time	**Room C - 03.30 PM - 05.30 PM**
Virtual	**Breakout Room - Session C**

Time	Paper ID, Title and Author(s)
03.30 PM - 03.45 PM	**S17058: Towards Successful Implementation of Offsite Construction in Sri Lanka: Barriers and Strategies** *L.P.T. Manodya, R.P.H.S. Bandara, P.H.Y. Buddhini*
03.45 PM - 04.00 PM	**S17023: Unlocking Efficiency in Timber Frame Construction: A Comparative Study of On-Site vs. Off-Site Approaches in Scotland** *Georgia Fraser, Nirodha Fernando, Deeksha Sharma*
04.00 PM - 04.15 PM	**S17031: Potential Use of Plastic Waste as a Sustainable Construction Material in Sri Lanka** *S. Geerthanan, S. Sivanraj*
04.15 PM - 04.30 PM	**S17043: Optimising Material Selection for Design for Deconstruction: A Kano Model-Based Evaluation of Doors and Windows** *P.H.G.M.A. Ranasinghe, K.G.A.S. Waidyasekara, D.N.L.S. Nuwantha*
04.30 PM - 04.45 PM	**S17050: Green Adaptive Re-Use of Buildings in Sri Lanka** *H.G.S. Dushmantha, Udayangani Kulatunga, N.B. Nanayakkara, W.S.D Perera*
04.45 PM – 05.00 PM	**S17059: Towards a Circular Economy: Evaluating Effective Implementation Strategies for Recycling and Reuse Programmes in Sri Lanka's Construction Industry** *S.D.V. Lakshan, W.M.C.L.K. Wijekoon, P.H.Y. Buddhini*
05.00 PM - 05.30 PM	**Q&A**

Session Coordinator: Ms. Anuki Kavirathna

FRIDAY, 15 AUGUST 2025

SESSION 2D

Theme	**Human-Centered and Technological Approaches to Urban Disaster Resilience**
Session Chair	**Dr. Sachie Gunathilake**
Venue/Time	**Room D - 03.30 PM - 05.30 PM**
Virtual	**Breakout Room - Session D**

Time	Paper ID, Title and Author(s)
03.30 PM - 03.45 PM	**S17013: Disaster-Resilient Cities: Temporal Analysis of Urban Land Use Land Cover Changes and Urban Floods from 1999 To 2022: Case Study of Colombo, Sri Lanka** *U. Abeysinghe, H.U.C.P. Hewawasam, J. Manatunga*
03.45 PM - 04.00 PM	**S17039: Sustainable Urban Mobility in Sri Lanka: The Imperative for an Inherent Human-Centered Approach for Holistic Development** *J.A.C.D. Jayalath, Udayangani Kulatunga*
04.00 PM - 04.15 PM	**S17061: Review on Technological Interventions to Enhance Flood Resilience in the Built Environment** *R.P.T. Nayanathara, M. Thayaparan*
04.15 PM - 04.30 PM	**S17098: Serious Games for Disaster Risk Reduction: Enhancing Community Preparedness for Sustainable Futures** *Udayangani Kulatunga, H. Tariq*
04.30 PM - 04.45 PM	**S17111: Crowdfunding for Post-Disaster Reconstruction Projects: A Conceptual Framework** *M.R.M. Riskan, K.D. Sepalage, D. Weerasooriya, K.A.T.O. Ranadewa*
04.45 PM – 05.00 PM	**S17126: A Human Centred Approach to Post Disaster Resettlement Housing: Case Study on Walk-Up Apartments in Sri Lanka** *M.S.N. de Zoysa, S.B.A. Coorey, M. Thayaparan, L. de Silva*
05.00 PM - 05.30 PM	**Q&A**

Session Coordinator: Mr. Yasith Sandaruwan

FRIDAY, 15 AUGUST 2025

SESSION 2E

Theme	**Digital Innovations and Strategies for Energy Management in Built Environments**
Session Chairs	**Dr. Chandanie Hediwattage**
Venue/Time	**Room E - 03.30 PM - 05.30 PM**
Virtual	**Breakout Room - Session E**

Time	Paper ID, Title and Author(s)
03.30 PM - 03.45 PM	**S17037: Developing a Satellite-Enabled Digital Twin Ecosystem Framework for Energy Monitoring in Smart Cities in Sri Lanka: A Literature Review** *Rusin Thathsara, Harshini Mallawaarachchi*
03.45 PM - 04.00 PM	**S17042: Short-Term Electricity Demand Forecasting in Sri Lanka Using Statistical and Deep Learning Models** *Ranju Kumari Shiwakoti, Piya Limcharoen, D.N.L.S. Uduwage*
04.00 PM - 04.15 PM	**S17049: IOT Implementation for Energy Management within Residential Buildings in Sri Lanka: Drivers and Barriers** *P. Theiventhiralingam, S. Sivanraj, K.H.K Dharmadasa, Udayangani Kulathunga*
04.15 PM - 04.30 PM	**S17071: The Effect of Vertical Greenery Systems on Building Energy Performance: Overall Thermal Transfer Value-Based Comparative Analysis** *R.A.A. Munsif, Harshini Mallawarachchi, Dimuthu Vijerathne*
04.30 PM - 04.45 PM	**S17073: Building Energy Data Management Systems in the World: A Review** *S.D.R.Y. Silva, H.W.N. Madhusanka, K.A.R.V.D. Kahandawa*
04.45 PM – 05.00 PM	**S17079: An Investigation into Effective Energy Behavior Control Strategies in the Apparel Manufacturing Sector** *N. Premananth, S.D.A. Soorige*
05.00 PM - 05.30 PM	**Q&A**

Session Coordinator: Ms. Nawanjana Manapperuma

SATURDAY, 16 AUGUST 2025

SESSION 3A

Theme	**Innovations in Sustainable Facilities and Maintenance Management**
Session Chair	**Dr. Tharusha Ranadewa**
Venue/Time	**Room A - 08.30 AM - 10.00 AM**
Virtual	**Breakout Room - Session A**

Time	Paper ID, Title and Author(s)
08.30 AM - 08.45 AM	**S17080: Rainwater Harvesting Systems as a Sustainable Water Management Strategy: Addressing Water Security Challenges in Sri Lankan Buildings** *W.M.S.D. Wijerathna, G.A.K. Dulshan, K.A.S.H. Wjayasenarathne, R.M.A. Dilini*
08.45 AM - 09.00 AM	**S17081: Applicability of Lean Maintenance Practices to Mitigate Maintenance Management Issues in Sri Lankan High-Rise Residential Buildings** *U.H.M.S. Samaranayaka, U. Rathnayake, A.S.W Karunarathna*
09.00 AM - 09.15 AM	**S17089: Shaping Regenerative Stormwater Management: A Conceptual Framework for Blue-Green Infrastructure** *H. Nethmini, C. Hadiwattage, S. Sivanraj, M.M.N. Mannapperuma*
09.15 AM - 09.30 AM	**S17101: Assessing the Impact of Organisational Culture on Digital Transformation in the Sri Lankan Facilities Management Industry** *A.S.W. Karunarathna, Jayantha Wadu Mesthrige*
09.30 AM - 09.45 AM	**S17102: Identifying Maintenance Training Needs in Sri Lanka's Apparel Industry and Augmented Reality as a Strategic Solution** *W.M.I.H. Wijesundara, P. Sridarran, P.A.P.Y. Gajaba*
09.45 AM – 10.00 AM	**Q&A**

Session Coordinator: Mr. Kawshalya Sepalage

SATURDAY, 16 AUGUST 2025

SESSION 3B (Hybrid)

Theme	**Sustainability, Social Impact, and Workforce in Global Construction**
Session Chair	**A/Prof. Gajendran Thayaparan**
Venue/Time	**Room B - 08.30 AM - 10.00 AM**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
08.30 AM - 08.45 AM	**S17004: Coping Strategies Adopted by Inhabitants with Asbestos Cement Roof Houses in South African Legacy Township** *Nonhlanhla Maphoso, Christopher Amoah*
08.45 AM - 09.00 AM	**S17087: Assessing Key Risk Factors for Workers During Nighttime in the Indian Construction Industry** *Naman Srivastava, Rohit Sahu, Sparsh Johari*
09.00 AM - 09.15 AM	**S17113: Community Benefit and Engagement Frameworks in Australian Renewable Energy Transition: A Thematic Analysis** *Umesha Weerapperuma, Navodana Rodrigo, M.K.C.S. Wijewickrama, George Zillante*
09.15 AM - 09.30 AM	**T17118: Assessing Factors Influencing Worker Retention in the Indian Construction Industry** *Akumoni Pegu, Rohit Sahu, Sparsh Johari*
09.30 AM - 09.45 AM	**S17135: Sustainable Solar: Addressing the Growing Need for PV Panel Recycling** *Tariq Umar, Sa'id Ahmed, Muhammad Qasim Rana*
09.45 AM – 10.00 AM	**Q&A**

Session Coordinator: Ms. Piumi Tennakoon

SATURDAY, 16 AUGUST 2025

SESSION 3C

Theme	**Innovative Data-Driven Approaches for Cost and Quality Optimization in Construction**
Session Chair	**Senior Prof. Kanchana Perera**
Venue/Time	**Room C - 08.30 AM - 10.00 AM**
Virtual	**Breakout Room - Session C**

Time	Paper ID, Title and Author(s)
08.30 AM - 08.45 AM	**S17001: Perceived and Expected Cost Optimization Affordances of Building Information Modelling in Sri Lankan Construction Projects** *J. Logendran, S. Sivanraj, V. Lingasabesan, Himal Suranga Jayasena, B.A.I. Eranga*
08.45 AM - 09.00 AM	**S17005: A Study Assessing the Application of Artificial Neural Network for Preliminary Estimation in Sri Lankan Building Projects** *U.P. Wijerathne, Udayangani Kulatunga, M.L.S.S. Fernando*
09.00 AM - 09.15 AM	**T17008: Predicting Cost Elements of Construction Projects Using Supervised Machine Learning Techniques** *K.A.M. Rasila, I. Mahakalanda, M.W. Edirisooriya*
09.15 AM - 09.30 AM	**S17036: Optimizing Quality Management in the Construction Industry: A COQ-Based Predictive Analysis** *Nandini Sharma, Rhijul Sood, Boeing Laishram*
09.30 AM - 09.45 AM	**S17128: Exploring Perceptual Mapping Technique as an Innovative Method of Representing Construction Cost Information** *D.N.L.S. Uduwage, Himal Suranga Jayasena, S. Piranavan*
09.45 AM – 10.00 AM	**Q&A**

Session Coordinator: Mr. Yasith Sandaruwan

SATURDAY, 16 AUGUST 2025

SESSION 3D

Theme	**Policy, Education, and Sustainability Challenges**
Session Chairs	**Prof. Menaha Thayaparan**
Venue/Time	**Room D - 08.30 AM - 10.00 AM**
Virtual	**Breakout Room - Session D**

Time	Paper ID, Title and Author(s)
08.30 AM - 08.45 AM	**S17028: Constructing National Policy for Future Generations: A Design Approach to Children's Books** *S. Samarawickrama*
08.45 AM - 09.00 AM	**S17044: Decent Work Enforcement Gaps: Adapting Global Lessons into Sri Lankan Construction Industry** *Sathyami Dissanayake, D.N.L.S. Uduwage, R.A.B.U.N. Perera*
09.00 AM - 09.15 AM	**S17095: Evaluating the Effectiveness of Approved Document in Mitigating Overheating in Buildings: A Focus on Modern Methods of Construction** *Patience Isaac, Roshani Palliyaguru, R.A.B.U.N. Perera*
09.15 AM - 09.30 AM	**S17117: Impact of the Sri Lankan Government Economic Reform Programmes on the Construction Industry since Year 2022** *B. Gheethanjali, Y.G. Sandanayake, D.M.L.N. Bandaranayake*
09.30 AM - 09.45 AM	**S17136: Present Realities and Future Directions of AI Integration within Built Environment Higher Education** *L. Jones, A. Manewa, M. Siriwardena, V. Anagal, S, Karve, A. Guard*
09.45 AM – 10.00 AM	**Q&A**

Session Coordinator: Ms. Anuki Kavirathna

SATURDAY, 16 AUGUST 2025

SESSION 3E

Theme	**Sustainable Waste Management and Material Innovation in Construction**
Session Chair	**Prof. Udayangani Kulatunga**
Venue/Time	**Room E - 08.30 AM - 10.00 AM**
Virtual	**Breakout Room - Session E**

Time	Paper ID, Title and Author(s)
08.30 AM - 08.45 AM	**S17027: A Bibliometric Analysis of Computer Vision Applications in Construction and Demolition Waste Management** *A.S.W. Karunarathna, G.G.N. Chandani*
08.45 AM - 09.00 AM	**S17021: Utilization of Textile Industry By-Products to Develop and Optimize Geopolymerized Mud Concrete for Sustainable Construction** *K.G.C. Gayashani, R.K.N.P. Piyasena, D.A. Oshadhi, S.M. Young, R.U. Halwatura*
09.00 AM - 09.15 AM	**S17076: Impact of Material Waste Management on Construction Cost of the Projects in Sri Lankan Construction Industry** *Malith Jaypadma, Kumari Wijekoon, Hansi Deheragoda*
09.15 AM - 09.30 AM	**S17124: Bridging the Gap: Enabling a Secondary Material Market for Construction and Demolition Waste** *A.V.R.S. Kavindi, I.E. Illeperuma, M.D.T.E. Abeynayake*
09.30 AM - 09.45 AM	**S17047: Urban Symbiosis in Municipal Solid Waste Management and Reduction: Insights from a Bibliometric Review** *G.G.N. Chandani, A.S.W. Karunarathna*
09.45 AM – 10.00 AM	**Q&A**

Session Coordinator: Ms. Saambavi Sivanraj

SATURDAY, 16 AUGUST 2025

SESSION 4A

Theme	**Enhancing Construction Performance through Innovation and Management**
Session Chair	**Dr. Nuwantha Uduwage**
Venue/Time	**Room A - 10.30 AM – 12.00 NOON**
Virtual	**Breakout Room - Session A**

Time	Paper ID, Title and Author(s)
10.30 AM - 10.45 AM	**S17012: Readiness to Implement Construction 4.0 Applications in Building Construction Projects in Sri Lanka** *I.H.G.Y.M.W.U. Yaparathne, D.D. Dias, Kavini Guruge*
10.45 AM - 11.00 AM	**S17077: Barriers for Time, Cost, and Quality Management in Polymer Modified Asphalt Road Construction in Sri Lanka** *M.M. Nilanka, R.M.T.D. Rajapaksha, S.D. Gallage, D.M.L.N. Bandaranayake*
11.00 AM - 11.15 AM	**S17086: A Scoping Review of Construction SMEs: Global vs Local** *M.R.I.U.K. Ratnayake, M.R.D.P. Wijerathna, K.A.T.O. Ranadewa, B.A.K.S. Perera*
11.15 AM - 11.30 AM	**S17099: Buildability Momentum across Project Stages: Empirical Insights from RIBA Plan of Work towards Sustainable Construction** *P.L.I. Wimalaratne, Udayangani Kulatunga*
11.30 AM - 11.45 AM	**S17120: Early Commissioning of MEP Works for Better Building Performance** *Chathuranga Jayasinghe, Sachie Gunatilake, Dasuni Kodituwakku*
11.45 AM - 12.00 NOON	**S17019: Artificial Intelligence-Driven Systems for Enhancing Worker Safety Monitoring in Construction Environments: A Comprehensive Review** *J.A.U.S. Jayakody, P.R.H.N.G. Thilakarathna*
12.00 NOON - 12.15 PM	**Q&A**

Session Coordinator: Ms. Nimaya Perera

SATURDAY, 16 AUGUST 2025

SESSION 4B (Hybrid)

Theme	**Innovative Approaches for Improving Construction Project Performance**
Session Chair	**A/Prof. Sivakumar Palaniappan**
Venue/Time	**Room B - 10.30 AM – 12.00 NOON**
Virtual	**Breakout Room - Session B**

Time	Paper ID, Title and Author(s)
10.30 AM - 10.45 AM	**S17010: Impact of Constructability Issues in Large-Scale Condominium Projects: A Case Study for Sri Lanka** *N.H.V.T.N. Nanayakkra, K.P.H. Perera, R.U. Halwatura*
10.45 AM - 11.00 AM	**S17064: Identifying and Quantifying the Challenges of Sri Lankan Public-Private Partnerships: A Sentiment Analysis Approach** *Hirusheekesan Selvanesan, Udayangani Kulatunga, M.P.A.P. Wijayasiri*
11.00 AM - 11.15 AM	**S17067: Unpacking Agile Project Management in Indian Construction: Adoption Barriers, Industry Readiness and Sustainability Viewpoint** *Ankit Rakshit, Santhosh Loganathan*
11.15 AM - 11.30 AM	**S17116: Financial and Socio-Economic Impacts of Implementing Active Design Principles in South African Office Buildings** *Liezl Le Roux, Tascha Bremer*
11.30 AM - 11.45 AM	**S17123: Beyond Efficiency: Rethinking Off-Site Construction for Post-Disaster Housing Reconstruction** *A.P. Rathnasinghe, R.V.A.D. Rahubadda, N. Thurairajah, Udayangani Kulatunga*
11.45 AM - 12.00 NOON	**Q&A**

Session Coordinator: Ch. QS Dilshan Akalanka

SATURDAY, 16 AUGUST 2025

SESSION 4C

Theme	**Building Performance and Resilience through Defect Analysis and Evaluation**
Session Chair	**Dr. Anupa Manewa**
Venue/Time	**Room C - 10.30 AM – 12.00 NOON**
Virtual	**Breakout Room - Session C**

Time	Paper ID, Title and Author(s)
10.30 AM - 10.45 AM	**S17009: Causes, Detection and Remediation of Water-Induced Building Defects: A Systematic Review** *Argaw Gurmu, Dulani Denipitiya, Pabasara Upalakshi Wijeratne*
10.45 AM - 11.00 AM	**S17051: The Impact of Incremental Vertical Housing Development on Quality of Space and Residential Environmental Satisfaction: A Case Study of Swarna Place, Colombo, Sri Lanka** *M.S.M. Senarathna, A.A. Hettiarachchi*
11.00 AM - 11.15 AM	**S17055: Post Occupancy Evaluation (POE) in Government Office Buildings: A Literature Review** *H.D. Subhasingha, P.A.P.V.D.S. Disaratna, M.R.D.P. Wijerathna*
11.15 AM - 11.30 AM	**S17057: Improving Insulation in Sri Lankan High-Rise Buildings: Defects, Causes, and Selection Criteria** *M.P.G.I. Priyanjith, H.W.N. Madhusanka, K.A.D.M. Natasha*
11.30 AM - 11.45 AM	**S17096: A Conceptual Framework for Capacity Building in Physical Asset Resilience** *S.P. Koralage, P.A.D. Rajini, W.K.U.R.M.K.P.K. Samarakoon*
11.45 AM - 12.00 NOON	**Q&A**

Session Coordinator: Mr. Kawshalya Sepalage

SATURDAY, 16 AUGUST 2025

SESSION 4D

Theme	**Sustainability Performance and Practices in the Built Environment**
Session Chairs	**A/Prof. Nirodha Fernado**
Venue/Time	**Room D - 10.30 AM – 12.00 NOON**
Virtual	**Breakout Room - Session D**

Time	Paper ID, Title and Author(s)
10.30 AM - 10.45 AM	**S17041: Assessing SDG 7 Performance: Identifying Relevant KPIs for the Sri Lankan Construction Industry** *K. Thiruchelvam, D.N.L.S. Uduwage*
10.45 AM - 11.00 AM	**S17070: Strategic Approach for Overcoming Barriers to Sustainable Entrepreneurship in Sri Lankan Construction Industry** *R.P.S. Ranaweera, P. Sridarran, M.N.U Maddakandage*
11.00 AM - 11.15 AM	**S17091: Systematic Literature Review for Re-Defining 'Green' in Hospitality: Typology-Sensitive Interpretations** *I.R. Wijesuriya, B.A.K.S. Perera, C.C. Abenayake*
11.15 AM - 11.30 AM	**S17119: Enhancing Sustainability in Renovation Projects: The Roles of the Contractor and Consultant** *R. Jathurshan, K.G.A.S. Waidyasekara, H.C. Victar, M.M.N. Mannapperuma*
11.30 AM - 11.45 AM	**S17121: Criteria for Selecting Retrofitting Options for HVAC Systems in Sri Lankan Commercial Buildings** *G.N.T.J. Bandara, Sachie Gunatilake, Dasuni Kodituwakku*
11.45 AM - 12.00 NOON	**Q&A**

Session Coordinator: Ms. Dewmini Wijerathne

SATURDAY, 16 AUGUST 2025

SESSION 4E

Theme	**Optimising Public Procurement through Social Value and Competency**
Session Chairs	**Ch. QS Vijitha Disaratna**
Venue/Time	**Room E - 10.30 AM – 12.00 NOON**
Virtual	**Breakout Room - Session E**

Time	Paper ID, Title and Author(s)
10.30 AM - 10.45 AM	**S17026: Integration of the Concept of Social Procurement into Construction Procurement in Sri Lanka** *Malintha H. Fernando, B.A.K.S. Perera*
10.45 AM - 11.00 AM	**S17065: Shaping Successful Procurement Futures: The Evolving Landscape of Public-Private Partnerships in Sri Lanka** *G. Fernando, C. Hadiwattege, M. Thayaparan, U. Kulathunga*
11.00 AM - 11.15 AM	**S17066: Establishing Schedule Quality Parameters for Effective Delay Analysis in Construction Projects** *Sneha Baskar, Murali Jagannathan, Dheeraj K Ubhayakar, K Hariharan*
11.15 AM - 11.30 AM	**S17093: Competency Requirement for Professionals Involved in Public Construction Procurement Process: A Review** *S.S. Weerathunge, K.A.T.O. Ranadewa*
11.30 AM - 11.45 AM	**T17106: Developing a Knowledge Value Chain Framework for Tendering in Sri Lankan Construction Organizations** *Lebunu Hewage Udara Willhelm Abeydeera, Jayantha Wadu Mesthrige, A.S.W. Karunarathna*
11.45 AM - 12.00 NOON	**Q&A**

Session Coordinator: Ms. Nishadi Nanayakkara

CHIEF GUEST

Emeritus Prof. Malik Ranasinghe



Emeritus Professor,
University of Moratuwa, Sri Lanka

Professor Malik Ranasinghe is an Emeritus Professor at the University of Moratuwa and the Vice President of the National Academy of Sciences Sri Lanka. He is a Chartered Engineer and Fellow of the Institution of Engineers, Sri Lanka, Fellow of the National Academy of Sciences, Sri Lanka, Fellow of the Institute of Project Managers, Sri Lanka and Graduate Member of Sri Lanka Institute of Directors.

Prof. Ranasinghe graduated with BSc Eng, (Hons). in Civil Engineering from the University of Moratuwa and obtained his MSc in 1987 and PhD in 1990 from the University of British Columbia, Vancouver, Canada in Civil Engineering Economics as a Canadian Commonwealth Scholar. He was awarded the DSc (Honoris Causa) by the University of Moratuwa, Sri Lanka in 2024. Prof. Ranasinghe's research focus is to combine civil engineering economics, risk analysis and environmental economics with project management. He has published over 145 research publications, of which 79 are international refereed publications. His Hirsch Index (h-Index) is 19 and he is a Sri Lanka Tier 4* researcher.

Prof. Ranasinghe is the former Vice Chancellor of the University of Moratuwa, and former Chairman of the Information and Communication Technology Agency (ICTA) of Sri Lanka, He is former Chairman of the Committee of Vice-Chancellors and Directors of Sri Lanka, Commission Member of the University Grants Commission, Council Member of the National Research Council, Council Member of the Association of Commonwealth Universities (ACU), former Dean of the Faculty of Engineering, and Chairman, Centre of Excellence in Project Management at the University of Moratuwa. He is a former Fellow of the National University of Singapore. Prof. Ranasinghe has also been involved with the corporate sector in Sri Lanka since 2003. He is an independent non-executive Director of Pan Asia Bank PLC and ACL Cables PLC, former Chairman of Sampath Bank PLC, and former independent non-executive Director of Access Engineering PLC, Resus Energy PLC, Teejay Lanka PLC, United Motors Lanka PLC, Sampath Bank PLC, Hemas Power PLC, Lanka IOC PLC, and the Colombo Stock Exchange.

KEYNOTE SPEAKERS

Prof. David Proverbs

Associate Pro Vice-Chancellor for Enterprise and Business Innovation,
De Montfort University, United Kingdom



Keynote on 'Building Resilient Communities: Lessons from the UK Flood and Coastal Resilience Innovation Programme (FCRIP)'

Professor David Proverbs is Associate Pro Vice-Chancellor for Enterprise and Business Innovation at De Montfort University, responsible for developing the knowledge exchange strategy. He has over 30 years of experience in higher education and held strategic leadership roles in four modern universities. He is passionate about the environment, a great believer in the benefits of working in a global society and committed to creating opportunities for our students to become global, climate aware citizens. He has developed significant regional, national and international research and enterprise collaborations drawing on a range of funding sources to pioneer innovative solutions towards improving resilience to flooding. His research has had significant national and international impact in the development of UK Climate Change Policy; as lead innovation adviser to the Environment Agency's Trent Regional Flood and Coastal Committee; and through supporting the development of national flood risk strategies, for example in Brazil, China, Nigeria, Peru and the UK. He is Editor in Chief for the International Journal of Building Pathology and Adaptation and the Journal of Flood Risk Management.

KEYNOTE SPEAKERS

Prof. Srinath Perera

Chair Professor of Built Environment and Construction Management, Founding Director - Centre for Smart Modern Construction (c4SMC), Western Sydney University, Australia



Keynote on 'Sustainability and Circularity through Digitalisation'

Professor Srinath Perera is the Chair Professor of Built Environment and Construction Management and Founding Director of the Centre for Smart Modern Construction (c4SMC) at Western Sydney University. He is President of AUBEA, Chair of the CIB Future Leaders Committee, and Founding Chair of the CIB Doctoral School. He also serves as Editor-in-Chief of Construction Innovation (Q1) and Specialty Editor-in-Chief of Frontiers Blockchain (Industry). A pioneer in construction informatics, Professor Perera integrates AI, Blockchain, IoT, BIM, Digital Twins, and sustainability into construction and project management. He has authored over 300 peer-reviewed publications and led major research initiatives, including securing over $700k in industry funding and participating as Chief Investigator in ARC grants exceeding $30 million. He currently holds a national grant to develop a digitalisation policy for the construction industry. He is a Fellow of the Royal Society of NSW and the Australian Institute of Building, and a Chartered Surveyor affiliated with RICS, AIQS, and AIPM. With over 30 years' experience in academia and industry, he has been recognised with awards such as the AIB Professional Excellence Awards (2019, 2024) and the 2024 Vice Chancellor's Award for Excellence in Postgraduate Supervision. His work continues to shape innovation and leadership in the built environment sector.

PANEL DISCUSSION

Panel Discussion on '2030 Step Ahead: Strategic Foresight for the Sri Lankan Construction Industry'

Panel Members	**:**	Prof. David Proverbs Prof. Srinath Perera Prof. Chithra Weddikkara Dr. Rohan Karunaratne Dr. Kalana Alwis
Panel Moderator	:	Ch.QS. Lalith Ratnayake
Thematic Summary Contributor	:	Dr. Suranga Jayasena

Panel Member



Prof. David Proverbs

BSc (Hons), PG Cert-Ed, PhD, MBA, PFHEA, FCIOB, FRICS
Associate Pro Vice-Chancellor for Enterprise and Business Innovation
De Montfort University, United Kingdom

Professor David Proverbs is Associate Pro Vice-Chancellor for Enterprise and Business Innovation at De Montfort University, responsible for developing the knowledge exchange strategy. He has over 30 years of experience in higher education and held strategic leadership roles in four modern universities. He is passionate about the environment, a great believer in the benefits of working in a global society and committed to creating opportunities for our students to become global, climate aware citizens. He has developed significant regional, national and international research and enterprise collaborations drawing on a range of funding sources to pioneer innovative solutions towards improving resilience to flooding. His research has had significant national and international impact in the development of UK Climate Change Policy; as lead innovation adviser to the Environment Agency's Trent Regional Flood and Coastal Committee; and through supporting the development of national flood risk strategies, for example in Brazil, China, Nigeria, Peru and the UK. He is Editor in Chief for the International Journal of Building Pathology and Adaptation and the Journal of Flood Risk Management.

Panel Member



Prof. Srinath Perera

PhD, MSc IT, BSc (Hons) QS, FRSN, FAIB, MRICS, AAIQS, ICECA, MICCPM, MAIPM
Chair Professor of Built Environment and Construction Management,
Director - Centre for Smart Modern Construction (c4SMC),
Western Sydney University, Australia

Professor Srinath Perera is the Chair Professor of Built Environment and Construction Management and Founding Director of the Centre for Smart Modern Construction (c4SMC) at Western Sydney University. He is President of AUBEA, Chair of the CIB Future Leaders Committee, and Founding Chair of the CIB Doctoral School. He also serves as Editor-in-Chief of Construction Innovation (Q1) and Specialty Editor-in-Chief of Frontiers Blockchain (Industry). A pioneer in construction informatics, Professor Perera integrates AI, Blockchain, IoT, BIM, Digital Twins, and sustainability into construction and project management. He has authored over 300 peer-reviewed publications and led major research initiatives, including securing over $700k in industry funding and participating as Chief Investigator in ARC grants exceeding $30 million. He currently holds a national grant to develop a digitalisation policy for the construction industry. He is a Fellow of the Royal Society of NSW and the Australian Institute of Building, and a Chartered Surveyor affiliated with RICS, AIQS, and AIPM. With over 30 years' experience in academia and industry, he has been recognised with awards such as the AIB Professional Excellence Awards (2019, 2024) and the 2024 Vice Chancellor's Award for Excellence in Postgraduate Supervision. His work continues to shape innovation and leadership in the built environment sector.

Panel Member



Prof. Chithra Weddikkara

BSc (BE), A. Arch. (Aust), B. App. Q.S. (Distcnt.) (Aus), MSc. Build. (Aus.),
PhD Law (Aus), FRICS, ARAIA, AAIQS FIA (SL), FIQS (SL) IPMSL
Emeritus Professor, Department of Building Economics, University of Moratuwa

Prof. Chitra Weddikkara is a globally respected authority in building economics and quantity surveying with over three decades of leadership in Sri Lanka's built environment sector. As a former Head of the Department of Building Economics and former Dean of the Faculty of Architecture at the University of Moratuwa, she guided the establishment of undergraduate and postgraduate programmes including Quantity Surveying, Facilities Management, Project Management, and Dispute Resolution and Law. Her influence extends to academia and professional governance: she is a Chartered Quantity Surveyor and Architect, and holds fellowships with RICS, AIQS, IQSSL and FIPMSL. Prof. Weddikkara has served as President of the Institute of Quantity Surveyors Sri Lanka (IQSSL), the Sri Lanka Institute of Architects (SLIA), and Commonwealth Association of Surveyors and Land Economists (CASLE). She has also held leadership roles with CIDA, ICTAD, RICS Sri Lanka, and the Green Building Council Sri Lanka.

Panel Member



Dr. Rohan Karunaratne

B.E (India), T.Eng. (CEI), MIE (Lon.), MBA (UK), FIIM (HK), FCIOB (Ceylon), PhD (USA)
President, Ceylon Institute of Builders (CIOB)

Dr. Rohan Karunaratne is a distinguished engineer, entrepreneur, and industry leader with an exceptional track record in construction, finance, and corporate governance across South Asia. Holding a B.E. from India, an MBA from the UK, and a Ph.D. from the USA, he is also a Chartered Engineer and a Fellow of multiple international professional bodies. He currently advises the Ministry of Justice, Prison Affairs and Constitutional Reforms and the Export Development Board and serves in the SAARC General Assembly. Dr. Karunaratne chairs several initiatives, including Human Resource Development, the Overseas Training Academy, and the South Asian Lean Construction Association, where he is President. His leadership portfolio includes serving as President of the Ceylon Institute of Builders (CIOB) and the Chamber of Construction Industry (Vice President), as well as Past President of the National Construction Association of Sri Lanka. In the corporate sector, he has chaired or directed multiple organisations, from AKK Engineers and Arpico Finance to Hatton National Bank and Sino Lanka Hotels and Spa. Renowned for championing lean construction, sustainable industry practices, and cross-border collaboration, Dr. Karunaratne brings with him a wealth of expertise and vision.

Panel Member



Dr. Kalana Alwis

D.Eng. (USA)
Director/Chief Executive Officer
Nawaloka Construction Company (Pvt) Ltd.

Dr. Kalana Alwis, D.Eng. (USA), is a distinguished civil engineer and business leader with over 40 years of experience in Sri Lanka's construction industry. Starting his career at the Department of Irrigation, he joined Nawaloka Construction Company in 1985 and rose to become its Director/Chief Executive Officer. Under his leadership, the company achieved ISO 9001:2015, ISO 14001:2015, and OHSAS 45001:2018 certifications, expanding its presence in high-rise, highway, heavy construction, and design-and-build projects locally and internationally. In recognition of his contributions, the American National Business University, USA, awarded him the title of Doctor of Engineering Management in 2022. He holds key leadership roles in the industry, including Chairman of Engineering & Construction at the National Chamber of Commerce of Sri Lanka, Vice President of the Major Constructors of Sri Lanka, the Ceylon Institute of Builders and Vice Chairman of Major and Specialist Constructors of Sri Lanka. He is also a Council Member of the Chamber of Construction Industry and the Advisory Committee Member of the Sri Lanka Export Development Board. His leadership extends internationally through his role on the Executive Committee of the Consulate of the Republic of Philippines in Colombo. Throughout his career, Dr. Alwis has not only elevated his company's industry standing but also brought pride to his alma mater, Rahula Vidyalaya, Matara.

Panel Moderator



Ch.QS Lalith Ratnayake

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A BIBLIOMETRIC ANALYSIS OF COMPUTER VISION APPLICATIONS IN CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT

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ABSTRACT

With approximately 10 billion tonnes of construction and demolition waste produced yearly, the construction sector is the biggest producer of solid waste, which accounts for 40% of urban solid waste that contributes to serious environmental issues, including soil degradation, resource depletion, and an excessive dependence on landfilling. Introduction of new avenues towards addressing these issues has been facilitated by recent advancements in computer vision that have yielded efficient, self-sustaining, and prudent construction and demolition waste management. The objective of this study is to conduct a rigorous bibliometric analysis to examine the role of computer vision towards improved construction and demolition waste management. This study will identify the growth of the research area, top contributing sources, and collaboration patterns. A bibliometric approach was employed to evaluate 29 peer-reviewed journal articles and conference proceedings between 2015 and 2025. Organized keyword searching to obtain information from Scopus and Web of Science was employed. Manual analysis was done for identifying publication patterns, top sources, and country output. Keyword co-occurrence and collaboration network analysis were done using VOS viewer software. Although computer vision techniques, including semantic segmentation, object detection, and deep learning, have been promising in recycling and waste sorting automation, existing literature is fragmented. Most studies are focused on a single application, without the extraction of broader trends or collaborative dynamics. The paper provides an integrated corpus of knowledge for researchers, practitioners, and policymakers by presenting an exhaustive bibliometric analysis that documents the historical patterns of computer vision in construction and demolition waste research.

Keywords: *Bibliometric Analysis; Construction and Demolition Waste; Computer Vision; VOS viewer; Waste Management.*

1. INTRODUCTION

The construction industry is a significant contributor to global CO_2 emissions and the world's largest producer of waste (Driouache et al., 2024). Due to the accelerated global urbanisation, the annual production of construction and demolition waste (CDW) surpasses 10 billion tonnes, accounting for up to 40% of total solid waste (Prasad &

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Arashpour, 2025), rendering it the most common type of urban solid waste (Wu et al., 2024). Moreover, CDW is one of the most significant energy consumers during the construction process (Gong et al., 2024). Inadequate management and disposal of CDW may result in significant environmental deterioration, including soil pollution, resource depletion, excessive landfill usage, and increased greenhouse gas emissions (Prasad & Arashpour, 2024b). Therefore, the efficient and sustainable handling of CDW has become a significant concern for stakeholders and regulators.

Over the past years, Computer Vision (CV) has been an emerging technology, proving itself capable of resolving challenging issues related to the management of CDW. CV is a field that focuses on enabling machines to interpret and understand visual information from the world, primarily through the analysis of images and videos (Sirimewan et al., 2024). CV revolutionises the administration of CDW by automating, precisely, and efficiently, the processes of identifying, classifying, and separating waste (Sun & Gu, 2022). Advanced techniques such as semantic segmentation (Lu et al., 2022), object detection (Zhou et al., 2023), and image recognition (Dong et al., 2022) enable computer vision systems to interpret complex and mixed detritus structures in real time. This process of automation not only significantly improves the efficacy and accuracy of material recovery processes, but it also reduces the need for human labour, thereby preventing health and safety issues (Ji et al., 2024). Further to the authors, in conjunction with automation solutions and deep learning platforms, CV enables intelligent decision-making along waste sorting lines, resulting in optimal recycling rates, reduced processing costs, and sustainable construction practices.

Despite this technological enthusiasm, the literature illustrates a non-linear and fragmented progression in the development of research in CV applications for CDW. Several studies have examined single-use cases, including the classification of recyclable images (Dong et al., 2022), the detection of objects for robotic categorisation (Wang et al., 2024), and the use of semantic segmentation (Lu et al., 2022) in waste management. However, these contributions frequently continue in their isolation, lacking a comprehensive synthesis of research trends, development paths, and collaboration networks. Therefore, this paper conducts a thorough bibliometric analysis of scholarly research on CV applications in CDW management to address this critical gap. The objective of this study is to conduct a comprehensive review of the current literature on CV in CDW to establish a comprehensive foundation for the further development and dissemination of knowledge. As a result, the objectives of this study are the following: (i) to identify the evolutionary progression of the research field in CV in the CDW and (ii) to reveal the primary research themes in the field. The paper structure begins with an introduction to the study and followed by the research methodology and findings. The final section of the paper presents the conclusion of this research.

2. METHODOLOGY

This study employs a comprehensive methodological approach, applying bibliometric analysis to identify the sophisticated literature which is in relation to the CV in CDW management. According to (De-Oliveira et al., 2019) bibliometric analysis is a statistical instrument that is employed to represent the current state of scientific knowledge. It identifies research opportunities, trends, and voids by analysing citations, authors, institutions, countries, and journals, thereby facilitating the development of scientific projects. For the bibliometric analysis of this study, Scopus and Web of Science were

employed due to their extensive coverage of subjects and adequate quality. Additionally, they possess the largest abstract and citation database of peer-reviewed articles in comparison to the other databases (Wijewickrama, 2025). Following key terms were used as the search string with the intention of extracting as many relevant, high-quality papers as possible. ("computer vision" OR "machine vision" OR "AI vision" OR "artificial vision") AND ("construction waste" OR "demolition waste" OR "C&D waste" OR "construction and demolition waste" OR "construction debris"). These keywords were selected for their relevance to the context of this study, with the objective of presenting a comprehensive overview of the trends and patterns in the expanding research on CV in CDW. This syntax was subsequently employed to search for articles in the selected databases using the search query "Article title, Abstract, Keywords."

A total of 52 records were retrieved from Scopus (42), and Web of Science (10) during the initial search of databases. The data was screened thoroughly, and 9 duplicate entries were removed to preserve the originality of the data for future analysis. Journal articles and conference papers were included in the literature search while books, book chapters and similar were excluded. Further publication years were limited to 2015-2025. Figure 1 illustrates the systematic review process.

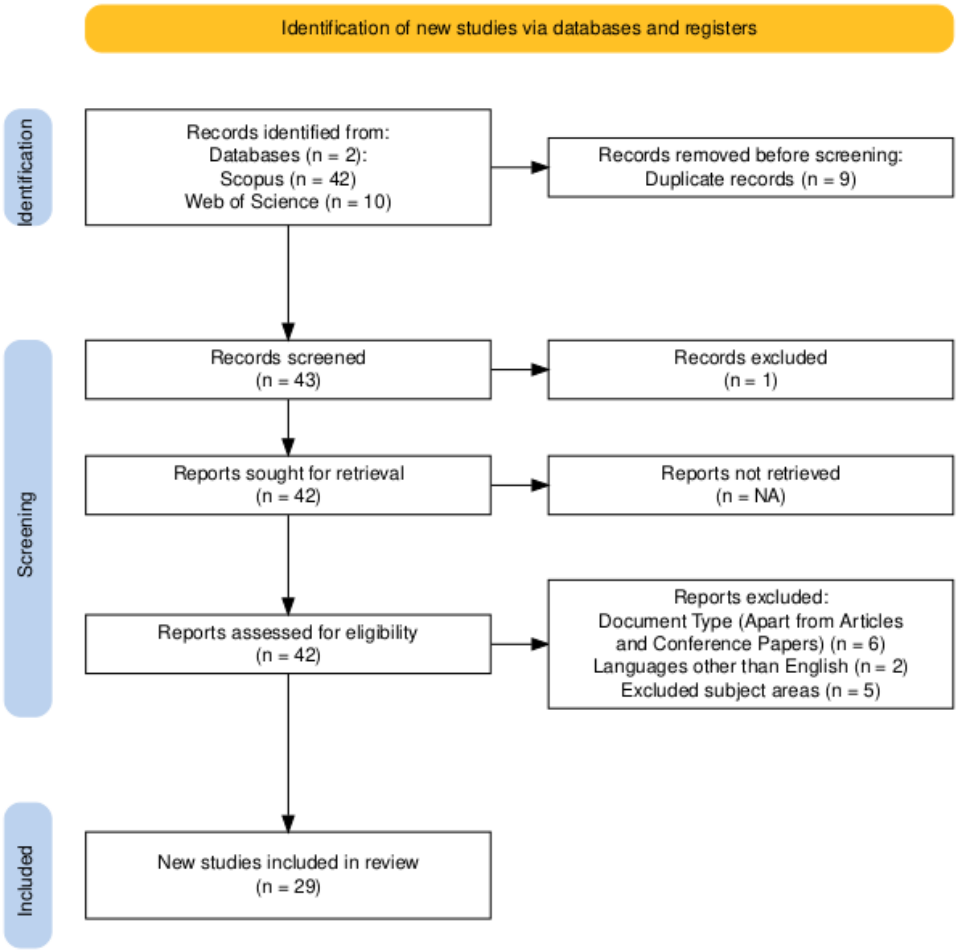


Figure 1: Systematic review process

Table 1: Inclusion and exclusion criteria

Criteria	Inclusion criteria	Exclusion criteria
Year	Publication years from 2015-2025	Publications before 2015
Document Type	Articles and Conference Papers	Books, Book chapters, reviews, notes, and editorial
Language	English language	Languages other than English
Subject Areas	Engineering, computer science, decision science, environmental science, energy, multidisciplinary	All the other subject areas

After applying the inclusion and exclusion criteria mentioned in Table 1, 29 papers from the search via databases were chosen for the analysis. This study conducted a variety of bibliometric studies using both manual techniques and VOS viewer software (version 1.6.20). The manual study concentrated on examining yearly publishing patterns and identifying the most impactful journals and conferences in the sector. Additionally, keyword co-occurrence analysis was conducted using VOS viewer to reveal significant research topics and emerging areas of interest. It also enabled the identification of prominent countries contributing to the field, as well as their patterns of international collaboration. These analyses jointly facilitated a qualitative interpretation of the bibliometric data, providing significant insights into the developing research landscape of CV in the context of CDW management.

3. RESULTS AND DISCUSSION

This section presents the results of the bibliometric analysis with relevant interpretations while addressing the objective of the study.

3.1 EVOLUTION OF PUBLICATIONS AND TOP CONTRIBUTING SOURCES

Figure 2 represents the yearly publication with related to the CV in CDW management from 2015-2025.

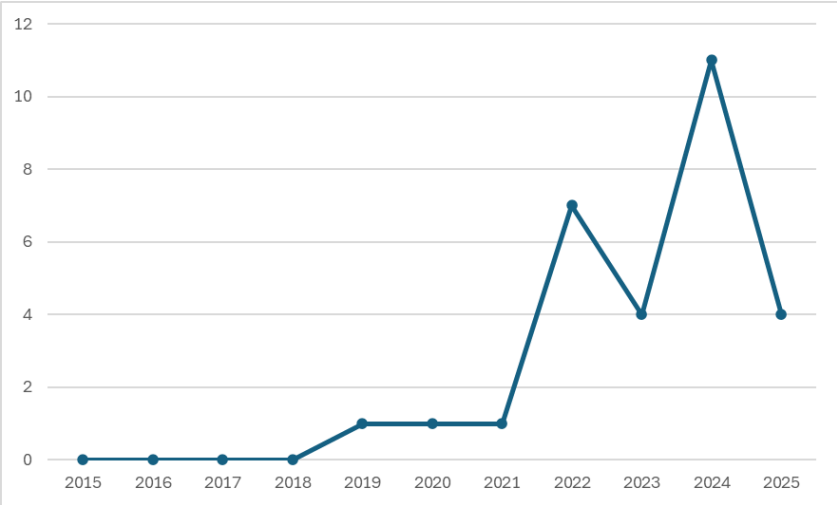


Figure 2: Publication distribution through 2015-2025

An analysis of research development patterns over the last 11 years was conducted based on the reviewed literature. According to Figure 2, there were no relevant publications concerning the chosen issue for the first four years of the specified time frame, 2015-2018. During 2019-2021 the publications remained constantly low. However, it is noticeable that there has been a gradual increase in research on computer vision in C&DW management over the past four years. This subject has attracted the attention of researchers, particularly in the years 2021–2022 increasing the publications from one to six, when it experienced a 600% rapid growth. In 2024, output reached a peak of 11 publications, exceeding the significant increase seen in 2022 by more than double. This indicates that computer vision has offered a practical solution to practical challenges in the administration of C&DW, including the generation, collection, transportation, and disposal stages. According to Wu et al. (2025), the rise in publications after 2021 is attributed to increased urbanisation, progress in intelligent technologies such as AI and computer vision, and an increasing focus on sustainable practices in the management of building and demolition waste, tackling complex difficulties within the industry. Given that merely four months have elapsed in 2025, and four publications have already been documented, it is reasonable to predict that the overall number of publications by year-end may near 12, contingent upon a steady publishing pace for the remaining months.

Table 2: Top contributing sources

Source Name	No of Articles
Journal of Environmental Management (Q1)	5
Resources, Conservation and Recycling (Q1)	5
Waste Management (Q1)	4
Sustainability (Switzerland) (Q2)	2
Buildings (Q2)	1

Table 2 shows the top five contributing sources of publication that have substantially contributed to advancing the area of study, publishing nearly 58% of the articles. The highest number of articles has been published by the Journal of Environmental Management (5) and Resources, Conservation and Recycling (5) followed by Waste Management (4). Even though most articles are published in journals related to waste management discipline, sources related to computer science and technology provide a substantial contribution to the knowledge in this area, providing a multidisciplinary nature to the concept.

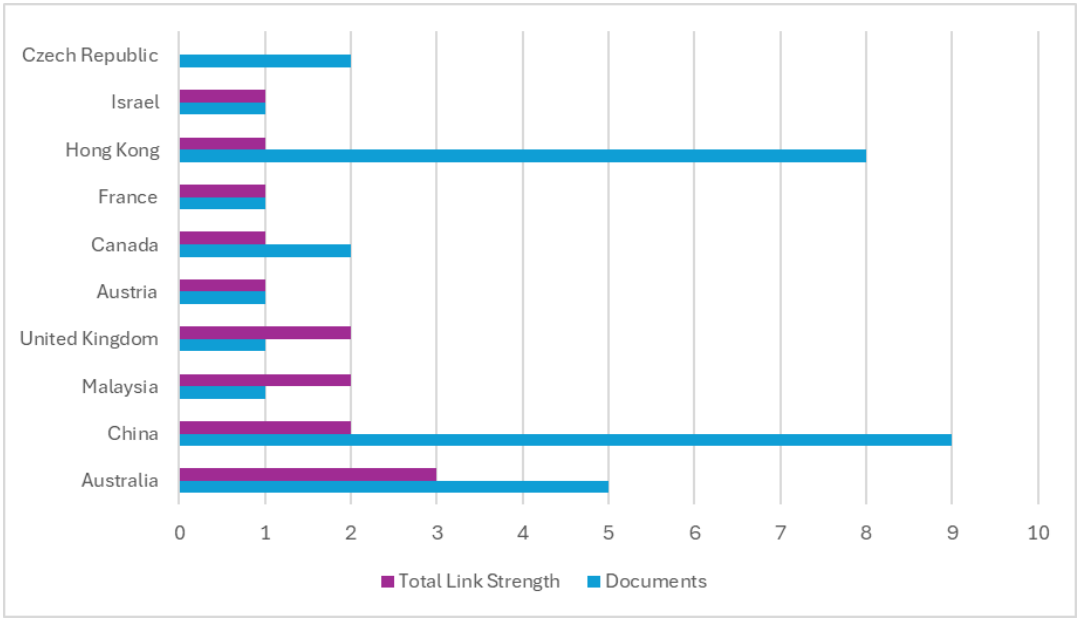
3.2 LEADING COUNTRIES UNDERTAKING RESEARCH ON CV IN CDW MANAGEMENT

Figure 3 indicates the top countries and their collaborative networks in advancing research on CV in CDW management. In Figure 3(a), circle sizes in the image likely indicate the quantity of publications, and lines between circles indicate the strength of collaborative ties. The analysis reveals Hong Kong and China as top contributors with 8 and 9 documents respectively, proving their high level of scholarly contribution. Australia also contributes at a high level with 5 documents and a link strength total of 3, proving an active contribution. Even so, countries like Austria, Canada, and France, though contributing fewer documents, prove the diversity of global interest in CV in CDW research. This difference indicates varying degrees of interaction and collaboration

between countries to advance CV research in the CDW management in the examination of collaborative activity across countries in the CV within the CDW research for the construction sector, Australia (total link strength of 3) and China (total link strength of 2) demonstrate the most significant level of collaborative linkages. The United Kingdom and Malaysia also demonstrate strong participation, with a link strength of 2, to signify their active engagement in international collaborative research efforts. While Hong Kong has a high document output of 8, a comparatively low link strength of 1 would suggest a more solo approach to research among its collaborative partners. Notably, developing nations such as Malaysia and China are well represented in collaborative research efforts. The presence of these countries along with developed nations such as Australia and the UK indicates an even contribution based on economic status. However, some countries with high scholarly contribution, such as the United States and Japan, indicate minimal cooperation (link strength of 0), indicating an independent research approach. This contrast highlights divergent strategies in CV in CDW research participation, with some nations focusing on partnerships while others focus on individual initiatives. The active co-operation of rising nations such as China and Malaysia, despite challenges, reflects their growing influence and role towards the advancement of CV research in the construction sector.



(a)



(b)

Figure 3: Representations of prominent countries and their collaborative networks in advancing research on CV in CDW management.

3.3 KEY WORD CO-OCCURRENCE

Figure 4 illustrates the results of the analysis conducted using VOS viewer software, with a minimum threshold of two occurrences for keywords. In the network, 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 the keywords. Furthermore, the closeness of nodes demonstrates the extent of linkage, with nearer nodes indicating more closely connected phrases. Keyword co-occurrence analysis is essential in academic research as it illustrates linkages between study subjects, uncovers temporal patterns, and assists researchers in comprehending the development of knowledge domains, hence informing future research paths (Zhao, 2024). Due to the associated search string, construction and demolition waste and computer vision appear as the most occurred keywords.

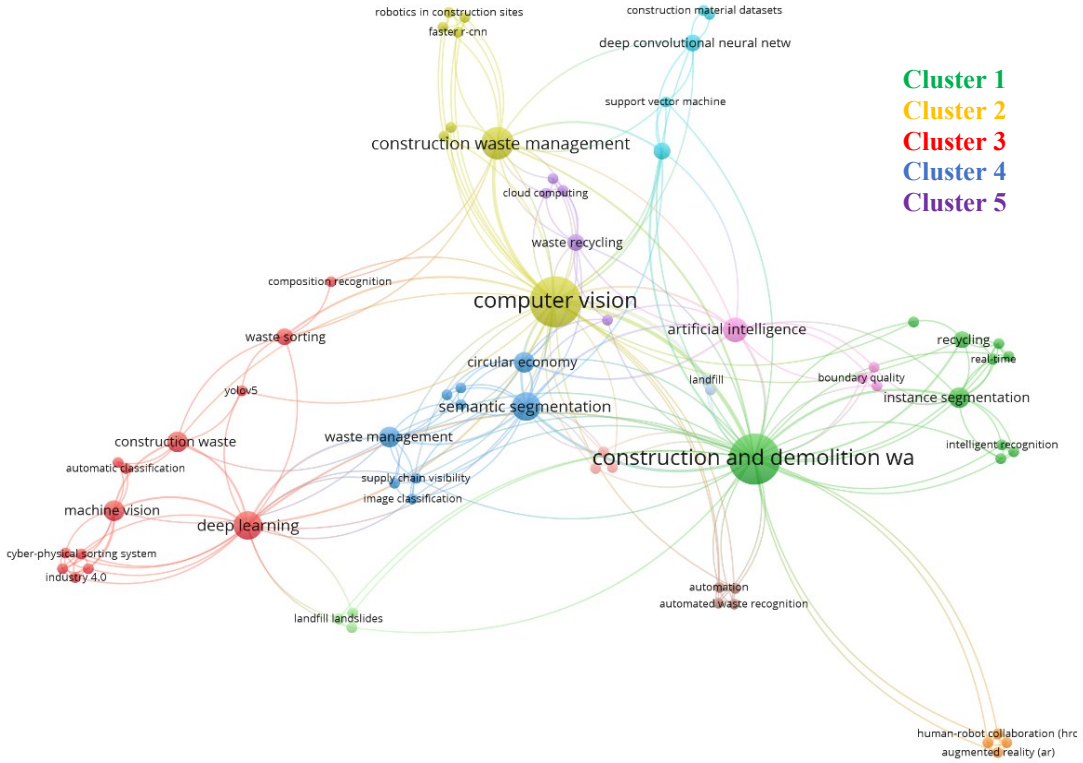


Figure 4: Key words co-occurrence analysis

The network visualisation identifies five separate research clusters in computer vision applications for construction waste management. Cluster 1 focuses on practical applications such as recycling, instance segmentation, and intelligent detection, establishing a domain-specific basis. Cluster 2 functions as a technology nexus, integrating visual analytic capabilities with waste management methodologies using technologies such as Faster R-CNN and computer vision. Cluster 3 includes sophisticated computational techniques such as YOLOv5, deep learning, automated classification, machine vision, Industry 4.0 and cyber-physical sorting systems designed for construction waste issues. Cluster 4 highlights image usage for accurate material identification across supply chains and a focus was gained in circular economy concept, whereas cluster 5 encompasses specialised neural architectures and machine learning

methodologies that facilitate these applications such as cloud computing and AI. Cross-cluster interaction is most intense at the intersections of technological advancement and practical application. The strong connections between deep learning and construction waste clusters illustrate the targeted optimisation of AI algorithms for waste material detection, while the linkages between computer vision and semantic segmentation indicate the integration of methodologies across AI fields. The integration of circular economy principles across several sectors emphasises the role of sustainability frameworks in encouraging technological innovation. Emerging domains such as human-robot cooperation and augmented reality at the network perimeter indicate new multidisciplinary frontiers where physical and digital technology intersect. The collaborative patterns illustrate a research ecosystem in which computer researchers, environmental engineers, and construction management specialists collaborate to create advanced waste management solutions that integrate visual intelligence with domain knowledge.

3.4 APPLICATION OF CV IN CDW MANAGEMENT

The CDW management faces several challenges due to waste volume and environmental impact (Sirimewan et al., 2024) such as illegal disposal, costly recycling, transportation challenges, and inadequate treatment facilities (Mager et al., 2025). Further to the author, the enforcement of policy directives such as the European Union's Waste Framework Directive is obstructed by inadequate resources and inappropriate attitudes towards products derived from recycled materials. The workers' health is also at risk when manually segregating, which is why there is an inclination to automate the process. Additionally, manual sorting methods are labour-intensive and inefficient (Chen et al., 2023) and these complexities highlight the importance of automating waste recognition and handling processes and technological advancements like CV and AI.

Recent advancements in deep learning and CV have revolutionized waste management, particularly in the identification, classification, and segregation of CDW (Wang et al., 2020; Yong et al., 2023). Advanced architectures like convolutional neural networks (CNNs), Mask R-CNN, U-Net, and DeepLabv3+ enable highly accurate waste detection and segmentation, significantly improving sorting and recycling processes (Sirimewan et al., 2024). These technologies have been successfully applied in various specialized applications, including semantic segmentation models like DeepLabv3+ and PromSeg-Waste (Sirimewan et al., 2024; Wang et al., 2020) that provide pixel-level accuracy for material identification, hybrid optical-physical systems (Chen et al., 2021) that enhance composition analysis in material recovery facilities, and real-time detection systems using YOLOv5 and vision transformers (Chen et al., 2022; Yong et al., 2023) that facilitate instant trash classification. Further innovations such as instance segmentation combined with Simultaneous Localization and Mapping (SLAM) technologies (Dong et al., 2025; Wang et al., 2020) improve trash detection in complex environments, while RGB-D data integration enhances object boundary detection for robotic sorting systems (Prasad & Arashpour, 2025). Together, these technological advancements reduce reliance on manual sorting, gradually improve recycling efficiency, and support more sustainable waste management practices. When integrated with Industry 4.0 principles, the integration of automated sorting systems, enhanced by artificial intelligence and machine vision, allows for efficient classification and recycling of materials, thereby reducing waste and promoting resource recovery (Konstantinidis et al., 2023; Prasad & Arashpour, 2024a). These systems, such as Cyber-Physical Sorting Systems (CPSS), utilize multi-

spectral imaging and deep learning to improve the accuracy of material identification, which is crucial for effective recycling (Konstantinidis et al., 2023). Furthermore, the application of Industry 4.0 principles facilitates the development of intelligent waste management solutions that can adapt to various waste types, ultimately supporting sustainable practices and reducing the environmental impact of CDW activities (Driouache et al., 2024; Nežerka et al., 2024). Table 3 demonstrates a summary of the selected articles for the study.

Table 3: Summary of the literature findings

Author	Type of model used	Usage	Dataset Size	Accuracy	Waste Type
Sirimewan et al., 2024	PromSeg-Waste model	Waste segmentation	5277 image-mask pairs corresponding to ten distinct waste classes	9% increase compared to the existing SOTA model	Concrete, Fill dirt, Wood, Hard plastic, Soft plastic, Steel, Fabric, Cardboard, Plasterboard, Glass
Konstantinidis et al., 2023	Cyber-Physical Sorting System (CPSS)	use of multi-sensor systems for real-time material classification and sorting	171 images, with 41.5% being plastic and 27.5% metal of urban-based samples from commercially available materials	80% detection accuracy	Glass, Metal, Paper, Plastic
Nežerka et al., 2024	Gradient boosting, multi-layer perception, Convolutional neural network	Waste recognition and sorting	2664 nos. of 1920 × 1280 px images of ∼30–250 mm fragments distance of about 70 cm	GB-92.3%; MLP-91.3%; CNN-85.9%	Light-coloured Aerated Autoclaved Concrete (AAC), Asphalt conglomerates, Ceramics (Roof Tiles and Bricks), Concrete
Dong et al., 2025	17 models including BEiT; DeepLab V3; OCRNet; FastFCN etc	Waste sorting	4396 common local construction waste images	Highest accuracy BEiT model with 58.31% accuracy	Rock, Gravel, Earth, Packaging; Wood, Non-inter; Mixed
Zhou et al., 2023	YOLOv5	Object detection and waste sorting	3046 construction waste images	0.9480 precision on the test dataset	Brick, Wood, Stone, Plastic

Author	Type of model used	Usage	Dataset Size	Accuracy	Waste Type
Lu et al., 2022	DeepLabv3+	Semantic segmentation approach for CW composition recognition	5,366 images	mean Intersection over Union (mIoU) of 0.56 for segmenting construction waste materials	Inert and non-inert waste
Mager et al., 2025	Segment Anything Model (SAM) and ResNet-50	Aerial image analysis for illegal construction waste	46,000+ manually labelled masks	86% (area classification), 67% (mask classification)	Mixed waste
Chen et al., 2022	Monocular vision-based volume estimation algorithm	Automatic quantification of material volumes	2,914 waste truckloads analyzed	Relative error: 0.065 (bucket size), 0.169 (material-level volume); Processing time: 3.3s/image	Rock, Gravel, Earth, Packaging, Wood, Non-inter, Mixed
Dong et al., 2022	Boundary-aware Transformer (BAT) with cascade decoder and edge refinement	Semantic segmentation of different waste materials in cluttered mixtures	5366 photos of highly cluttered construction waste mixtures	69.19% Mean Accuracy	Rock, Gravel, Earth, Packaging, Wood, Non-inter, Mixed
Prasad & Arashpour, 2025	ShARP-WasteSeg: Shape-Aware Real-Time Precise Waste Segmentation (multi-modal with RGB + depth)	Real-time instance segmentation using boundary and shape info for cluttered CDW objects	3568 high-definition colour and depth images	ShARP-WasteSeg improved Mask Average Precision (AP) by 7.91%, and the boundary-sensitive Boundary Average Precision by a significant 11.44%	Aggregate, Cardboard, Hard plastic (HDPE), Metal, Soft plastic (LDPE), Timber
Yong et al., 2023	DeepLabV3+	Semantic segmentation of remote sensing	Case study in Shenzhen (52 landfills identified)	96.30% accuracy	Landfills

Author	Type of model used	Usage	Dataset Size	Accuracy	Waste Type
		imagery to detect CDW landfills			
Wang et al., 2024	Pixel-level recognition model with edge (YOLO-Tiny) & cloud computing integration (YOLACT)	Real-time automated recognition and instance segmentation for robotic waste sorting	Not specified	90.81% accuracy (edge), 93.2% instance segmentation accuracy (cloud)	Not specified
Prasad & Arashpour, 2024a	RGB-DL architecture with efficient depth fusion strategy	Intelligent segmentation of valuable recyclables from cluttered CDW streams	3,500+ RGB & depth images; 160,000+ labeled object instances	+13% segmentation accuracy	Aggregate, Cardboard, Hard plastic (HDPE), Metal, Soft plastic (LDPE), Timber
Prasad & Arashpour, 2024b	9 models including YOLACT++; CenterMask; CondInst; SOLOv2; RTMDet-Ins etc	Accurate, fast localization and segmentation of CDW recyclables	Not specified	+12.9% segmentation performance; +68% correct mask predictions	Aggregate, Cardboard, Hard plastic (HDPE), Metal, Soft plastic (LDPE), Timber
Driouache et al., 2024	Semantic segmentation DeepLabv3+	Identify and classify CDW materials in dump trucks before landfill entry	From the month of February 2022 to May 2022, 806 images were collected	accuracy: 99.0%; Homogeneity: 94.8%	Block, Gravel, Soil, Metal

4. CONCLUSION

Sustainable CDW management is crucial due to the fact that CDW accounts for up to 40% of the total solid waste produced worldwide and poses over 10 billion tonnes of waste annually. Even though the integration of computer vision (CV) in CDW processing in the form of automation of waste identification, classification, and categorisation offers potential solutions that can lead to increased recycling efficiency and a reduced environmental burden. The growth of co-related studies was prompted by global sustainability objectives and artificial intelligence in 2021, as evidenced by bibliometric metrics. China, Hong Kong, and Australia are among the countries that have been at the forefront of academic production and collaboration on an international scale. Cluster and keyword analysis reveal five critical research areas, including semantic segmentation, circular economy convergence, cyber-physical systems, and deep learning. The

YOLOv5, Mask R-CNN, and DeepLabv3+ models were used to demonstrate real-world applications of high-precision material classification and identification. In the meanwhile, the implementation of Industry 4.0 technologies, including cyber-physical systems, has enabled the development of scalable and intelligent waste management facilities. Future research should further investigate human-CV collaboration systems and adaptable models based on transfer learning. Further, the incorporation of CV with life cycle assessment methods may improve its environmental benefits, and research on its economic feasibility will enable it to be applied to a broader range of applications. In order to ensure the equitable and effective integration of CV in CDW management, it is also necessary to develop ethical artificial intelligence and smart policy-supporting tools. In conclusion, computer vision has the potential to transform CDW management by enhancing its sustainability, intelligence, and efficiency, which is consistent with the objectives of the circular economy and the global environmental community.

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A CONCEPTUAL FRAMEWORK FOR CAPACITY BUILDING IN PHYSICAL ASSET RESILIENCE

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ABSTRACT

Physical assets, defined as tangible resources with intrinsic value, play a major role in organisations. The concept of Physical Asset Resilience (PAR) is a physical asset's ability to prepare for, absorb, recover from, and adapt to disruptions. The resilience of physical assets is increasingly recognised as important for maintaining operational continuity and allowing long-term sustainability in the face of disruptions within the organisation. For capacity building in PAR required to develop or strengthen the four capacity building elements, including skills, resources, policies, and practices needed to enhance physical asset resilience capacities. However, the extant literature does not provide a clear picture of how capacity-building elements interactively contribute to capacity building in the PAR or how organisations currently approach PAR. Accordingly, by adopting a comprehensive literature review, this study proposes a conceptual framework for capacity building in PAR, focusing on four capacities: anticipative, absorptive, restorative, and adaptive, with their sub-elements. For instance, sub-elements in policies include the maintenance policy, communication policy, practices, including conducting physical assets risk assessments, resources, including backups, physical assets, financial resources, and finally, skills, are technical skills, maintenance skills. This proposed framework provides a structured foundation for future researchers who are in the field of PAR, and for practitioners, offering guidance for improving PAR in organisations.

Keywords: *Capacity Building; Physical Asset; Physical Asset Resilience; Physical Asset Resilience Capacity.*

1. INTRODUCTION

Physical Asset Resilience (PAR) is becoming a popular pillar of organisations. The resilience of physical assets is significant for ensuring continuous operations and minimising the impact of different disruptions, whether the disruption has arisen internally or externally (Aruväli et al., 2023). PAR is characterised by four capacities: anticipative capacity, absorptive capacity, adaptive capacity, and restorative capacity. Capacity building in PAR can be identified as a promising approach for developing these

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capacities. In the context of PAR, capacity building refers to the development or strengthening of the skills, resources, policies, and practices to enhance PAR capacities. Despite the growing recognition of PAR's importance, the role of capacity building for the four PAR capacities remains underexplored. Existing literature does not clearly understand how skills, resources, policies, and practices contribute to strengthening PAR in business organisations. Therefore, this paper addresses this gap by proposing a conceptual framework with capacity building and four capacities of PAR. The paper is structured as follows. The next section discusses the research method, while the third and fourth sections present a thorough review of the literature and the development of the conceptual framework, respectively. Finally, the paper concludes with implications of the findings and future directions of the study.

2. RESEARCH METHODOLOGY

This study adopts a literature review to explore the existing studies related to PAR and capacity building. A literature review serves as a foundation for understanding prior work, identifying research gaps, and synthesising key concepts (Saunders et al., 2009). This study used a non-systematic literature review, which allows flexible integration of diverse studies to support conceptual development (Lilley et al., 2020). Compared to the structured systematic reviews (Snyder, 2019; Lame, 2019), this method is more suitable for exploratory research while improving the conceptual insights needed for framework development. The review focused on literature from the past 10–15 years to include both foundational and recent insights. Sources were selected based on their relevance to capacity building and physical asset resilience. It was based on a structured search of academic databases such as Scopus, ScienceDirect, along with professional platforms like Google Scholar and ResearchGate for supplementary sources. The sources included peer-reviewed journal articles, conference papers, and industry reports. The following search string was used to guide the review. "Physical Asset Resilience", “Capacity Building Elements”, “Capacity Building in PAR”. In addition, a manual content analysis technique was employed to analyse and synthesise the literature relevant to the development of the conceptual framework. The process of development of the conceptual framework for capacity building in PAR involved: (1) identifying key concepts related to PAR and capacity building from the literature, (2) identifying the relationships between these concepts, (3) organising the concepts and their relationships into a coherent conceptual structure and (4) developing the conceptual framework in a way that capacity building in PAR is easily understood. Hence, it developed solely through literature synthesis and is intended to guide future research.

3. LITERATURE REVIEW

3.1 PHYSICAL ASSET RESILIENCE

The word resilience originated from the word “resiliere”, a Latin word that denotes the bounce back (Hosseini et al., 2016; Rose, 2009). Wu et al. (2013) defined resilience as the ability to withstand in the face of disruptions, whereas Fleming and Ledogar (2008) mentioned it as the process and outcome of successfully adapting to disruptions. A physical asset is a tangible item with economic or operational value to an organisation, such as equipment, machinery, tools, infrastructure, or inventory (Hayes, 2022). These assets form the backbone of organisation operations, supporting efficiency, productivity,

and organisational success (Schuman & Brent, 2005; Trojanowski, 2015). However, physical assets are also faced with various disruptions, such as breakdowns, natural disasters, deterioration, operational disruptions, and unexpected external conditions (Gardoni et al., 2021; Heckmann et al., 2015; Linkov et al., 2013), and therefore, PAR has become a fundamental component in a business organisation's operations (Madni et al., 2020). The concept of PAR has been defined by researchers from different perspectives, reflecting several ranges of characteristics. The primary focus of the PAR is emphasising the ability of physical assets to withstand disruptions. For instance, a return to the previously designed condition or state of the physical assets after a disruption can be made by PAR (Norris et al., 2007). PAR refers to the ability of these systems to withstand, adapt to, and recover from disruptions, including natural disasters and other adverse events. In contrast, Ayyub (2013) demonstrated that the "PAR notionally means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions". These retrievals, PAR, is beyond the bounce back or return to their original state. A broader perspective incorporates preparedness and adaptability. On the other hand, recognising that PAR involves absorbing potential disruptions. Further, highlights the importance of not only withstanding disruptions but also needing efficient restoration of functionality. Hence, the above definitions highlight the common and distinct characteristics of PAR, which can be defined as the capacity of a physical asset to anticipate, absorb, recover, and adapt from disruptions. PAR helps organisations to maintain operations continuously even within disruptive conditions. Correspondingly, PAR allows organisations to adapt to external disruptions like economic fluctuations, ensuring that assets continue to support operational continuity. Besides, PAR can lead to financial achievements (Beemsterboer, 2023). Simultaneously, resilient physical assets can recover more quickly after disruptions, minimising downtime and associated financial losses (Coffee, 2019). On the other hand, resilient physical assets can enhance the overall value of physical assets, thus, organisations often willing to pay a premium for physical assets that are less likely to incur damage from disruptions, thereby increasing the market value of these physical assets (Coffee, 2019). Monitoring physical assets before disruptions and understanding their impacts helps identify vulnerabilities and inform measures for improving resilience (Asia Pacific Economic Cooperation [APEC], 2009). Accordingly, by understanding the potential risks, business organisations can introduce mitigation strategies such as maintenance, repair, retrofitting, and recovery activities (Gardoni et al., 2021; Silva et al., 2024). Similarly, PAR also facilitates effective risk management by supporting the implementation of appropriate mitigation techniques. These actions reduce the vulnerability of physical assets to future disruptions and enhance their ability to recover from disruptions (Gardoni et al., 2021). On the other hand, organisations increasingly needed to adhere to standards and regulations based on physical asset resilience (Costella et al., 2017). Therefore, by incorporating resilience into the physical asset management, organisations can ensure compliance with these regulations while also indicating transparency and accountability to the organisation's stakeholders.

3.2 PHYSICAL ASSET RESILIENCE CAPACITY OF AN ORGANISATION

According to Brown et al. (2001), capacity is the ability to obtain the stated objectives. Simultaneously, capacity can be defined as the combination of resources, skills, and abilities that allow organisations to effectively respond to and recover from disruptions (Albright & Crow, 2021). Further, it is an exclusive concept (Brown et al., 2001).

However, prior research has identified and explored various capacities associated with PAR, highlighting their significance in the ability of assets to withstand, adapt, absorb, and recover from disruptions (Braynt, 2021; Manyena et al., 2019). As mentioned by Yarveisy et al. (2020), absorptive, adaptive, and restorative capacities are the capacities associated with PAR. In addition to these capacities, Kozine et al. (2018) noted that anticipative, adaptive, absorptive, and restorative capacities achieve PAR. Simultaneously, Rathnayaka et al. (2024) demonstrated that anticipative or planning capacity is necessary for PAR with the other capacities. A thorough probe into the available literature found four main capacities which determine the PAR of an organisation. In other words, the PAR capacity of an organisation is composed of four capacities, which can be named as anticipative capacity, absorptive capacity, restorative capacity, and adaptive capacity. According to Kozine et al. (2018), anticipative capacity refers to the capacity of physical assets to foresee potential disruptions and provide proactive measures to reduce their impacts. Anticipative capacity provides preparedness for future disruptions, including environmental disruptions. As Vugrin and Camphouse (2011) mentioned, absorptive capacity is the extent to which a system can absorb shocks from different disruptions. On the other hand, 20 it refers to the capability or inherent ability of the system to minimise the negative impacts caused by disruptions. Further, absorptive capacity is the degree to which a system can absorb the negative impact of system disturbances and minimise consequences with much effort (Richter, 2015). According to Mottahedi et al. (2021), restorative capacity is the degree to which the system can effectively restore its damaged performance. Similarly, this capacity incorporates the vital ability to restore complete functionality efficiently and effectively based on disruptions (Rahi, 2019; Yang et al., 2023). Finally, adaptive capacity expresses the ability to adapt (Engle, 2011). Adaptive capacity is considered the ability to quickly and effectively adapt to changing conditions and respond to disruptions that could impact its functionality (Comes & Van De Walle, 2014; Kim et al., 2024).

3.3 CAPACITY BUILDING IN PHYSICAL ASSET RESILIENCE

Capacity building is a concept that rose to provide practices, policies, and thoughts for the management of disruptions (Tadele & Manyena, 2009). As mentioned by Brown et al. (2001), capacity building is an ongoing process that is continued through several levels, including individuals, groups, and organisations, to improve their capabilities to identify and achieve improvement obstacles (Brown et al., 2001). Therefore, to perform major activities effectively and to enhance and strengthen over time, capacity building provides the evidence-based process of building abilities of any context (Brown et al., 2001). Specifically, capacity building strengthens an organisation's ability to achieve its objectives by developing effective practices, resources, policies, and skills (Lammert et al., 2015). Through reviewing existing literature, four key elements of capacity building have been identified. They are policies, practices, resources, and skills. Accordingly, capacity building in the context of PAR refers to the systematic process of developing or strengthening the skills, resources, policies, and practices needed to enhance physical assets' ability to anticipate, absorb, adapt to, and recover from disruptions. The following explains how these elements collectively contribute to capacity building in the PAR in an organisation.

3.3.1 Establishing Policies for Capacity Building in PAR

As mentioned by Moteff (2013), policy is a deliberate combination of principles to guide decisions and achieve rational outcomes, serving as a foundation for making consistent decisions and can be applied in various contexts. Simultaneously, in this context, policies underlie the other three elements. i.e., practices, resources, and skills depend upon the organisation's PAR policy. Accordingly, regular maintenance helps prevent asset failures by addressing potential issues before they become major problems (Organisation for Economic Co-operation and Development [OECD], 2021). However, this can be allowed through the maintenance policy, and it ensures that physical assets are regularly maintained to prevent disruptions and improve their ability to withstand disruptions. The maintenance policy incorporates the preventive and predictive maintenance strategies that can significantly improve PAR (Aspell, 2024). Regularly scheduled maintenance tasks based on manufacturer recommendations and organisation standards help maintain physical asset functionality and prevent unexpected failures. On the other hand, utilising data analytics and technology can help to forecast when maintenance should occur, preventing failures before they happen (Aspell, 2024). Another significant aspect of policies is employee training. This policy should be developed to allow employees to be trained in all aspects of the physical assets, including emergency procedures, asset management, and business continuity planning (Tadele & Manyena, 2009). For instance, regular fire drills and emergency preparedness training should be incorporated into the organisation's overall training policy, certifying that employees are familiar with procedures for managing various types of disruptions (Robertson et al., 2015). Thus, this revealed, these policies should outline the frequency of training and the types of scenarios that employees should be prepared. On the other hand, by having physical assets procedures for disruptions management and a clear plan in place, business organisations can minimise downtime and ensure business continuity, which is essential for maintaining resilience (Australian Capital Territory [ACT], 2024). While a disruption management policy is important, effective communication is equally essential for enabling PAR. It facilitates coordination, risk management, and stakeholder engagement throughout the resilience-building process. This revealed the requirement of the communication policy. It not only affects immediate response but also supports long-term restorative efforts. For instance, assessing the effectiveness of communication precautions post-event can inform future improvements and adaptations, ensuring that lessons learned are integrated into ongoing PAR planning. Therefore, a robust communication policy is essential in this context. In addition, worker preparation involves maintaining physical assets effectively, ensuring they can withstand and recover from disruption (Robertson et al., 2015). Therefore, this preparation can be introduced as a policy in PAR. The operator preparation policy is an essential aspect of a commitment to continuous improvement. Organisations must regularly review their resilience strategies, learn from past disruptions, and adapt their approaches based on new insights and emerging disruptions.

3.3.2 Implementing Practices for Capacity Building in PAR

Practice is generally referred to as repeated activity for acquiring or maintaining proficiency in it (Esmalian et al., 2022). It includes the working methods and approaches that improve the efficiency and effectiveness of an organisation (Luenendonk, 2017). According to Bukowski and Werbińska-Wojciechowska (2020), the implementation of maintenance protocols aimed at ensuring the continued functionality, efficiency, and

safety of physical assets throughout their lifecycle and having the proper maintenance recovery approaches can enhance resilience in the physical asset. This highlights that improving the maintainability of physical assets can contribute to it. Continuous monitoring can detect potential disruptions before they increase into severe failures or other interruptions. However, by analysing real-time data, predictive maintenance can be implemented to address disruptions before they cause disruptions. Monitoring physical assets before disruptions and understanding their impacts helps identify vulnerabilities and inform measures for improving resilience (APEC, 2009). Thus, conducting post-event damage assessment as a practice helps to take recovery planning by highlighting areas where physical assets can be restored with enhanced resilience characteristics. On the other hand, post-event damage assessments for physical assets involve rapid and comprehensive evaluations of disruption impacts on infrastructure, buildings, and critical physical assets to inform recovery and disruption impact reduction. These assessments combine hazard modelling, exposure data, structural vulnerability analysis, and advanced technologies to quantify damage and prioritise reconstruction (Johnston et al., 2024). The development and implementation of standard operating procedures (SOPs) for routine operations, maintenance, and emergency response are essential in allowing consistent, efficient, and safe practices (Harwood & Nieto-Gomez, 2017). Consequently, it provides structured processes for maintaining and repairing physical assets, as well as responding to disruptions, including natural disasters, fires, and physical asset failures (Harwood & Nieto-Gomez, 2017). According to Borg et al. (2022), allowing staff to be well-trained in the SOPs and emergency response protocols allows quicker recovery from disruptions. The regular conducting of fire drills and ensuring staff are trained in emergency procedures helps maintain preparedness for all disruptions (Robertson et al., 2015). On the other hand, Tracey et al. (2017) pointed out that business continuity planning allows an organisation can continue to operate their physical assets during and after disruptions. Further, it emphasised, organisations to identify and map their physical assets, which is essential for understanding what resources are available during a disruption. This asset-mapping process helps organisations recognise the strengths they possess. In addition to these practices, physical asset risk assessments help identify vulnerabilities in physical assets, allowing for the mitigation of the impacts of disruptions (Klerk, 2024). Along with conducting risk assessments, it supports continuous development by aligning with goals that focus on building resilience capacity in physical asset investments (Cassottana, 2023). Hence, conducting the physical assets risk assessments is essential for this context. On the other hand, business organisations are concerned about the continuous business process within the organisation (Zhang et al., 2021). Therefore, companies need to require their physical assets to be properly repaired. So that they can optimise the inventory of spare parts. Further, an optimised inventory spare parts system ensures that critical spare parts are readily available, consequently reducing unplanned downtime and associated costs (Ajayat, 2024). Another one is scenario planning for disruptions. As pointed out by Bullis (2024), scenario planning is a strategic practice that enhances resilience by preparing for potential future disruptions. For instance, by developing strategies for various scenarios, organisations can enhance their resilience and adaptability, ensuring they remain operational even during disruptions (Harris, 2024). Further, this can involve exploring a range of potential disruptions in the future. Utilising this practice, organisations can create flexible plans that allow them to respond effectively to unforeseen disruptions (Skemp et al., 2020). Hence, this adaptability is essential for this context.

3.3.3 Enhancing Resources for Capacity Building in PAR

Resources refer to anything that can be available within a community, society, or organisation that can be utilised to achieve specific goals related to a particular field (Dharmadasa et al., 2023). One key resource in building PAR is having a backup physical asset that can maintain the operation even in disruptive conditions (Alberti, 1999; Kusumastuti et al., 2014; Pant et al., 2014). Consequently, by having physical backups, business organisations can minimise downtime and the impact of unexpected disruptions. This helps in safeguarding against potential financial losses associated with physical asset breakdowns (Crudu, 2024). Simultaneously, this is essential for maintaining service delivery and customer trust (Todd, 2024). Warehouses and evacuation centres are also important resources. Warehouses serve as storage facilities for major spare parts and backup physical assets, ensuring that essential resources are readily available when needed (Ciriaco & Wong, 2022). On the other hand, during disruptions, evacuation centres provide safeguarding personnel and shelter, and supplies. Similarly, supportive equipment and vehicles are also significant for physical asset resilience. Reliable, supportive equipment and vehicles for maintaining service delivery, as they support operations and confirm the smooth functioning of major physical assets. For instance, vehicles provide mobility during disruptions, allowing organisations to move resources efficiently. Another one is that the incorporation of new technology can allow more advanced users to access physical assets. Physical asset monitoring systems, which include IoT devices and sensors, provide real-time data on the condition and performance of physical assets. For instance, IoT sensors play a key role in real-time physical asset condition monitoring, predictive maintenance, and the reduction of risk from unexpected failures. On the other hand, simulation and modelling Platforms, including a physical assets risk model network, allow for wide effects of disaster-induced failures and post-disaster restoration. Renger et al. (2002) noted that Geographic Information Systems (GIS) provide visualisation of disruption impacts and resilience challenges, and support to scenario analysis and strategic planning for disaster preparedness and recovery. In addition, adequate financial resources increase physical asset performance against disruptions. Besides, many business organisations face a backlog of deferred maintenance, which can increase vulnerabilities to disruptions. However, investing in resilience is critical to prevent minor issues from escalating into significant problems that compromise physical asset integrity. This retrieval, developing comprehensive capital plans that prioritise resilience, can be more cost-effective than reactive measures post-disaster. It is important to separate them into specific categories. Firstly, capital investments refer to long-term financial allocations aimed at upgrading or acquiring physical assets with enhanced resilience features, such as climate-proof physical assets or sensor-based monitoring systems (Corti et al., 2022). Secondly, operational budgets support routine maintenance activities and daily operational needs that contribute to resilience through consistent performance and early problem detection (Karamouz & Hojjat-Ansari, 2020). Thirdly, contingency funds are significant for answering sudden disruptions, allowing for rapid repairs or temporary replacements to maintain continuity. In addition, pre-arranged financial mechanisms, including insurance, reserve funds, or pre-approved emergency financing, allow organisations to act swiftly when early warning systems indicate a potential disruption (Azadegan et al., 2021). Moreover, reliable physical assets are a crucial resource for enhancing PAR (OECD, 2024). Along with this, reliable physical assets allow operations to continue smoothly, even in the face of disruptions such as natural disasters or mechanical breakdowns. On the other hand, this

resource is important for maintaining stakeholder trust during turbulent situations (Beemboster, 2023). Another significant resource is a skilled workforce. According to Sam (2021), a skilled workforce ensures timely inspection, maintenance, and repair activities, which are critical for managing physical asset life and mitigating risks. The training and development of this workforce are significant for building capacity in PAR (Madrigano et al., 2017). The workers need to be regularly trained on the latest practices within their work and new technologies, and emergency procedures (Madrigano et al., 2017). On the other hand, leadership and governance structures affect fostering a skilled workforce by setting clear policies, providing ongoing support, and aligning human resources with the organisation's strategic goals in asset management (Helmrich & Chester, 2022). Consequently, they ensure that the workforce is adequately prepared for both routine operations and emergency response (Helmrich & Chester, 2022). In addition to internal resources, external resources are involved in this context. One such major external resource is having a proper supply chain, which ensures the continuity of material, equipment, and service flows required for physical asset resileince (Trucco et al., 2018). Additionally, the stakeholder network includes partnerships with local authorities, emergency responders, service contractors, community groups, and professional bodies that provide valuable resources such as technical expertise, regulatory support, and emergency coordination (Li & Ji, 2021). This revealed, these networks strengthen PAR by facilitating information sharing, mutual aid, and coordinated responses.

3.3.4 Enhancing Skills for Capacity Building in PAR

According to Perera et al. (2017), skills are the abilities that individuals or groups possess. Further emphasised that they significantly contributed to overcoming the desired outcomes effectively. Skills refer to the abilities and expertise that people can build through knowledge, training, and experience. Particularity in the context of PAR requires a combination of technical skills that can support human behaviour and physical assets (Thomas et al., 2019). For instance, having familiarity with specific tools and technologies that support resilience, such as simulation software and monitoring systems, is important (Woods, 2015). Thus, these skills can help in modelling scenarios and evaluating the resilience of physical assets. Similarly, as a technical skill, utilising Internet of Things (IoT) sensors allows continuous monitoring of physical asset conditions (Klerk, 2024). Therefore, these skills allow for proactive maintenance and rapid response to potential disruptions, significantly enhancing PAR during disruptions. On the other hand, community engagement skills require engaging with local parties to understand their needs and involve them in planning and decision-making processes. These include skills in public outreach, education, and participatory

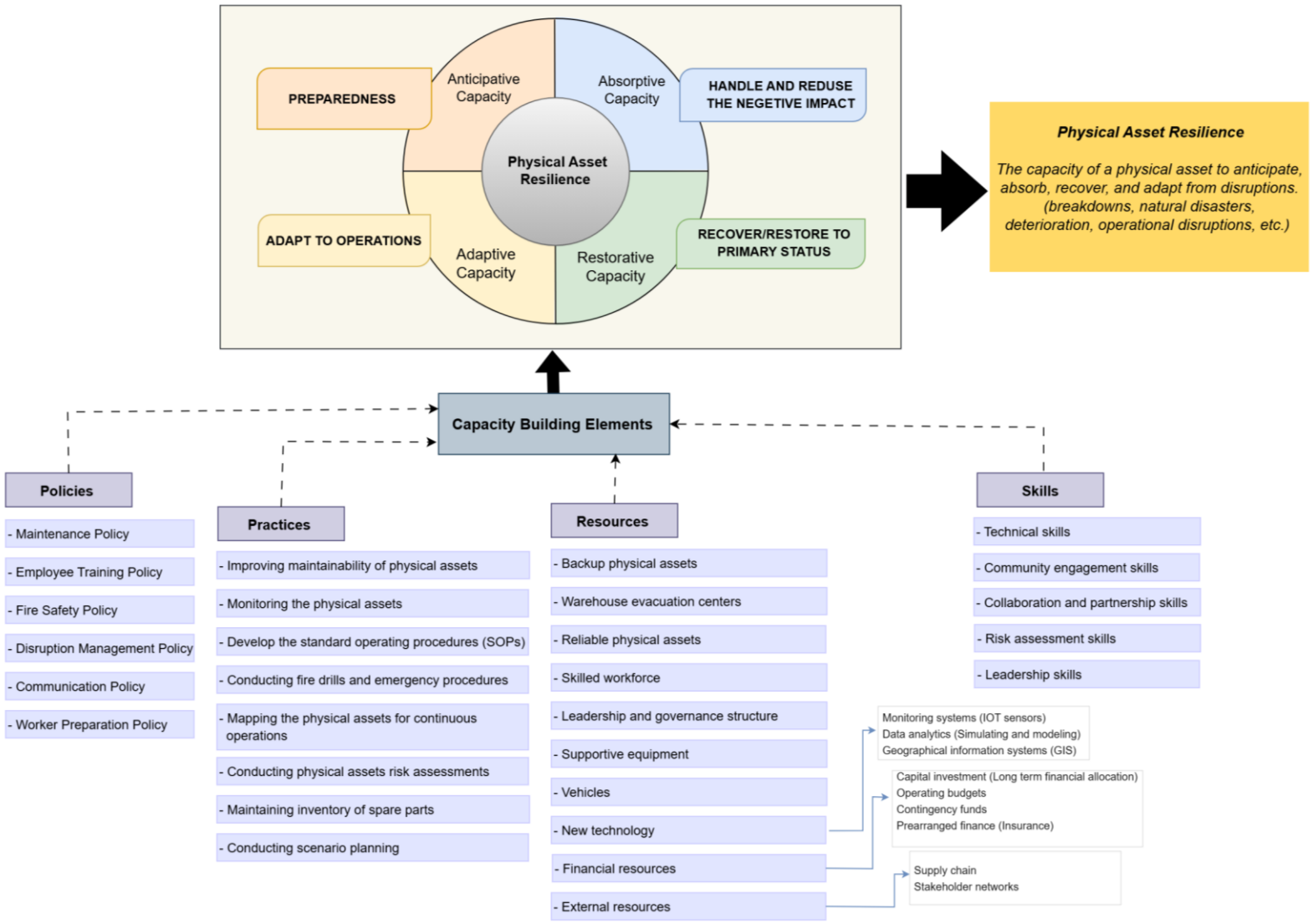


Figure 1: Conceptual Framework for Capacity Building in PAR

planning stages (Danaher et al., 2014). Moreover, community engagement should assist combined efforts among various stakeholders (Johnston et al., 2024). Thus, collaboration helps develop effective emergency plans. Strong community engagement and partnership skills are essential, as coordination among stakeholders, such as the government and private sector, enables knowledge sharing (Wieszczeczynska et al., 2024). Another one is understanding and addressing vulnerabilities, which is a contribution to developing resilience strategies. This involves skills in data collection, analysis, and interpretation to identify vulnerabilities and identify measures (Fleming & Ledogar, 2008). This emphasises that risk assessment skills are essential for capacity building in PAR. Moreover, having properly structured leadership skills is significant for coordinating disruption response efforts and managing resources efficiently (Danaher et al., 2014). In addition, leaders or top managers need to adjust strategies and operations in response to changing circumstances. This adoption is crucial in environments characterised by volatility, uncertainty, and ambiguity (Zamani & Ait Soudane, 2022).

4. CONCEPTUAL FRAMEWORK FOR CAPACITY BUILDING IN PAR

The conceptual framework developed in this study (Figure 1) integrates four key PAR capacities with essential capacity-building elements: policies, practices, resources, and skills. It serves as a guide to understanding how this works together to strengthen PAR in organisations. Anticipative capacity involves preparedness and the ability to foresee disruptions. Absorptive capacity refers to minimising the impact of disruptions, while restorative capacity focuses on the quick recovery of physical asset functionality. Adaptive capacity allows long-term improvement by adjusting operations. Capacity-building elements support these capacities through policies (e.g., maintenance, disruption, and fire safety), practices (such as risk assessments and monitoring), resources (financial, technological, and network-based), and skills (technical and community engagement). Together, these aspects contribute holistically to building resilience in physical assets. The legend of the conceptual framework (Figure 01) is as follows,

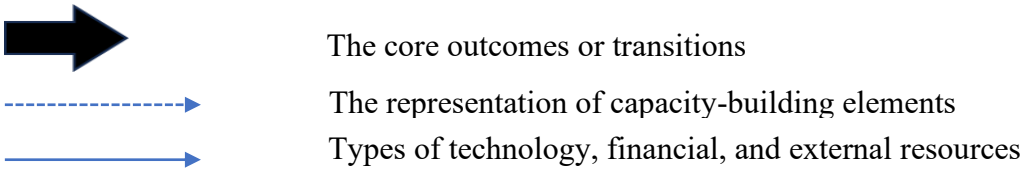


Figure 2: Guide to the conceptual framework

5. CONCLUSION

This study emphasises that the capacity building (PAR) in business organisations strongly depends on four key capacity-building elements. This review of literature aimed to identify the key capacity-building elements that contribute to strengthening PAR in business organisations. By reviewing existing studies, it was established that PAR is characterised by four capacities: anticipative, absorptive, restorative, and adaptive. The review further emphasised that policies, practices, resources, and skills are significant elements of capacity building, each allowing a critical place in improving PAR within business organisations. The findings identified six policies, eight practices, ten resources, and five skills that collectively allow physical assets to anticipate potential disruptions,

absorb their impact, recover or restore efficiently, and adapt to operations Thus, this study fills a gap in the existing literature by proposing a conceptual framework that includes the key elements of capacity building with the four capacities of PAR. However, in this study, it was not examined separately for each PAR capacity. Instead, a general approach to capacity building was considered to support the overall PAR. The need for capacity building in PAR is particularly critical for the apparel manufacturing sector. Which is one of the key economic contributors in Sri Lanka, and these organisations are highly reliant on their physical assets when driving their business, hence capacity building in this sector becomes an essential need. The conceptual framework developed through this study is intended to be explored further in apparel manufacturing organisations in Sri Lanka, and a more detailed analysis of how capacity building in individual PAR capacities will be conducted.

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A HUMAN CENTRED APPROACH TO POST DISASTER RESETTLEMENT HOUSING: CASE SUDY ON WALK-UP APARTMENTS IN SRI LANKA

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ABSTRACT

The rapid increase of post-disaster involuntary resettlement presents a significant global challenge. Integral to the disaster management cycle, post-disaster reconstruction is pivotal, serving as the backbone of the entire resettlement process. As post-disaster resettlement is a far more sensitive process than providing shelters, it should address the multidimensional requirements of the resettling community as well as the host community from different perspectives. Despite its criticality, existing research indicate, still there is a distrust about the community satisfaction of post-disaster involuntary resettlement in long-term. In Sri Lanka, recent decades have seen floods, landslides, and tsunamis trigger significant resettlements, highlighting a research void concerning the design aspects of these relocations, which critically influence long-term community contentment. Hence, the study focuses on the identification of design related issues of involuntary resettlements with special reference to post-disaster involuntary resettlement walk-up apartments in Sri Lanka which have an essential and futuristic requirement in the resettlement process. Qualitative approach was used for filling the knowledge gaps about the phenomenon, and development of a descriptive knowledge framework of the phenomenon. Accordingly, this study reinforced by a comprehensive literature review and interviews with beneficiaries to validate the findings of the literature. The beneficiary interviews were conducted by selecting two case studies representing two different types of disasters. The anticipated outcome is the formulation of design indicators to guide policymakers and practitioners towards enhancing the efficacy and community satisfaction in future post-disaster housing projects over the long term.

Keywords: *Human Centred; Case Study; Post-Disaster Involuntary Resettlement; Walk-up Apartments; Sri Lanka.*

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1. INTRODUCTION

The increasing frequency and intensity of natural disasters globally have led to an escalation in disaster-induced population displacements. In Sri Lanka, floods, landslides, and the 2004 tsunami have significantly contributed to internal displacement and necessitated state-led post-disaster resettlement programmes (UN-ISDR, 2009; Correa et. al., 2011).

Disasters have devastating impacts on communities, infrastructure, and the environment. The interpretation of the term 'disaster' varies among different authors and institutions.

The United Nations Office for Disaster Risk Reduction (UNDRR) defines a disaster as a serious disruption of the functioning of a community or a society involving widespread human, material, economic, or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources. The Federal Emergency Management Agency (FEMA) (United States) defines a disaster as a sudden event causing significant damage, destruction, and disruption to normal life, resulting in a need for external assistance. Moreover, the International Federation of Red Cross and Red Crescent Societies (IFRC) defines a disaster as an event that causes harm to people, property, and livelihoods, disrupts the normal functioning of a community or society, and results in a need for external assistance. Haigh and Amaratunga (2012) viewed disasters as a social phenomenon that occurs when a community suffers exceptional, non-routine levels of disruption and loss.

As Haigh and Amaratunga (2012) stated, disasters caused considerable damage around the world every year, and the need to respond, recover, rebuild or reinstate the built environment affected by disaster can be identified as a major challenge for the countries affected by disasters. Consequently, the post-disaster resettlement is a crucial aspect of disaster response and recovery. It involves the process of relocating affected individuals, families, or communities from their original homes/locations to safer or more suitable locations after a disaster (Silva & Ballinger, 2021; Iuchi & Mutter, 2020; Tiwari et al., 2023). This process is complex and requires careful planning and design to ensure the long-term sustainability of the new settlements. In this context, architectural design approaches play a vital role in ensuring the sustainability of post-disaster involuntary resettlements.

In the context of post-disaster resettlement housing, various design approaches can be observed globally. Accordingly, one of the key design approaches in post-disaster involuntary resettlements is the use of low-rise, high-density housing typologies. This approach has been widely used in several post-disaster resettlement projects worldwide. This approach allows for the efficient use of land and resources while providing adequate living space for the affected communities. However, the use of low-rise, high-density housing typologies also have several drawbacks in the areas of physical and functional aspects (Pellinan, 2012; Davidson et al., 2007), infrastructure and services (Ozumba et al., 2024), social integration and livelihoods (Archer & Boonyabancha, 2011; Mohit & Raja, 2014; Iuchi & Mutter, 2020), cultural appropriateness and psychological anchoring (Iuchi & Mutter, 2020; Haigh & Amaratunga, 2012) reflecting an alignment between housing provision and the physical, social, cultural, and psychological needs of residents (Lizarralde et al., 2010; Asian Development Bank Report, 2014; Bakar & Osman, 2022; Haigh & Amaratunga, 2012; Ahmed, 2010; Pellinen, 2012). Therefore, it is crucial to incorporate appropriate design strategies to address these challenges and ensure the long-

term sustainability of the resettlement projects. As such this research aims to identify the design related issues in post-disaster involuntary resettlement walk-up apartments in Sri Lanka.

2. LITERATURE REVIEW

2.1 POST-DISASTER RESETTLEMENT HOUSING

Maslow's Hierarchy of Needs is a psychological theory proposed by Abraham Maslow in 1943, in his paper "A Theory of Human Motivation." It suggests that humans have a hierarchy of needs that must be fulfilled in a specific order, starting from the most basic physiological needs and progressing to higher levels of psychological and self-fulfilment needs. The hierarchy is often depicted as a pyramid with five levels, arranged from the bottom to the top.

Accordingly, 'housing' is a basic human need that Maslow explained in the hierarchy of needs as a first important level of need similar to food and drink; therefore, it is at the centre of wellbeing; People must have food to eat, water to drink and a place to call home before they can think about anything else. Furthermore, Maslow's theory also demonstrates how important adequate housing is for security and positive development, and this is the second level of need; people must possess the security of a home and family in order to achieve the higher stage of need "self-actualisation" (Bakar & Osman, 2021).

According to Maslow's theory, individuals progress through these levels sequentially, with higher needs becoming dominant only after lower needs are satisfied. However, it is essential to note that not everyone follows this hierarchy in the same way, where individual experiences and cultural differences can influence how people prioritize and pursue their needs. Additionally, Maslow later proposed a sixth level called "Self-Transcendence," acknowledging that some individuals may prioritize helping others or spiritual growth beyond self-actualization.

In this theoretical sense, shelter is one of the key needs that we need to satisfy in a post-disaster context. The classification of shelters can vary based on different perspectives. In a study by Iuchi & Mutter (2020), post-disaster housing arrangements were categorized into four subsequent stages. These stages were based on the accommodation's purpose, the intended duration of stay for disaster-affected individuals, and whether they would resume their regular household activities in that location. Additionally, provided an explanation of how soon these housing provisions need to be provided.

The categories are 1) Emergency sheltering: Quarters for short periods, for hours or overnight, and to be provided within hours; 2) Temporary sheltering: People's temporary displacement into other quarters, within an expected short stay, and to be provided within a day or two; 3) Temporary housing: Resuming household responsibilities and activities in new quarters, arrangements that exceeded a mere emergency or temporary basis, and extend for months, if not years, to be provided within weeks preferably; and 4) Permanent housing: Returning either to their repaired or rebuilt original homes or moving into new permanent quarters, to be provided within few years.

Irrespective of the type of shelter provided, every shelter has fundamental needs that encompass the key requisites shown in Figure 1. Security and protection from weather can be the priority for those who are relocating to such shelters immediately aftermath of a disaster. However, the priorities of the people change over time when they tend to stay

in such shelters for a longer period. Hence, post-disaster resettlement projects should consider all the key requisites of a shelter into account, not just the immediate priorities of the affected communities.

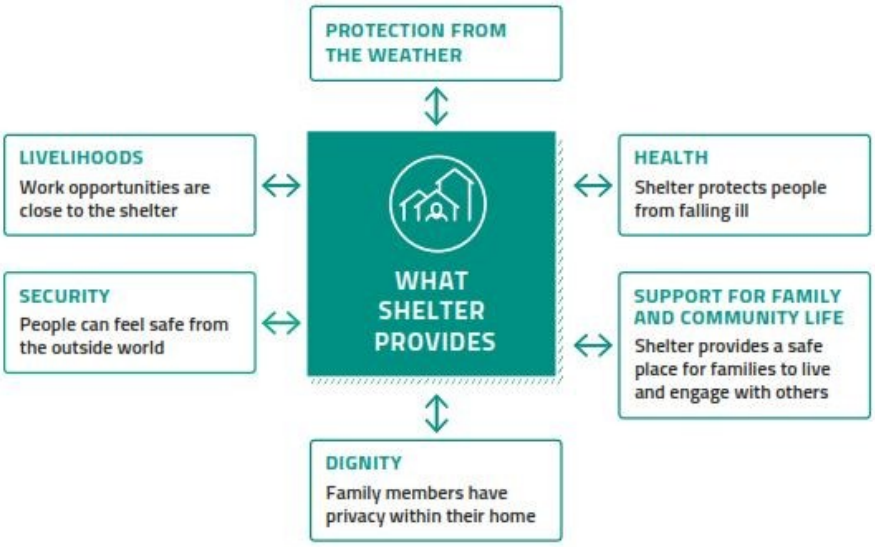


Figure 1: What shelter provides
Source: The Sphere Handbook: Humanitarian Charter and Minimum Standards in Humanitarian Response, fourth edition, Geneva, Switzerland, 2018. www.spherestandards.org/handbook

The impacts of disasters on the built environment sector and vice versa have been widely discussed in the literature by various scholars in the field (Haigh & Amaratunga, 2012; Paul et al., 2023; Ozumba et al., 2024). As highlighted in the National Involuntary Resettlement Policy (NIRP), the resettlement process should restore the affected community's living standards and integrate them into their new settlements (Godamunne, 2013). Also, it should ensure that the affected people are not negatively impacted. Further, it describes that those people who are living in vertically developed resettlements, have key issues in landlessness, joblessness, homelessness, marginalization, food insecurity, loss of access to common property resources, increased morbidity, mortality, and community disarticulation (Godamunne, 2013).

When considering the current design approaches, single-story individual houses are the most commonly available and community acceptable typology in the involuntary resettlements. However, with the issues of the availability of limited safer lands and other related issues, single-story individual housing is the most critical typology in the present context. Further, as Atmowardoyo (2018) stated, the use of valuable, productive agricultural lands for the reconstruction of new settlements is also a critical factor. Because the economic loss and the degradation of agricultural land could cause some serious problems in the future which could not be exactly estimated from now. Accordingly, the study was mainly focused on the post-disaster involuntary resettlement walk-up apartment housing, which has a futuristic requirement. The following section discusses the issues identified in the post-disaster resettlement housing.

2.2 DESIGN RELATED ISSUES IDENTIFIED IN THE POST-DISASTER RESETTLEMENT HOUSING

The community satisfaction in post-disaster permanent housing provision is determined by various indicators, including physical, social, and economic factors (Pellinan, 2012; Shrestha et al., 2025; Asnudin et al., 2024; Dharmadasa et al., 2024; Xiang et al., 2024; Capell & Ahmed, 2021). The physical indicators relate to the quality of housing infrastructure and amenities, such as the availability of clean water, sanitation facilities, and electricity. Adequate space, ventilation, and lighting are critical factors that contribute to the physical well-being of residents (Shrestha et al., 2023; Montalbano & Santi, 2023; Dias et al., 2016; Mohit, 2014). In addition, accessibility to healthcare facilities, schools, and transportation systems is an important consideration in determining community satisfaction. Social indicators relate to the social fabric of the community, including the quality of relationships among neighbours and with outside agencies, the sense of safety and security, and the degree of social cohesion (Dharmadasa et al., 2024; Hassan et al., 2023; National Academies of Sciences, Engineering, and Medicine, 2015; Mohit, 2014). Community engagement and participation in decision-making processes are important social indicators that contribute to community satisfaction. Economic indicators are critical in determining community satisfaction, including the availability of employment opportunities, access to credit and financial services, and access to markets for the sale of goods and services. The affordability of housing and the cost of living are important economic considerations that contribute to community satisfaction (Islam et al., 2025; World Bank, 2025; Tiwari et al., 2023; Haigh & Amaratunga, 2012).

Based on the information gathered through the literature review, it has been identified that the multifaceted challenges of post-disaster housing resettlement, both globally and Sri Lanka, can be comprehensively analysed through a structured framework comprising three critical phases: planning, implementation, and evaluation. This categorization not only provides analytical clarity but also aligns with contemporary disaster risk reduction frameworks and best practices for resilient and sustainable housing recovery (Davidson et al., 2007). Though the following analysis is presented in three phases, the design related issues are mainly to be addressed during the planning stage as any design-related errors will create impacts during the implementation and evaluation phases.

The planning phase serves as the conceptual foundation for resettlement initiatives. However, this phase is often characterized by significant gaps in site selection, community engagement, and context-sensitive design. Resettlement sites are frequently chosen based on land availability or administrative convenience rather than robust hazard assessments, participatory consultations, or social impact evaluations (Boano & García, 2011; Davidson et al., 2007). As a result, communities are frequently relocated to peripheral or environmentally vulnerable areas, as documented in post-tsunami India and post-earthquake Iran (Bakar & Osman, 2022). Sri Lanka has not been immune to similar challenges, with resettlement sites often developed on marginal lands lacking essential infrastructure and services (Senanayake et al., 2022).

Furthermore, the absence of genuine community participation in the planning process undermines both the suitability and acceptance of housing solutions. Standardized designs; typically produced by external consultants or donor agencies; tend to neglect cultural norms, spatial traditions, and household structures (Dayaratne & Kellett, 2008;

Pellinan, 2012). The exclusion of culturally significant features such as verandahs, internal courtyards, and semi-outdoor kitchens can disrupt daily routines and diminish the adaptability of living spaces (Pellinan, 2012). Compounding this issue is the dominance of technocratic, risk-centric planning paradigms, which prioritize structural resilience while neglecting broader recovery dimensions such as emotional well-being, cultural continuity, and livelihood proximity (Iuchi & Mutter, 2020). This misalignment with community values often leads to dissatisfaction, informal alterations, or even abandonment of provided housing (Pellinan, 2012; Davidson et al., 2007).

The implementation phase, which operationalizes the resettlement plan into physical environments and services, reveals additional deficiencies. Uniform housing templates are commonly deployed with little regard for household diversity or evolving needs. In Sri Lanka, walk-up apartment resettlements have drawn criticism for rigid layouts, poor ventilation, and limited communal space, which collectively restrict residents' capacity for spatial personalization (Pellinan, 2012). Comparable issues have been observed internationally; in Iran, Indonesia, and Haiti; where inflexible housing solutions ignored vernacular knowledge and environmental responsiveness (Bakar & Osman, 2022; Ozumba et al., 2024).

The evaluation phase, which should function as a mechanism for accountability and continuous improvement, is arguably the most underdeveloped. Post-disaster housing programmes tend to focus on quantitative metrics such as unit completion and financial expenditure, while qualitative indicators like user satisfaction, cultural relevance, and psychosocial recovery remain underexplored (Ahmed & McEvoy, 2010; Xiang et al., 2024). This narrow evaluative lens curtails the ability of institutions to adapt practices based on lived experience. In Sri Lanka, evaluations such as those by researchers like Senanayake et al. (2022) have exposed persistent dissatisfaction, particularly in high-density apartment schemes. Common issues include overcrowding, poor ventilation, lack of privacy, and geographic dislocation from employment and services.

Equally problematic is the limited application of evaluation outcomes in future planning and design. Institutional learning is often minimal, and many of the same planning and implementation flaws are repeated across different projects (Davidson et al., 2007; Iuchi & Mutter, 2020). Moreover, most evaluations lack participatory methodologies, excluding the perspectives of the very communities they are intended to serve (Haigh & Amaratunga, 2012). Without integrating community voices, such assessments fail to capture the complex social and cultural dynamics that influence housing success.

In summary, the analysis underscores the multifaceted impact of disaster-induced involuntary resettlement housing emphasizing the need for design professionals to consider the broader implications of their design decisions on community building, resident satisfaction, and the integration of functional spaces. Accordingly, the data highlights a compelling argument for a more resident-centred approach in housing development, one that prioritizes the creation of spaces that support community engagement, personalization, and overall quality of life. Finally, involuntary resettlement can be identified as a transformation of a specific environment in social, cultural, environmental, and economic terms. Hence, the entire resettlement should be a sustainable solution for society.

3. RESEARCH METHODOLOGY

This study adopts a qualitative approach to examine design-related issues surrounding disaster-induced involuntary resettlement housing in both global and local contexts. A comprehensive literature review was conducted to establish a theoretical and contextual foundation, drawing on existing research to identify key design related issues in the disaster-induced involuntary resettlement housing. These findings were validated and contextualized for the involuntary resettlement housing in Sri Lanka. A case study research strategy was adopted for this purpose. A case study is a comprehensive analysis of an individual, a group within an organisation, or a specific event that has distinctive properties (Atmowardoyo, 2018). A multiple holistic case study was conducted to identify the design related issues in post-disaster resettlement housing. 'Post-disaster resettlement housing' was identified as the case study boundary and 'design-related issues' was selected as the unit of analysis. As such, two case studies focused on post-disaster involuntary walk-up apartment resettlement housing projects representing two different types of disasters (landslide and tsunami) in Sri Lanka were selected.

The first case study examined a tsunami-induced resettlement housing project with 100 two-roomed housing units. This case represents coastal displacement and the corresponding resettlement strategies adopted in such contexts. The second case study explored a housing project initiated due to landslide displacement with 75 two-roomed housing units, thereby reflecting a contrasting geographical and environmental context, namely, inland displacement due to terrain instability. In both cases, the occupants have been living in these facilities for almost 10 years, which was intentionally considered to ensure that the satisfaction level of the occupants to be more realistic. Each case study involved the collection of data through semi-structured interviews with twenty (20) beneficiaries from each resettlement project. Accordingly, 40 interviews with respondents from different households in the resettlement apartment, which consisted of houses from different floor levels, were conducted. The interviews were arranged face-to-face with the intention of the researcher to visit these facilities in person to observe the design-related issues persistent in those housing projects. The selection of these two cases enables the study to analyse variations in resettlement outcomes, planning approaches, and community responses across different disaster types. Both cases serve to validate the key design relate issues identified in the literature while contributing practical insights for future resettlement planning and policy development.

4. ANALYSIS AND FINDINGS OF CASE STUDIES

The case studies aim to provide grounded insights into the lived experiences of affected communities and to assess the effectiveness of current resettlement housing in terms of architectural design features. The occupation of the community from Case study 1 consisted of private sector workers and fishermen, whereas Case study 2 consisted of private sector workers and self-employed workers.

Table 1 presented the interview findings in a structured manner based on the cross-case analysis.

Table 1: Contextualised design related issues in case studies

Design related issues	Case study 1	Case study 2
Design deficiencies	Satisfied with internal layout, except the size, building orientation and parking facilities. Inadequate space for home gardening.	Satisfied with internal layout. Inadequate space for recreational facilities, parking facilities and home gardening.
Administrative convenience of site selection for housing	Transportation is not a concern.	Need for safe and accessible transportation infrastructure.
Quality of construction	Not satisfied.	Satisfied.
Quality and accessibility of infrastructure and amenities	Need for enhanced utility services, concerns with the adequacy of water supply, electricity, and waste management systems.	Need for enhanced utility services, concerns with the adequacy of water supply, electricity, and waste management systems. The community desires for internet connectivity.
Economic actives	Inadequate space for income-generating activities.	Inadequate space for income-generating activities.
Absence of genuine community participation in the planning and decision-making process	Lack of community involvement in the planning and construction process.	Lack of community involvement in the planning and construction process.
Exclusion of culturally significant features and misalignment with community values	Satisfied with culturally significant features.	Culturally significant features like worship areas are not included.
Little regard for household diversity or evolving needs	No provision for future extensions.	No provision for future extensions.
Social cohesion due to limited communal space	Comparatively satisfied with the communal space provided in the building design.	Limited communal space to associate with neighbours or recreational activities.
Poor ventilation	Not a concern.	Compared to case study 1, the ventilation is considered poor.
Safety and Security	Dissatisfaction with privacy, safety and security issues.	Dissatisfaction with privacy, safety and security issues.
Sustainability features	Strong interest in incorporating sustainable features such as solar panels.	Strong interest in incorporating sustainable features such as solar panels. Demonstrated collective awareness of renewable energy sources and their benefits.

As per Table 1, the key design-related issues identified in the literature were contextualised and validated through real-life case studies. There has been similarities and differences between the case studies with respect to the identified design related features. Accordingly, Case Study 1 community is comparatively more satisfied with the communal space and culturally significant features provided in the buildings, along with the transportation infrastructure. This was mainly due to the selection of building sites of case study 1 which was at a sub-urban area where the accessibility and spacing were comparatively better than the Case Study 2 which are located in rural areas. However, the level of satisfaction with quality of construction was comparatively low in Case Study 1. Further case study 2, the community emphasized the importance of reliable internet access in today's digital world.

There have been more similarities than differences between the two cases, as observed in Table 1. The issues related to quality and accessibility of infrastructure and amenities, inadequate space for income-generating activities, lack of community involvement in the planning and construction process, lack of provision for evolving needs and safety and security were the key concerns in both case studies. Additionally, the respondents from both cases expressed their strong willingness and support towards sustainable features.

These findings suggest that while certain infrastructural needs are universally relevant across resettlement contexts, and specific concerns influenced by the geographic setting, and socio-cultural dynamics which require site specific responses. Addressing both the shared and unique concerns identified in each case study will be essential for the development of future resettlement projects that are not only functional and safe but also resilient, inclusive, and aligned with the evolving needs of affected communities. Proposing solutions for the design related issues will be the way forward of this ongoing research study.

5. CONCLUSIONS

Housing must not only provide shelter but also support community building, facilitate personalization, and enhance the overall quality of life for residents. Accordingly, a resident-centred approach is essential, which can actively foster social engagement and long-term satisfaction. Further, the involuntary resettlement represents a profound transformation across social, cultural, environmental, and economic dimensions. As such, resettlement efforts must aim to deliver sustainable and holistic solutions that extend beyond physical infrastructure to include cultural continuity and social cohesion.

The study reveals both similarities and differences in terms of design related issues across different resettlement contexts representing different types of disaster, geographical conditions, and socio-cultural backgrounds of the occupants. Accordingly, the issues related to quality and accessibility of infrastructure and amenities, inadequate space for income-generating activities and evolving needs, lack of community involvement in the planning and construction process, and safety and security related issues were highlighted as the key concerns in both case studies. Additionally, certain design related issues were highlighted more by one case study than the other indicating the context-specific findings. Accordingly, the findings emphasize the importance of tailoring resettlement strategies to address both common needs and context-specific concerns. This dual approach is critical for developing resettlement projects that are not only functional and secure but also resilient, inclusive, and adaptive to the evolving needs of displaced communities.

Although recent efforts have increasingly focused on structural resilience, there remains a lack of theoretical and practical frameworks to assist design professionals in creating built environments that address the psychological, cultural, and symbolic dimensions of space which factors that are essential for meaningful recovery and identity reconstruction. Accordingly, this research intended to address this gap by analysing the satisfaction level of the communities that occupied post-disaster resettlement housing.

In providing solutions to the identified design related issues, this research intends to conduct interviews with design professionals in Sri Lanka using qualitative survey strategy as the way forward of this study. Sri Lanka is prone to disasters such as flood, landslide and tsunami. The data collected mainly reflect two types of disasters such as landslide and tsunami. However, as both the landslide and flood are similar in terms of the frequency and intensity of disaster risk in Sri Lanka, the findings obtained can be generalisable within the Sri Lankan context.

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A REVIEW OF PROCUREMENT AND MANAGEMENT OF BUILDING SERVICES SYSTEMS: COMPLEXITIES AND TECHNOLOGY ADOPTION

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ABSTRACT

Rapid advancements in digitalisation are reshaping the global supply chains and revolutionising traditional procurement and management practices. Within the construction industry, the procurement and management of building services systems present greater complexities compared to other construction elements. This study aims to identify these complexities and explore the potential of emerging technologies to address them. A scoping literature review of 32 peer-reviewed articles was conducted to identify the complexities in the procurement and management of building services systems from different perspectives and to identify applicable digital technologies. The findings reveal that complexities span across collaboration, approvals, design requirements, technical calculations, life cycle, communication, regulatory requirements, maintenance, cost, technical skills, etc. Technologies such as Building Information Modelling (BIM), Blockchain, Data Analytics and Artificial Intelligence (AI), Digital Twin and IoT, and Building Management Systems have been widely adopted to address these complexities. This identification urges the necessity of a systematic and technology-integrated approach to the procurement and management of building services systems. The findings from this research assist construction professionals in selecting appropriate technologies aligned with the specific requirements and phases of building services procurement and management.

Keywords: *Building Services; Complexities; Procurement and Management; Technology Adoption.*

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1. INTRODUCTION

Building Services Systems (BSS), including heating, ventilation, and air conditioning (HVAC), electrical, plumbing, fire services, and vertical transportation, play a critical role in making buildings comfortable, functional, and safe for end-users. They often contribute significantly to both the duration (up to 50%) and cost (up to 50%-60%) of construction projects, depending on project size and complexity (Chauhan et al., 2022). The installation of BSS frequently lies on the critical path of construction schedules, directly influencing project timelines and outcomes (Shoesmith, 2010). Unlike conventional building components, such as structural and non-structural components, BSS are highly specialised, requiring expert knowledge for installation, long-term lifecycle management, multidisciplinary coordination, and compliance with strict performance standards (Akhil & Das, 2019; Wan & Kumaraswamy, 2012; Wu et al., 2022). These inherent complexities are further intensified by fragmented supply chains, changing client requirements, compliance with regulatory guidelines, and frequent design changes during the initial phases of construction projects (Khan et al., 2023). Because of this nature, procurement and management (P&M) of BSS are challenging, remain inefficient and prone to errors (Hewavitharana et al., 2024). Here, procurement and management refer to operations throughout the lifecycle of BSS.

Consequently, with the advent of industry 4.0, construction companies have explored ways of utilising technologies such as Building Information Modelling (BIM), Blockchain, Internet of Things (IoT) and Building Management Systems (BMS) in the P&M of BSS (Francis & Zhou, 2025; Husin & Kristiyanto, 2024; Perera et al., 2024). The adoption of these technologies in building services systems is still emerging with varying degrees of success and acceptance. Hence, it is vital to identify the promising research directions in this domain.

This study aims to identify the complexities of P&M of BSS and drivers and limitations of adopting trending technologies in P&M of BSS. The rest of the paper is organised in the following order: The methodology adopted for the study is presented in Section 2. Section 3 presents the findings and discussion section. Lastly, the conclusion, along with the practical implications of the research and recommendations for further investigation, is presented in Section 4.

2. METHODOLOGY

In this study, a scoping review was carried out instead of a systematic review. The reason for selecting a scoping review was to focus on the breadth of the literature in this area, as it had not been explored extensively in the past. Accordingly, three research questions were formulated to guide the scoping review.

1. Why is the P&M of BSS complex than the P&M of other construction elements?
2. What are the trending technologies in P&M of BSS?
3. How can the identified technologies reduce the complexities in P&M of BSS?

Scopus and Web of Science databases were used to identify relevant documents during the scoping review due to their reputation as the most appropriate and reliable sources for literature reviews. The search string; *("Procure*" OR "Tender*") AND (“Construction” OR “Built Environment” OR “Building services” OR "MEP" OR "Mechanical" OR "Electrical" OR " Plumbing" OR “Structure*” OR “Architecture*” OR “Civil*

Engineering" OR "Construction Engineering" OR "Construction Industry" OR "Construction Management" OR "Construction Engineering and Management") AND (complex OR challeng* OR difficult* OR "high uncertainty" OR inefficien*) AND ("Digital Technologies" OR "Blockchain" OR "BIM" OR "Building Information Modelling" OR "Industry 4.0" OR "AI" OR "Artificial Intelligence" OR "Digital Twin" OR "BMS" OR "Building Management System")* was used in titles, abstract or keywords of a publication. The search query resulted in a list of 407 papers from Web of Science and 421 from the Scopus database. Only journal papers written in the English language were considered as an inclusion criterion. However, the search process was not limited to the publication date, as most of the evidence in this domain is recent. After using the inclusion criteria, it resulted in 236 papers in Scopus and 188 in Web of Science. As some studies existed in both lists, duplicates were removed, and only 196 papers were retained. After careful screening of the title, abstract, only 32 remained for the in-depth review. Figure 1 illustrates the methodology followed in the scoping review.

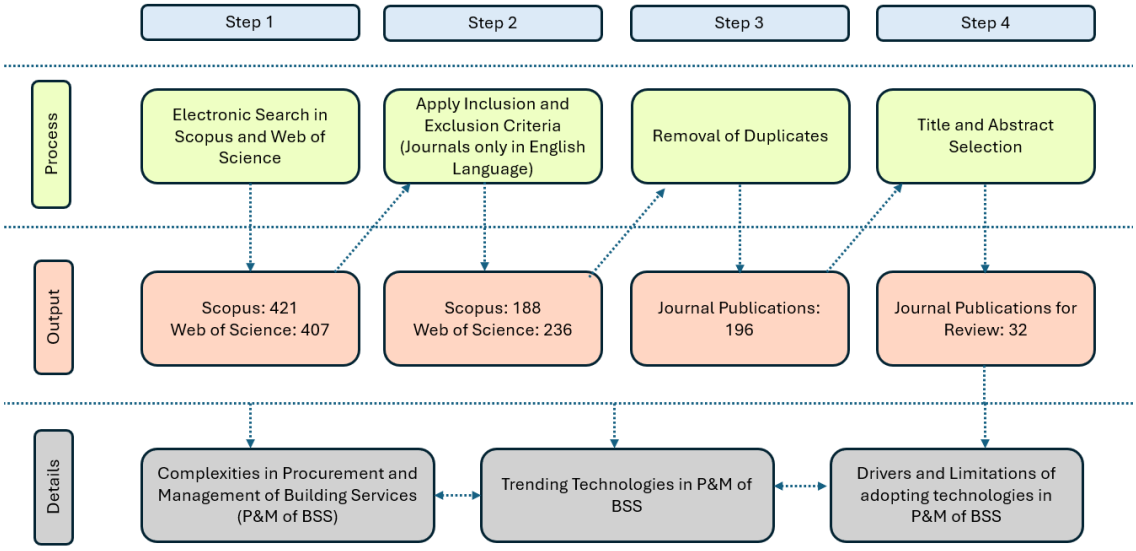


Figure 1: Research methodology adopted in the study

3. FINDINGS AND DISCUSSION

This section discusses the findings of the scoping literature review.

3.1 COMPLEXITY OF PROCUREMENT AND MANAGEMENT OF BUILDING SERVICES SYSTEMS

In general, procurement involves acquiring goods or services from external suppliers and includes activities such as requirement identification, source selection, quotation requests, and vendor evaluation (Boniface et al., 2024). However, the P&M of BSS extend beyond these conventional steps due to several factors, including the long lifecycle of systems, the involvement of multiple stakeholders, the need for specialised knowledge for installation, and strict regulatory and technical requirements. Table 1 summarises the complexities of building services from different perspectives. The areas in Table 1 were logically derived based on the literature review findings.

Table 1: Comparison of procurement and management of general building elements and building services systems

Identified Area	P&M of Building Services Systems	P&M of General Building Elements	References
(C1) Collaboration	These systems (e.g., HVAC, electrical, vertical transportation, plumbing, fire protection) are highly technical and interdependent, requiring precise integration with other building elements and subsystems. This complexity increases procurement challenges as specifications must align with performance criteria, regulatory compliance, and future adaptability.	Procurement of structural or architectural elements (e.g., concrete, steel, or finishes) has comparatively less technical integration and fewer interdependencies, making specifications and vendor selection more straightforward.	(Arora, 2023; Hassanain et al., 2019; Korman et al., 2003; Marsh, 2012; Shoesmith, 2010)
(C2) Approvals	Planning and Design require specialised knowledge, which leads to third-party consultants, builders and vendors. This process requires multiple back-and-forth approvals, which affects the schedule of the construction project.	More standardised designs and codes reduce the reliance on niche expertise.	(Abdelhameed & Saputra, 2020; Khan et al., 2023; Singh et al., 2018; Wu et al., 2022)
(C3) Design Requirements	BSS designs might include proprietary systems or vendor-specific solutions based on the intended functionalities and client requirements. Special subcontractors and manufacturers need to be selected through a tendering process for the installation.	More standardised designs and codes reduce the complexity of the designs. Subcontractor selection does not require high technical capacity.	(Akhil & Das, 2019; Rabb & Vesali, 2022; Smart Hospitals Project & Pan American Health Organization, 2020; Wan & Kumaraswamy, 2012; Wang et al., 2016)
(C4) Technical Calculations	BSS designs are more iterative, with frequent adjustments based on evolving requirements (e.g., load calculations and equipment specifications) demanding smooth collaboration.	Designs for structural and architectural components typically follow a more linear process with fewer iterations.	(Gurmu & Mudiyanselage, 2023; Smart Hospitals Project & Pan American Health Organization, 2020)

Identified Area	P&M of Building Services Systems	P&M of General Building Elements	References
(C5) Lifecycle Management	Requirements evolve over the building's lifecycle, from design, installation, commissioning, operation, and maintenance to eventual upgrades or decommissioning, ensuring the service continuity after the handover phase.	These elements typically have static specifications that end after the project handover or the defect liability period.	(Chauhan et al., 2022; Hu et al., 2016; Ni et al., 2021; Tyrrell, 2023)
(C6) Communication	The integration of BSS involves multiple stakeholders, including engineers, architects, consultants, contractors, and facility managers. Misalignment or lack of communication between these stakeholders can lead to delays, cost overruns, and performance issues.	While coordination is still necessary, the roles and responsibilities are often more clearly defined, and the integration is less complex.	(Rejeb et al., 2018; Tatum & Korman, 2000; Wan & Kumaraswamy, 2012)
(C7) Regulatory Requirements	Stringent regulations related to energy efficiency, safety, and environmental impact require meticulous documentation, testing, and approvals. Non-compliance can result in significant legal and operational risks.	These typically face fewer regulatory hurdles, and compliance tends to focus on structural integrity and material standards, which are easier to validate.	(Australian Building Codes Board 2021; Gossain, 2023; Greeno & Hall, 2009; Tyrrell, 2023).
(C8) Commissioning and Handover	The commissioning and handover of the BSS are complex, involve all stakeholders and often lie in the critical path of the construction project.	The construction of conventional elements is a well-established process in the construction schedule.	(Khan et al., 2023; Schneidera et al., 2015; Xie, 2024)
(C9) Procurement Management	BSS requires specialised procurement methods, such as performance-based contracts, due to its technical component.	Traditional (design-bid-build, design-build) and modern methods (Public Private Partnership, Engineering, Procurement and Construction) can be adopted.	(Aibinu & Papadonikolaki, 2016; Akhil & Das, 2019; Heydari et al., 2024; Kim & Kim, 2024; Mosley Jr & Bubshait, 2017)
(C10) Maintenance Management	Frequent disputes over maintenance contracts, service-level agreements (SLAs), extended warranties, and system upgrades are generated.	Limited post-construction claims, mostly related to structural defects within the liability period, are created.	(Ismail, 2021; Kumar et al., 2022; Remedial, 2022)

Identified Area	P&M of Building Services Systems	P&M of General Building Elements	References
(C11) Cost	High initial costs, coupled with unpredictable operational and maintenance costs, pose challenges in estimating. Also, delays due to custom manufacturing, technological obsolescence, and specialised installation requirements create risks in deliveries and quality.	Cost estimation is generally more predictable, and risks are limited to common issues like material shortages or weather delays.	(Akhil & Das, 2019; Cai et al., 2018; Johnson & Babu, 2020; Siren & Pennanen, 2014)
(C12) Technical Skills	Maintenance is a continuous process requiring specialised skill sets and tools. Lifecycle costs often exceed initial procurement costs, necessitating robust planning and resource allocations	Maintenance requirements are generally lower and less technically demanding, with costs concentrated upfront.	(Gurmu & Mudiyanselage, 2023; Hu et al., 2018; Khana et al., 2020; Smart Hospitals Project & Pan American Health Organization, 2020)
(C13) Future Extensions	Systems often need to be scalable and adaptable to accommodate future building expansions, changing user needs, or technological upgrades, complicating P&M.	These elements rarely require scalability or adaptation after installation.	(Gunasekara et al., 2021; Howkins, 2017; Ismail, 2021; Kumar et al., 2022; Remedial, 2022)

3.2 AVAILABLE TECHNOLOGIES FOR PROCUREMENT AND MANAGEMENT OF BUILDING SERVICES SYSTEMS

In response to these complexities, an adoption of systematic procurement and management (P&M) is required in Building Services Systems (BSS) using emerging technologies. The following section discusses the potential technologies which can be used in the P&M of BSS.

3.2.1 Building Information Modelling (BIM)

Building information modelling is a significant advancement in the construction industry, which digitally presents the building or infrastructure project's physical and functional characteristics. During the pre-construction planning stage, BIM plays a vital role in visualising the project, detecting potential conflicts and optimising the design. The 3D models generated by BIM can be used for compliance checking of building services systems and spatial requirements. This clash detection highlights the potential conflicts in the design phase, preventing expensive on-site variations (Shahruddin & Zairul, 2020). Further, BIM is used to generate accurate cost estimates and is linked with budgets so that project managers can make accurate decisions on project budgets (Pérez-García et al., 2021). Additionally, BIM can be linked with project schedules and stakeholder collaborations. This transformative approach enhances visualisation, streamlines coordination, and improves communication among stakeholders, leading to improved efficiency and reduced errors in building services projects. The capability of BIM extends beyond the initial phases of the projects. It can support the facilities management of BSS and lifecycle analysis, which enhances long-term project sustainability and operational efficiency. These insights are vital for decision-making, which seeks to optimise the resources and minimise the negative environmental impact. However, BIM adaptation faces some challenges, including high initial implementation cost, the requirement of expert knowledge of using the tool, interoperability issues with data formats and drastic workflow changes. Further, the data in the BIM models is not tamperproof, so it can be subjected to manipulation without any authorisation (Husin & Kristiyanto, 2024; Li et al., 2022; Ni et al., 2021).

3.2.2 Data Analytics and Artificial Intelligence (AI)

Data analytics and AI can be used for data-driven insights that guide strategic procurement and management of building services systems. Data analytics not only evaluate suppliers' performance but also uncover market trends, offering a holistic view of the procurement landscape. This understanding allows professionals to make better decisions on procurement strategies (Ibem & Laryea, 2014). On the other hand, AI improve the decision-making capabilities by predicting purchasing trends and optimising clients' requirements. Further, AI can automate repetitive tasks by reducing the number of intermediaries. AI can be used to analyse the contract documents and identify variations with dynamic changes in site operations (Alaloul et al., 2020). Moreover, in the post-installation phase, AI-powered systems are enabled to monitor predictive and preventive maintenance measures without human involvement. However, the adoption of AI presents several limitations. One major challenge is the requirement for large, high-quality datasets to support predictive decision-making. In practice, data within the construction sector is often fragmented across multiple software platforms, making it difficult to consolidate, trace, and extract the necessary information for effective AI

model training. Additionally, many AI models, particularly deep learning algorithms, operate as "black boxes," offering limited interpretability of the underlying decision-making processes. This lack of transparency reduces stakeholder trust and confidence in AI-generated outcomes. Furthermore, ethical concerns arise regarding the use of sensitive or confidential data, particularly in relation to data security, ownership, and privacy protection (Francis & Zhou, 2025; Perera et al., 2024).

3.2.3 Digital Tools for Communication and Collaboration (DTC)

Before Procurement 4.0, construction project teams were challenged with coordinating and collaborating with diverse stakeholders such as architects, contractors, subcontractors, manufacturers and installers, especially in the planning and design phase of the building services systems (Chopra, 2018). The invention of numerous software with cloud-based systems has significantly improved stakeholder integration and promoted teamwork. Cloud-based platforms, such as file-sharing software and email communication software, facilitate real-time access to essential project data, thereby reducing the likelihood of miscommunication and ensuring everyone is aligned with project objectives and requirements (Puolitaival et al., 2018). Especially in the planning and design phase, numerous documenters are transferring among stakeholders, which is difficult to handle without a real-time update mechanism. Further to above, advanced functionalities such as version control, document tracking and permission-based access ensure data accuracy, support traceability and maintain consistency, which helps project teams to maintain a clear audit trail and ensure that everyone is working with the most updated document. A key challenge of using DTC is the fragmentation and lack of interoperability across platforms. This fragmentation makes it difficult for users to trace data origins, leading to frustration and a lack of accountability, as it becomes unclear who generated or modified specific information. In building services systems (BSS), data manipulation is a recurring issue, particularly during the maintenance phase, further undermining data integrity. If a system does not effectively prevent data manipulation, users are unlikely to have confidence in its reliability and integrity. Additionally, data security concerns and inconsistencies in stakeholder adoption of different software platforms exacerbate these limitations.

3.2.4 Blockchain (BT)

Blockchain technology represents a new era of security and transparency within procurement processes. Its integration into construction procurement workflows ensures secure, transparent, and tamper-proof execution of transactions (Jeoung et al., 2022). Moreover, the transactions recorded in the blockchain are immutable thus, the data in the blockchain is secure. The use of smart contracts in blockchain further automates procurement activities, reducing reliance on intermediaries and lowering associated costs and delays. This automation not only streamlines operations but also accelerates transaction timelines, contributing to improved project efficiency. Additionally, the distributed ledger in blockchain architecture provides real-time visibility into procurement actions, ensuring traceability and accountability while mitigating the risk of fraudulent activities (Mahmudnia et al., 2022). Blockchain support in building services systems in the maintenance period as well. Inspection data can be securely recorded on the blockchain, ensuring tamper-proof documentation that is free from manipulation or human bias. This immutable record-keeping mechanism serves as a reliable audit trail, supporting the development of asset condition reports at the end of the system’s lifecycle.

This transparent approach supports data-driven decision-making, allowing construction organisations to shift smoothly throughout the procurement lifecycle. Despite the benefits of blockchain, the practical implementation of it in P&M of BSS is not without challenges. Integration of blockchain with existing legacy systems is complex and requires substantial architectural changes, as it operates as an underlying technology. Moreover, P&M of BSS generate huge data, leading to scalability and performance limitations, particularly in balancing on-chain storage with off-chain data processing. The deployment of smart contracts also raises regulatory and legal uncertainties, especially concerning contract enforceability, liability attribution, and compliance with regulations (Hijazi et al., 2021).

3.2.5 Digital Twin (DT)

A digital twin, also called a data twin, is a dynamic digital representation of a physical asset created by gathering real-world data through technologies such as 3D laser scanning, drones, IoT-enabled sensors, cameras, and other smart devices. When combined with Artificial Intelligence (AI) and the Internet of Things (IoT), digital twins can learn and autonomously update to mirror changes occurring in their physical counterparts. These models capture a wide range of asset properties, including spatial orientation, operational status, and environmental interactions. Synchronisation between the digital and physical environments is affirmed with BIM, 3D modelling software, point cloud data, and real-time sensor feedback. Digital twins significantly enhance the analytical power of BIM by transforming static models into intelligent, "living" systems capable of real-time monitoring and decision support. They enable construction teams to gain granular insight into each building service system, facilitating proactive maintenance, performance optimisation, and lifecycle assessment. This arrangement of physical and virtual environments allows stakeholders to visualise real-time asset conditions and simulate operational scenarios before implementation. For facility owners and managers, digital twins are useful for comprehensive asset monitoring, enabling the digital reconstruction of physical environments and supporting data-driven decision-making throughout the asset lifecycle**.** However, DT application involves high set-up and maintenance costs with many resources. Further, it requires real-time data inputs, which is challenging with IoT sensors in a construction environment. Additionally, modelling the dynamic behaviour of complex building systems remains technically demanding due to limited standardisation across platforms (Opoku et al., 2021).

3.2.6 Building Management Systems (BMS)

Building Management Systems (BMS), also called Building Automation Systems (BAS), are centralised, computer-based control systems designed to monitor and manage a building service infrastructure. Acting as the central control point for all facilities within the building, the BMS enables facility managers to remotely control and adjust equipment performance through desktop or mobile interfaces, without physically walking to each building floor and room to shut down, switch on or manually adjust the systems.

BMS enhances building performance by real-time data acquisition and automated control algorithms while reducing energy consumption and operational costs. The system plays a critical role in sustainable facility management by optimising resource usage and maintaining predefined environmental conditions. Additionally, modern BMS platforms often incorporate data analytics, fault detection, and predictive maintenance capabilities, further supporting strategic decision-making and extending asset lifespan. The key

challenges associated with Building Management Systems (BMS) include limited flexibility for custom integration and reliance on expensive proprietary platforms. These systems often involve complex setup and configuration processes, and they require ongoing technical support for effective operation and maintenance.

Table 2 illustrates the summary of the potential technologies in addressing the identified complexities in P&M of BSS.

Table 2: Technological solutions to identified complexities

Complexities in P&M	Features of the technology to address the complexity in P&M	BIM	AI	DTC	BT	DT	BMS
(C1) Collaboration	BIM enables centralised design data, Digital collaboration tools improve real-time coordination, and Blockchain ensures transparency and traceability of design changes.	√		√	√		
(C2) Approvals	Blockchain ensures immutable approval logs and digital signatures, BIM helps visualise compliance for approvals, AI assists in document classification and automated review workflows.	√	√		√		
(C3) Design Requirements	BIM allows for coordination of proprietary systems and data-rich object representation; AI supports selecting optimal systems, Digital Twins simulate performance and refine requirements early in the design phase.	√	√			√	
(C4) Technical Calculations	AI automates load and energy calculations; BIM integrates technical data in design, IoT provides real-time performance data that informs calculation accuracy.	√	√			√	
(C5) Lifecycle Management	Digital Twins enable ongoing monitoring, BMS manages and adjusts systems with real time data with IoT and manages lifecycle.					√	√
(C6) Communication	Cloud-based tools facilitate cross-stakeholder collaboration, BIM provides a visual single source of truth for technical and functional data. Blockchain enhances the trust among parties.	√		√	√		
(C7) Regulatory Requirements	BIM tracks compliance throughout the design; Blockchain secures compliance records, AI detects non-conformities automatically.	√	√		√		
(C8) Commissioning and Handover	BIM and Digital Twins support accurate as-built records and operational handovers, Blockchain secures commissioning documentation and responsibilities.	√			√	√	
(C9) Procurement Management	Blockchain supports smart contracts and procurement transparency, AI assists in supplier selection and tender evaluation	√	√		√		

Complexities in P&M	Features of the technology to address the complexity in P&M	BIM	AI	DTC	BT	DT	BMS
	(Predictive analytics). BIM provides clear designs and specifications for procurement.						
(C10) Maintenance Management	BMS automates monitoring, fault detection and energy analytics. IoT provides real-time fault data with remote monitoring, Digital Twins simulate maintenance needs and optimise schedules (Performance forecasting), Blockchain maintains accountable and immutable maintenance records.	√				√	√
(C11) Cost	AI predicts cost overruns, BIM improves cost estimation through model-based quantity take-offs, Digital Twins help simulate long-term operational costs.	√	√			√	
(C12) Technical Skills	AI and digital platforms reduce dependency on manual skills, Digital Twins support remote diagnostics, IoT simplifies complex data gathering for technicians. Further Digital twin supports scenario testing.		√			√	
(C13) Future Extensions	BIM allows scalable modular designs, Digital Twins forecast performance under future changes, IoT provides feedback for reconfiguration. Blockchain provides all historical records for knowledge management.	√			√	√	

BIM: Building Information Modelling, AI: Artificial Intelligence, DTC: Digital tools for Communication and Collaboration, BT: Blockchain, DT: Digital Twin, BMS: Building Management System

4. CONCLUSION AND RECOMMENDATIONS

This study highlights the complexities involved in the Procurement and Management of Building Services Systems (P&M of BSS) due to their lengthier lifecycles, the engagement of multiple stakeholders, and the requirement of specialised technical knowledge. A scoping literature review was conducted with 32 journal papers and identified complexities in P&M of BSS in terms of collaboration, approval process, design requirements, technical calculations, lifecycle, communication, regulatory requirements, etc. The findings highlighted the importance of systematic, technology-driven approaches to address these complexities.

Technologies such as BIM, blockchain, digital communication platforms, digital twins, and building management systems have been identified as trending technologies which have the potential to streamline workflows, enhance transparency, and support informed decision-making across different phases of the building services systems lifecycle. It is important to emphasise that these technologies should go hand in hand with each other for better performance. Further, there are limitations of each technology which need attention before the adaptation, including technical, environmental, and people considerations.

Given the limited research focused specifically on building services systems procurement and management, this study contributes to bridging that gap by identifying the complexities and proposing potential technological solutions. The findings are intended to assist project stakeholders, specifically decision-makers, in selecting appropriate digital tools to manage complexity more effectively. By promoting technology adoption, the research underscores the potential for improving efficiency, collaboration, and overall project success in the construction industry, leading to the achievement of sustainable development goals. Future research can focus integration of these technologies for systematic P&M of BSS.

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A REVIEW ON CIRCULAR ECONOMY AND ITS SYNERGY WITH INDUSTRIAL SYMBIOSIS

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ABSTRACT

The construction industry, a major contributor to global material consumption and environmental impact is also pivotal for economic growth and job creation. Hence, transitioning to concepts like Circular Economy (CE) and Industrial Symbiosis (IS) offers a sustainable pathway in reinforcing the industry by mitigating the negative impacts. CE emphasizes principles like reduce, reuse and recycling to close loops, while IS fosters this through cross-industry collaboration by repurposing waste and by-products. This study explores synergies between CE and IS in the context of the construction industry to address the implementation gaps of the two concepts. Through a narrative literature review, this study analyses definitions, and principles to CE adoption in construction sector, such as fragmented regulations, high costs, technical limitations. Moreover, findings reveal that IS is a critical enabler for CE in bridging implementation gaps. This is by facilitating material exchanges between different industries This study also explored current practices of these concepts in various regions. Though the studies prove this synergy, between CE and IS, it was also highlighted that practical challenges persist, at the same time underscoring role of the IS concept due to the lack of trust and systemic linkage. In concluding the research, it was emphasized that policymakers and industries must prioritize in creating and working on collaborative frameworks, standardising regulations while ensuring the construction sector aligns with sustainable development goals.

Keywords: *Circular Economy; Construction Industry; Industrial Symbiosis; Sustainability; Waste Management.*

1. INTRODUCTION

Construction industry with its special features offers unique opportunities to a country, significantly contributing to the economic growth, creating job opportunities, and simulating development processes through projects such as infrastructures. However, the construction industry is known to be among the most material-intensive sectors globally, consuming massive amounts of raw material and generating massive amounts of waste. In the European Union, for instance, the construction industry consumes 1.2 to 1.8 million tons of raw material annually. In Netherlands, constructions industry accounts for approximately 50% of the overall material consumption (Yu et al., 2021). The situation

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is not all that different in the Asian region as well. Even though compared to Northern Europe and North America, many regions of Asia have a low material consumption, it still accounts for a considerable amount (Schiller & Roscher, 2023). Overall, the construction and building sector annually incorporates about 40% of the over 90 billion tonnes of raw materials extracted from the earth (Valentini, 2023). Further, the global consumption of building materials has tripled from 6.7 billion tons to 17.5 billion tons during the period from 2000 to 2017 (Huang et al., 2020). According to the global status report for building and construction, this sector significantly contributes to global climate change while accounting for about 21% of global greenhouse gas emissions. It also states that buildings were accountable for 37% of energy and carbon dioxide (CO_2) emission and 34% of global energy demand specifically in 2022 (United Nation Environment Programme, 2024). Most importantly, the process from extraction to manufacturing of these building materials itself has resulted in almost 90% of the life cycle environmental pollution.

These staggering environmental impacts has brought the need for a transformation towards Circular Economy (CE), a principle which the Ellen MacArthur Foundation defines as an industrial system which brings in a transition from linear "take-make-waste" model into a circular approach (Ellen MacArthur Foundation, 2013). One of the main reasons for a major part of waste generation is the linear economy, whereas in a CE, the circular approach can take the role and work in reducing waste generation. As a sustainable concept, CE shows a significant potential in actualization of the sustainable development goals. Therefore, CE was placed as the heart of sustainable development (Ogunmakinde et al., 2022). Hence, CE has the potential to effectively address the aforementioned issues that the construction sector is struggling with due to the environmental, social and economic pillars globally.

However, this transition towards CE requires practical measures. The actions that stand out among the current CE practices used in the industrial sectors are almost limited in aiming at recycling and reusing within a small range, usually within an organisation. In addition, there are number of studies conducted related to the importance of CE concept, even though the practical implementation of it seem to be lacking. However, recently, the necessity for the implementation of cross-cutting intersectoral networks have been raised as a way forward in transitioning towards a CE (Oskam et al., 2021). Therefore, rather than working in isolation, stronger connections and interactions between sectors have been recognized as important to improve the effectiveness of recovering and reusing materials. To ensure this, Industrial Symbiosis (IS), which focuses on intersectoral exchange of waste or by-products, should be uplifted and implemented universally (Castellet-Viciano et al., 2022). While the theoretical knowledge on CE and IS are well-established, and their individual benefits are acknowledged, yet there is notable gap in literature that explicitly addresses their combined potential to overcome the implementation barriers within specific industrial context, particularly the construction sector. Existing studies often discuss and explore these two concepts in isolation or provide a general overview of their synergy in various other context. However, this synergy has not been explored from a construction industry perspective

This study, therefore, aims to explore the CE and IS concepts and their synergy in the construction industry. This includes the lessons learned throughout the past decades by different countries, and both advantages and disadvantages experienced along with

studying how to fill in the gaps of CE implementation through IS. Accordingly, to achieve the aim of the research, three objectives were formulated as follows:

1. Objective 01: To explore both CE and IS concepts.
2. Objective 02: To find the similarities and differences between CE and IS.
3. Objective 03: To create synergy in bridging the gaps in implementation of CE through IS in the construction context.

2. RESEARCH METHODOLOGY

The research aim was set to explore the concept of CE and its synergy with IS. To fulfil the aim, a narrative literature review was conducted. Selected existing literature sources were use to collect data for this study. Literature sources including journal articles, books and conferences papers were used to gather in-depth knowledge regarding the study area. Moreover, reports, news articles and well-established websites were also used to provide statistics to reinforce the findings. The data was collected by searching key words strings of "Circular Economy", "Industrial Symbiosis" and "Circular Economy" AND "Industrial Symbiosis" in combination. This method made it possible to explore more broadly and openly different sources related to the research topic. The search targeted scientific databases such as Google Scholar, Scopus, and Web of Science with an interest in literature on IS, CE and their integration with specifically focusing on the construction industry. During the process peer-reviewed journal articles, conference papers, and institutional reports were given a priority. Grey literature from Government reports, industry websites, and reputable news sources, gathered through an internet search, were also utilized to ensure that current viewpoints and actual scenarios were captured. This approach which included gathering data from a range of literature sources facilitated producing a wide overview of the field of study, beyond solely academic writing (Snyder, 2019).

3. CIRCULAR ECONOMY (CE)

The concept of the CE has been studied over the past decades and is now gaining significant traction among both researchers and practitioners. According to research, there is no specific single originator or an origin for the CE concept. Yet, many has contributed to bringing up this concept. Some of the significant contributors are Michael Braungart, a German chemist; John Lyle, a U.S. professor along with his student William McDonough and Walter Stahel, an economist and an architect, respectively. Later, in the 1990s, the CE concept was popularized, especially in China, as a response to natural resources scarcity and economic growth. Recycling was a noticeable factor within this concept (Winans et al., 2017). The CE practises in China, which were well-recognized with '3R" concept, was originated from Germany and Japan, where there was a greater desire in forming a more closed loop society (Geng & and Doberstein, 2008). Since there have been various countries and various researchers showing interest towards the CE concept with different views, this section intended to explore the concept of CE in detail, including its definitions, principles, benefits and its applicability for the construction industry.

3.1 DEFINITIONS AND PRINCIPLES OF CIRCULAR ECONOMY

There are various definitions for CE that can be found in different research papers, and minor changes can be seen based on aspects such as the year of introduction, the

researchers, and the study contexts. Some studies have also attempted to collate these different definitions to develop a common definition for CE. Table 1 presents studies identified through an in-depth search of available resources.

Table 1: Existing studies on different CE definitions

Authors	Title	Definition
Kirchherr et al., (2017)	Conceptualizing the circular economy: An analysis of 114 definitions	Acknowledge that CE understanding can be broader than a definition. They define CE as "an economic system that replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes." It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.
Geisendorf & Pietrulla (2018)	The circular economy and circular economic concepts-a literature analysis and redefinition	Stated that "The circularity indicators of the Ellen MacArthur Foundation (2013) only capture the product and company level but fail to provide ideas for the macroeconomic level." They have revised the CE definition with distinguishing between core characteristics of a circular economy and framing conditions enabling its implementation. Their revised distinguish how the most common concepts mentioned by others are situated in different dimensions like efficiency/zero waste target, industry/service oriented, or micro/macro scope.
Awan, et al., (2020)	A Literature Analysis of Definitions for a Circular Economy .	Twenty-eight definitions were taken into consideration covering a period from 1999 to 2019. This analysis revealed that up to this period, stakeholder perspective and resilience were not included explicitly in the definitions. Ultimately it stated, "Circular Economy (CE) is an activity, set of process for reducing the material used in production and consumption, promoting material resilience, closing loops and exchange sustainability offering in such a way that maximize the ecological system."
Alhawari et al., (2021)	Insights from Circular Economy Literature: A Review of Extant Definitions and Unravelling Paths to Future Research	Study focused on capturing the key aspect from the definitions that varied in their coverage and provide better understanding of the CE concept. The authors have defined CE

Authors	Title	Definition
		in the following manner considering the organizational perspective - "CE is the set of organizational planning processes for creating and delivering products, components, and materials at their highest utility for customers and society through effective and efficient utilization of ecosystem, economic, and product cycles by closing loops of concerning resource flows."
Kirchherr et al., (2023)	Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions	The authors believed a clearer, more practical and relevant CE conceptualization can aid in maintaining proper connection between CE practice and research. Through their framework used to examine 221 definitions they also expected to see whether they are universally or locally tailored. This study focused on contributing an updated systematic analysis of CE definitions, while aiming to illustrate where the academic fields currently sit on its own understanding about this concept. They recognized and stated that final definition may never materialize. Moreover, they stated that depending on the regular shifting state of environmental conditions, technologies and economic and socio-political context the definition of CE is more likely to be on a state of evolution.
Sardianou, et al., (2024)	What are the key dimensions that CE emphasizes on? A systematic analysis of circular economy definitions	The authors found that CE definitions have focused on "waste management", "resource scarcity" and "recycling" activities. They also stated that "CE is typically viewed through the lens of waste management, emphasizing the need to reduce unnecessary demand, in addition to promoting efficient resource and product usage." The authors have not provided a specific definition but have analysed several existing definitions. They found and highlighted that "waste" and "recycling" as the central concepts of CE.

3.2 CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY

The concept of CE offers a sustainable solution to the issues created by the linear material consumption trend which is "take, make, dispose" in the construction industry. CE seeks to maintain the material value at the highest point by following practices such as reducing, reusing, and recycling (Andrews, 2015; Lieder & Rashid, 2016). Academic definitions of CE in construction have converged around several key principles like reuse, recycle, recover, and all-together-framework like 3R and 4R (Kirchherr et al., 2023). Over the past decades, a significant transferring has been occurring in the industry, with the CE model adoption. It made a huge change in providing greater potential to reduce both

resource extraction and waste generation for the construction industry. However, as stated by Benachio et al., (2020), there is a greater level of awareness which has been found within CE in the built environment research area about the need of change to a CE from the traditional linear economy concept. Yet, the real-world practitioners argue on the lack of standardized practices and methods to aid in proper implementation of CE in construction industry.

4. INDUSTRIAL SYMBIOSIS AS A SYSTEMIC ENABLER FOR CIRCULAR ECONOMY

The transformation from linear to circular economy needs efforts from everyone and especially from industries, as they play a vital role in transformative consumption and production patterns. European Commission being one of the practitioners had put their focus on different recommendations with measures for the transformation of the industrial sector to maximize recyclability and durability of materials, and through that, ultimately reduce the environmental impact. The initial step of industrial sector in CE strategies is aimed at implementing action plans like using recycled and reused products within production systems (Sardianou et al., 2024). Yet, as the CE concept move further towards seeking advanced criteria, in early 2000s they implemented an action plan transversally rather than vertically along the supply chain (Neves et al., 2020).

Hence, the need of cross-cutting intersectoral networks had arisen to ensure the sustainability of the industrial sector. IS is a subsector within industrial ecology that studies the flows of energy and materials. It has now evolved to an extent where it is viewed in broader terms rather than in isolation. As a result, it tries to interconnect the industries and their process in maximizing the use of energy and materials (Wadström et al., 2021). On the other hand, with the CE concept remarkably being more conceptualized and defined, IS also had started gaining more attention by companies to reduce waste emissions along with an urge to find alternatives for primary resource consumption. Thereby, IS was considered as one of the effective solutions that brings down the primary input consumption and environmental impact of waste emissions (Yazan et al., 2016). Chertow (2007) defined IS as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and byproducts. The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2007). According to the location and the case, the specificity of IS may change. Most importantly, IS only succeeds if companies are willing to take a risk and at the same it lasts only if both the waste supplier and waste user has build-up trust among them (Yap, 2005). Regardless of individual efforts, companies and industries must get together and interact to receive the maximum results of their actions and guarantee a smooth, effective and efficient flow of recovered and reused materials. To achieve this, IS, which is being practiced in some of the European countries must be universally implemented (Castellet-Viciano et al., 2022). According to Martin et al., (2015), IS can be identified as an effective enabler in accomplishing the principles of the CE.

4.1 DEFINITIONS AND PRINCIPLES OF INDUSTRIAL SYMBIOSIS

IS promotes physical exchanges of wastes, energy, and by-products among traditionally separated industries in a collective manner (Chertow, 2007). It is a sub-field of industrial ecology, which is now gaining attention through literature as a key strategy being

supportive for the transition towards CE (Fraccascia & Giannoccaro, 2020). The main principle here is that two parties in particular, identified as waste producer and waste user, get together to establish a relationship where one would exploit the waste of the other party to make a new product or to replace an input in the production process (Patricio et al., 2022; Chertow, 2000). Chertow (2000) had defined the IS as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity". This definition is widely being disseminated (Neves et al., 2020). A more recent definition by Haq et al. (2021) defines IS as "a collaboration scheme for competitive advantage where industrial trade is essential to developing a sustainable future because it involves resources, energy, water, and/or by-products being exchanged among various industries".

4.2 SYNERGIES BETWEEN CIRCULAR ECONOMY AND INDUSTRIAL SYMBIOSIS

CE concept's first roots run back to almost sixty years early consists of a fundamental part similar to Green Economy and industrial ecology, where IS is a sub-field of the industrial ecology. According to Andersen, (2007), IS seeks to optimize the management of the flow of materials, energy, water by-product, and ultimately to enhance the linear chain of consumption and production just as the CE concept. IS in particular, having a string to the CE, focus on operating at the inter-firm level (Yazan et al., 2016). As a result, IS has been identified as great potential component in facilitating CE by the European Commission (Álvarez & Ruiz-Puente, 2017).

4.2.1 Similarities and Comparative Analysis between Circular Economy and Industrial Symbiosis

Further to above findings from various literature, this section provides an overview of the most relevant similarities and differences between the two concepts, CE and IS, as depicted in Table 2.

Table 2: Similarities between circular economy and industrial symbiosis

Similarities between CE and IS
Aims to integrate the principles of environmental sustainability.
Foster material circularity to ensure more efficient usage.
The idea of waste can be repurposed is central in both.
Thrives to build linkage and relationships in different level of degree.
Contribute and encourage in local collaboration, job creation and cost saving.

The following Table 3 further provides a comparison on the key aspects of CE and IS concept.

Table 3: Comparative analysis between CE and IS
Source: Adapted from Vargas-Merino et al., (2022), Chertow & Park (2016) and Neves et al., (2020).

Factor	Circular Economy	Industrial Symbiosis
Main Goal	Slow down the scarcity of natural resources while minimizing environmental	Collaboration between industries to exchange materials, waste,

Factor	Circular Economy	Industrial Symbiosis
	damage through reducing pollutions.	energy and by-products to reduce environmental impact.
Research area	A wider range of recovery system	Generally, the direct physical exchange of materials, energy and by-product through pipelines system
Focus/Emphasizes on	Materials and products of all kinds	Largely industrial waste and by-product
Bottomline of the Term	Encourage resource efficiency and reduce waste through recycling	Enhance industrial collaboration and facilitates resource sharing.
Mainstream	Minimization of resource extraction; minimize waste	Waste-to-Resource, Inter-industry collaboration
Fundamental Principles	Developing imperative of sustainable development R; 3Rs improved to 9Rs	Cross-Sector collaboration, Sharing among waste producer and waste user

4.2.2 Industrial Symbiosis to Address Gaps in Circular Economy Implementation

CE is well-known to be a broader concept that tries to bring out the sustainability. In fact, the system-level approach of CE has been organized into three levels, named as the macro, meso and micro level. Each level has gaps which are needed and are being address. As the Figure 1 below elaborates, along with our key consideration on both levels of CE and IS, has been found go to hand in hand. In fact, IS has the potential to fill the gap within a wider approach to fill the one of the gaps of CE in practical implementation (Palagonia et al., 2025).

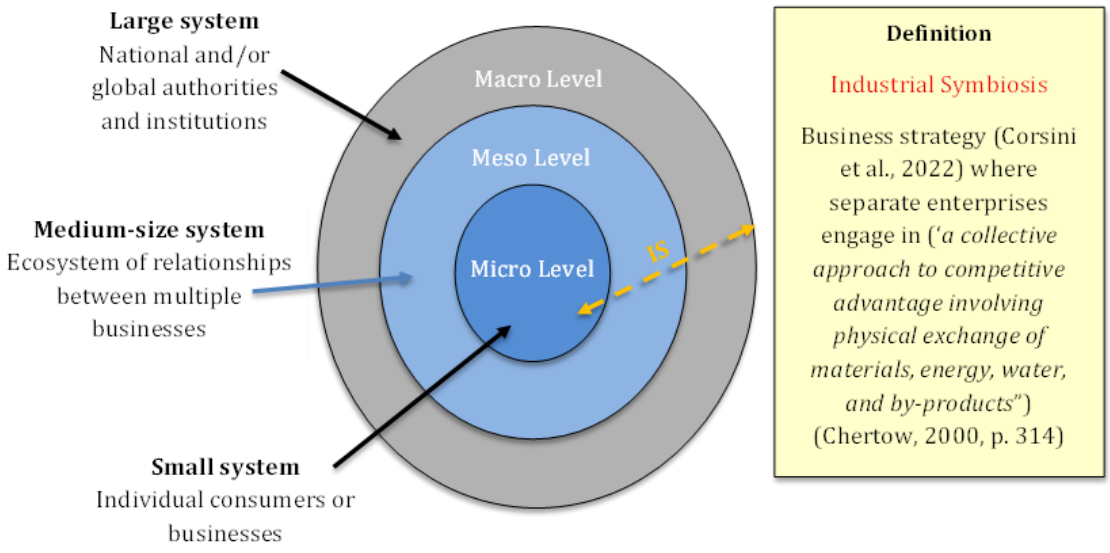


Figure 1: The industrial symbiosis within circular economy system level
Source: (Palagonia et al., 2025)

4.2.3 Collaborative Opportunities between Construction and other Industries

Park et al. (2015), had studied nine case resources circulating under IS development, where those projects delivered major benefits in Korea without a requirement of any investments. For instance, heat transfer salt which has reach the end-of-life stage in petrochemical process was repurposed in an easy manner as descaling salt for stainless steel. In another case, a waste organic solvent was directly used as a paint ingredient. For this no extra process was needed. Moreover, there have been IS activities seen in Europe as well regardless less attention in the literature related to this area. The European commission had introduced a revised CE package as an action plan for the CE where they refer the role of IS in focusing on the concept where "*waste or by-products of one industry to become inputs for another"* (Domenech et al., 2019). There has been waste recovery practice through IS found in two construction projects in Brazil. Through this it was found that those two project had 9% and 30% of waste was recovered through IS (Freitas & Magrini, 2017).

4.2.4 Conceptual Framework for Bridging Circular Economy Gaps through Industrial Symbiosis in the Construction Sector

According to the findings, a conceptual framework is proposed in Figure 2 which illustrates how the IS enables the implementation of CE principles within the construction sector by bridging the gap.

At the base of the framework, lies the construction industry which is traditionally resource-intensive and operates under a largely linear model of "take-make-dispose". Regardless, the increasing recognition of CE principles like reuse, recycling, and resource efficiency, there is a clear and greater implementation gap that hinders their full adoption in practice. Hence, the "gap" has been positioned at the centre of the framework representing the disconnection caused by barriers such as fragmented regulations, limited collaboration, technical challenges and high cost. The framework highlights that IS can effectively address this gap along with the proper contribution from Strategic/Policy Layer and Industry Actors. Through encouraging collaboration between different industries, IS facilitates the exchanges and repurposing of material, energy, and by-product transforming waste from one process into valuable input of another.

Finally, the goal is presented on top of the framework, which is an improved CE in the construction industry. As a result, the construction industry can move beyond isolated efforts and adopt more systemic, sustainable practices that align with the broader goals of environmental and sustainable development.

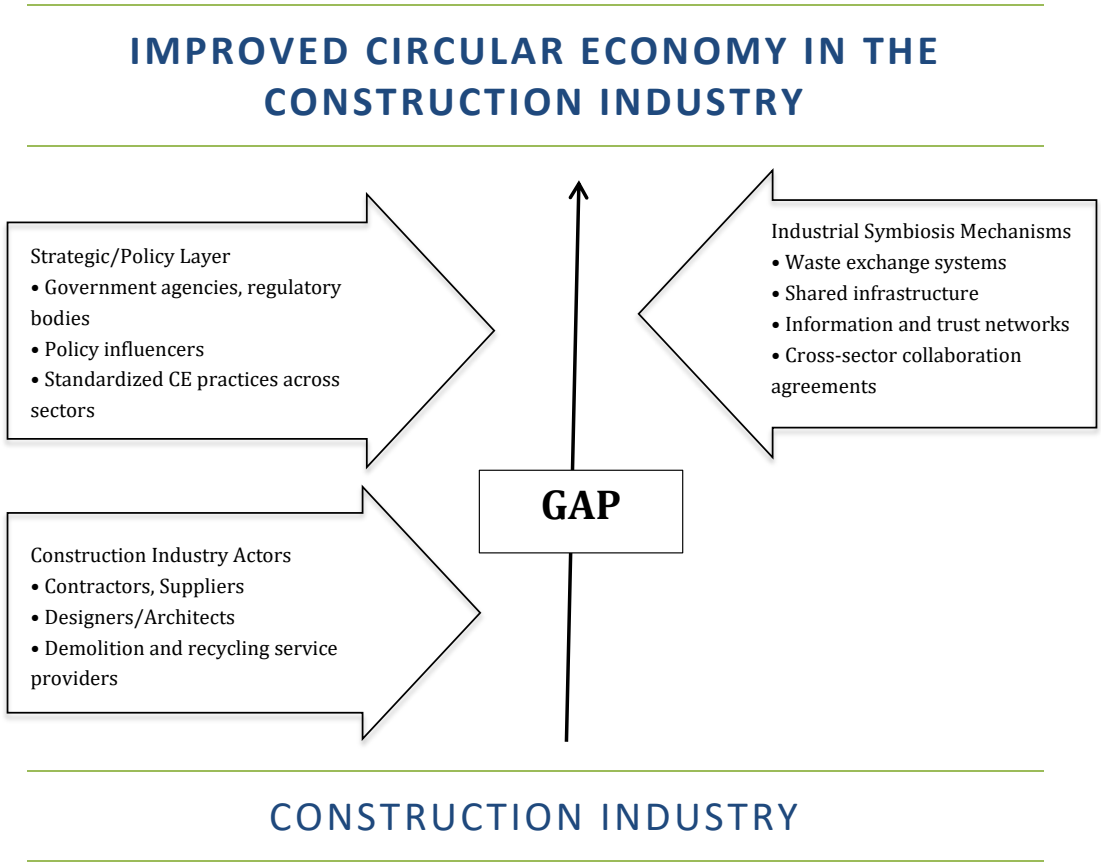


Figure 2: Conceptual framework for bridging circular economy gaps through industrial symbiosis in the construction sector

5. CONCLUSION

At present, CE is gaining attention increasingly as one of the promising solutions to address the environmental issues and the challenges of resource depletion. It was also found that even though CE has the potential to deliver significant environmental, economic and social benefits, it also includes gaps that has impacted on the proper and effective implementation of the concept in terms of all three levels (macro, meso, and micro). IS has the potential to connect within wider approach of CE and shift towards a multilevel framework. Studying about the synergies between CE and IS can help in better understanding the concepts and their effective implementation for beginners. Among the many definitions, understanding the concepts in an analytical manner and comparing the two concepts based on their similarities and differences, this study aimed at building awareness about the linkage between the two concepts. Through this narrative literature review, the authors presented various definitions on the concepts and similarities of both the concepts, where it was clear that CE and IS has goals in-line, except that CE is a broader concept than IS. The findings of this study highlights that IS directly addresses several crucial implementation gaps in CE, such as lack of systemic linkages, fragmented material flows and challenges faced in establishing cross-sectorial collaboration. Considering that this study provides evidence for the potential of IS in filling implementation gaps within CE, it would be a great contribution to study on the

mechanism to initiate this and recommend frameworks for better progression. The construction industry must see to it that they are actively seeking and establishing collaborative partnerships for material and energy exchange. This can be achieved through fostering trust and investing in infrastructure that supports inter-firm resource flows. Policymakers may boost this process through developing and enforcing regulatory frameworks and incentives that may specifically promote IS networks within the construction industry. It could include tax breaks while researchers focus on developing practical tools and guidelines to facilitate the formation and management of IS networks.

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A SCOPING REVIEW OF CONSTRUCTION SMES: GLOBAL VS LOCAL

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ABSTRACT

The small and medium-sized enterprises (SME) sector is a significant driver of economic growth, significantly contributing to employment and gross domestic product (GDP) worldwide. However, Sri Lankan construction SMEs are lagging behind compared to those in other countries, where innovative legal frameworks and good practices have supported SME development and competitiveness. Learning from these global practices presents an opportunity to strengthen the local SME sector. Therefore, this study aims to investigate SMEs in local and global contexts comparatively. It explores SME definitions, legal provisions, and their role in economic development, while examining international best practices to enhance SME performance and resilience in Sri Lanka. A scoping review, supplemented by manual data analysis, reveals the absence of a universal SME definition and dedicated legislation, particularly in the construction sector. A comparative analysis of SME definitions across India, Japan, Europe, and Sri Lanka highlights varying approaches, often based on multiple criteria. Sri Lanka lacks dedicated SME act, relying instead on a policy framework and general legislation, with no specific provisions for construction SMEs. The study emphasises the vital role of SMEs in economic development as incubators for larger firms, drivers of employment and innovation, and contributors to social mobility and international trade. Their significance in economic recovery is examined, along with a review of legal frameworks, comparing dedicated SME acts with broader policies, including the current strategy of Sri Lanka. To support SME growth, the study proposes targeted legal provisions, digital transformation, e-commerce promotion, innovation support, and improved access to global markets.

Keywords: *Definitions; Global; Legal Provisions; SME Contractors; Sri Lanka*.

1. INTRODUCTION

The construction industry is crucial for driving the economic growth of a country and serves as an indicator of development (Ahmed, 2017; Peter et al., 2019). In most countries, this sector consists of a small number of large firms alongside a substantial proportion of small and medium-sized enterprises (SMEs) (Tezel et al., 2018). Despite the importance of SMEs, which is evident globally, there is no official definition which

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is universally followed. The most common indication is by the number of employees, and there are certain other parameters that are used to define SMEs as well (Economic and Social Commission for Asia and the Pacific [ESCAP], n.d.). According to Acar et al. (2005), the term SME is interpreted differently across regions and countries, with the number of employees being the primary criterion for determining the size of construction firms. Despite this challenge, SMEs play a significant role as economic drivers, acting as employment providers and job creators with the flexibility to foster new developments. In fact, they contribute a greater proportion of output in many countries around the world. SMEs account for nearly two-thirds of global employment and more than 50% of GDP in numerous nations (Madhavika et al., 2024).

SMEs are important to the economic development in both global and local contexts in several ways. SMEs are where large companies originate, making them the breeding grounds for larger organizations (Central Bank of Sri Lanka, 2021). Moreover, they are important as employment providers, which assist in improving the social status of people by reducing poverty. It is stated that SMEs cover 70% of employment worldwide ("The Power of small", 2019). According to World Bank estimates, by 2030, there will be a need for 600 million jobs for the growing population. Considering the high population growth in developing countries, SMEs will become considerably important as an employment provider (Central Bank of Sri Lanka, 2021). The flexible nature of SMEs makes them an essential sector during different downward economic situations, such as economic crises and pandemics, as well (Rizkiya, 2024). They can absorb new technology and knowledge more easily, which makes start-ups and SMEs be used as incubators for innovations which in future could be developed into major organizations (Xinhua, 2021). In Sri Lanka, SMEs are crucial in exports as well. Even though not seen, SMEs play a crucial role in Sri Lankan exports and can contribute more if the necessary frameworks to support SMEs are developed (Sri Lanka Export Development Board, 2022).

While recognizing the importance of SMEs, it is essential to adopt good practices that can enhance their capacity and capabilities. Legal provisions for SMEs vary significantly across countries. A key aspect is the establishment of proper legislation governing SME operations, including company registration, which has proven successful in countries like Japan (Nakagawa, 2012). Japan, which recognizes SMEs as a major economic driver, has dedicated legislation supporting them (Nakagawa, 2012). In contrast, countries such as the Philippines and Singapore lack specific laws targeting SMEs (Association of Southeast Asian Nations [ASEAN], 2025). Additionally, Sri Lanka does not have a dedicated SME act, relying instead on a National Policy Framework. However, several acts, such as The Inland Revenue Act No. 24 of 2017 and The Intellectual Property Act No. 36 of 2003, address certain aspects of SMEs' operations (Diriya Sri Lanka, 2024).

Construction industry SMEs play a similar role in driving economic growth; however, the sector requires unique approaches due to its specific characteristics. Most SME legislations are generic and not tailored to the construction industry. Therefore, it is important to develop a construction-specific legal framework (Mengistu et al., 2024). In addition to legal provisions, fostering innovation within SMEs is essential (Central Bank of Sri Lanka, 2021). Creating opportunities for SMEs to network with other industry organizations will help enhance their knowledge base and compete globally with confidence (Chen & Mitra, 2022). Digital transformation plays a crucial role in the development of SMEs, with legal and financial support facilitating progress, as evidenced

by successful examples in Brazil (Patterson-Waites, 2023). Furthermore, adherence to e-commerce is vital, particularly for Sri Lanka (Gunawardene, 2017).

Given these challenges, there is a pressing need to examine the role of SMEs in both local and global contexts and explore the best practices, legal frameworks, and innovations that can be adopted to strengthen the SME sector, particularly in Sri Lanka. Therefore, it is crucial to identify how Sri Lanka can adapt successful global practices to its unique context and enhance the capacity of its SME sector, particularly in construction, to contribute more effectively to economic growth and development. Therefore, this study aims to investigate SMEs in local and global context comparatively focusing on four main areas; (1) definitions of SMEs in global and local contexts, (2) importance of SMEs in the economic development in global and local contexts, (3) legal provisions related to SME contractors in global and local contexts and (4) good practices that can be derived from global context to enhance the local SMEs. The structure of the paper is as follows: The introduction is followed by the methodology section. The findings, based on a scoping review, are then presented. The paper concludes with a summary and suggestions for future research.

2. METHODOLOGY

This study employed a scoping review to collect data, and the findings were interpreted through content analysis.

Scoping Review

A Scoping Review Methodology was utilised to systematically examine existing literature and assess the significance of best practices in SMEs, comparing global and local contexts. This approach aimed to provide a factual and relatable understanding of SME development, particularly in the context of a developing country.

Scoping reviews serve as an evidence synthesis tool, mapping the breadth of available research on a specific topic, concept, or issue within defined contexts (Pollock et al., 2024). Authors have followed nine key steps (Peters et al., 2021) and JBI (Joanna Briggs Institute) guidelines when conducting the scoping review, as illustrated in Figure 1.

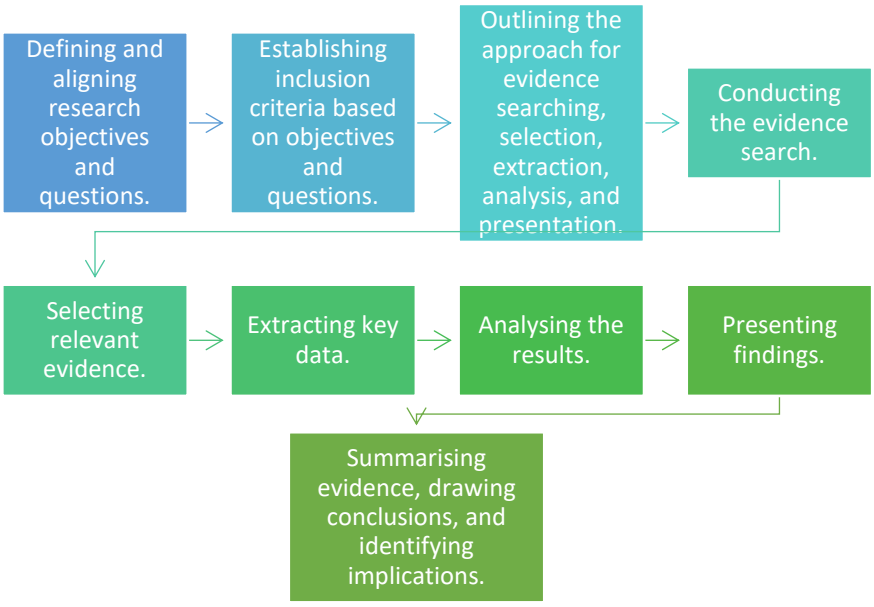


Figure 1: Steps followed when conducting the scoping review

Content Analysis

Qualitative data collected from scoping review was analysed using content analysis, a systematic method for identifying patterns, themes, and insights within textual data (Ullah & Ameen, 2018). This approach involves categorizing and coding information to uncover relationships and trends relevant to SME contractors in the construction sector. The insights generated through content analysis assisted in identifying the viability of good practices that can be adopted and effective steps to be taken.

3. FINDINGS AND ANALYSIS

3.1 DEFINITIONS OF SMES IN GLOBAL AND LOCAL CONTEXTS

Definitions of SME distinctly vary from country to country. Hence, there is no universally recognized definition (Acar et al., 2005). Acar et al. (2005) further added that the term SME has varying definitions are a result of the different phases of economic development, size and prevailing social conditions of the country. However, most of these definitions are based on criteria that refer to employment, annual turnover, size of balance sheet, assets, invested capital, sales volume and production capacity, while the most conventional reference is the number of employees (ESCAP, n.d.)

Table 1: Definitions of SMEs

Country	Sector	Currency	Criteria	Micro		Small		Medium	
				No. of Employees	*Value*	*No. of Employees*	*Value*	*No. of Employees*	*Value*
Malaysia	Manufacturing [1]	RM	Sales turnover	1-4	< 0.3 Mn	5-74	0.3 – 15 Mn	75-200	15-50 Mn
	Services and other [1]	RM	Sales turnover	1-4	< 0.3 Mn	5-29	0.3 – 15 Mn	30-75	3-20 Mn
Philippines	[1]	PHP	Total assets exclusive of land		≤ 3 Mn		3- 15 Mn		15- 100 Mn
Singapore	[1]	SGD	Sales turnover	≤ 200	≤ 100 Mn	≤ 200	≤ 100 Mn	≤ 200	≤ 100 Mn
Vietnam	Agriculture, forestry and fishing Industry and construction [1]	VND	Total revenue	1 - 10	< 3 billion & < 3 billion	11 - 100	3-50 billion & 3-20 billion	101 - 200	50-300 billion & 20-100 billion

Country	Sector	Currency	Criteria	Micro		Small		Medium	
				No. of Employees	*Value*	*No. of Employees*	*Value*	*No. of Employees*	*Value*
European countries	[2]	Euro	Turnover	< 10	≤ 2 Mn	< 50	≤ 10 Mn	< 250	≤ 50 Mn or
		Euro	Balance sheet		total ≤ € 2 Mn		total ≤ 10 Mn		≤ 43 Mn
India	Manufacturing and Service Sector Enterprises [3]	Indian Rupees	Investment in Plant and Machinery or Equipment		up to 10 Mn		up to 100 Mn		500 Mn and
		Indian Rupees	Annual Turnover		< 50 Mn		< 500 Mn		< 2500 Mn
Japan	Manufacturing and Others (including construction sector) [4]	Yen	Capital			20 or less		300 or less	300 Mn or less
	Wholesale [4]	Yen	Capital					100 or less	100 Mn or less
	Retail [4]	Yen	Capital					50 or less	50 Mn or less
	Service [4]	Yen	Capital			5 or less		100 or less	Capital 50 Mn or less
Sri Lanka	Manufacturing Sector [5]	Rupees	Annual turnover	Less than 10	less than 15 Mn	11 - 50	16 – 250 Mn	51 - 300	251 – 750 Mn
	Services Sector [5]	Rupees	Annual turnover	Less than 10	less than15 Mn	11 - 50	16 – 250 Mn	51 - 200	251 – 750 Mn

Country	Sector	Currency	Criteria	Micro		Small		Medium	
				No. of Employees	*Value*	*No. of Employees*	*Value*	*No. of Employees*	*Value*
	Construction Sector [6]	Rupees	Annual turnover				Rs. 16 - 250 Mn, CIDA grade C9 – C4		250 - 750 Mn, CIDA grade C3 – C2

[1]: (ASEAN, 2024), [2]: (European Commission, n.d.), [3]: (SME Chamber of India, n.d.), [4]: (Organization for SME and Regional Innovation, n.d.), [5]: (Ministry of Industry and Commerce, 2016), [6] :(Ranadewa, et al., 2018)

Table 1 shows a comparison of several countries' definitions of SMEs. In Southeast Asia, the definitions vary depending on the country's income level. For instance, Malaysia, an upper middle-income country with a population similar to Sri Lanka's, defines SMEs differently from the Philippines, which is a lower middle-income country. On the other hand, Singapore, a high-income and developed country, does not differentiate between micro, small, and medium enterprises (Metreau et al., 2024; Wickrmatilake, 2018). Furthermore, it can be observed that most ASEAN countries do not specifically have classified construction SMEs. However, Vietnam stands out as it provides a definition for construction SMEs alongside other industrial SMEs.

In Europe, where most countries are high-income nations (Metreau et al., 2024), the definition of SMEs is typically based on three key criteria (European Commission, n.d.). In India, a fast-developing country, SMEs are defined according to a composite criterion that includes investment in plant and machinery/equipment and annual turnover (SME Chamber of India, n.d.). The definition for construction industry SMEs in India aligns with this general SME definition, as stipulated in the MSMED Act 2006 and the Industries Development and Regulations Act 1951. Similarly, Japan, another high-income country (Metreau et al., 2024), defines SMEs in accordance with the criteria depicted in Table 1 (Organization for SME and Regional Innovation, n.d.).

In Sri Lanka, SMEs are generally defined by the number of employees and annual turnover, as outlined in the National Policy Framework for SME Development by the Ministry of Industry and Commerce (Ministry of Industry and Commerce, 2016). For construction SMEs, the definition is proposed to be based on annual turnover and CIDA grading, as provided by the Ceylon Institute of Construction Development (Ranadewa et al., 2018). However, it is important to note that there is no universally recognized classification system for construction industry SMEs.

3.2 IMPORTANCE OF SMES IN ECONOMIC DEVELOPMENT IN GLOBAL AND LOCAL CONTEXTS

In developing economies, construction SMEs play a crucial role in job creation and poverty reduction (Usman & Alaezi, 2016). Consequently, acknowledging the economic significance of SMEs within the construction sector is essential (Ranadewa et al., 2015). The following section provides a summary of the contribution of SMEs to economic development in both global and local contexts.

3.2.1 A Breeding Ground for large Organisations

Most of the present business giants have once been initiated as small businesses. Large businesses are more productive, have better access to finance, the capacity to invest in bigger projects and the ability to facilitate research and development, while MSMEs play the role as the breeding ground for the large businesses. A successful economy should have a healthy mix of both large and small businesses. MSMEs contribute to influencing the general public's entrepreneurship, which helps the growth of the economy by enhancing human capital (Central Bank of Sri Lanka, 2021).

3.2.2 Employment and Job Creation

SMEs contribute to approximately 70% of global employment, serving as key drivers of job creation, particularly in developing economies ("The Power of Small", 2019). In the construction sector, SMEs play an essential role in employing both skilled and unskilled labourers, directly impacting income levels and poverty reduction (Anaman & Osei-Amponsah, 2007). The Employment-Intensive Investment Program (EIIP) highlights that 220 million people worldwide are employed due to the construction industry ("The Power of small", 2019). However, challenges such as job continuity and workforce retention persist, especially in developing countries where SMEs operate under uncertain and volatile market conditions (Ranadewa et al., 2018).

3.2.3 Innovation

SMEs are recognised as hubs for innovation, contributing to economic development by introducing new products, services, and technological advancements (Amoah et al., 2022). Their flexible structure enables them to adapt quickly to market demands and invest in creative solutions. Countries such as China have actively supported SME-led innovation through initiatives like the incubation of "little giants" in high-tech industries (Xinhua, 2021). Similarly, European SMEs have played a significant role in patent development, particularly in fields like biotechnology (Bayraktar & Algan, 2019). Sri Lankan SMEs also contribute to innovation, offering unique solutions that enhance competition and drive industry advancements (Rizkiya, 2024).

3.2.4 Fulfilment of Corporate Social Responsibilities

Amoah et al. (2022) discussed the importance of SMEs, including employment, job creation, and innovation, which have ultimately contributed to Africa's economic growth. Additionally, Sri Lanka is a country with a similar developing economy to Ghana in Africa, in which SMEs have given their contribution to the fulfilment of social responsibilities and economic growth as mentioned in the table above (Central Bank of Sri Lanka, 2021).

3.2.5 Exports

According to what is mentioned in the table above SMEs represent a hopeful market for goods and services exports in Sri Lanka (Sri Lanka Export Development Board, 2022). It is said that export of construction services, which could be categorized as construction work, consultancy in construction work and project development work, could become the panacea for the laid-up construction industry of the country as well as the Sri Lankan Economy (Wijeratne, 2023).

3.3 LEGAL PROVISIONS RELATED TO SME CONTRACTORS IN GLOBAL AND LOCAL CONTEXTS

SMEs, or small enterprises, play a crucial role in engaging with communities and fostering innovation in the development of products and services for consumers within a market economy. As economies undergo digital transformation, SMEs act as catalysts for change, driving the shift towards a new market structure. Governments must ensure that laws, regulations, and policies support the establishment and growth of SMEs. Consequently, many countries have implemented legislation and strategies designed to promote the development of SMEs.

In Sri Lanka, there is no exclusive legal provision for SMEs, but there is the National Policy Framework for SME development, which outlines the vision, mission and strategies for promoting and supporting the MSME sector (Diriya Sri Lanka, 2024). Additionally, there are certain other acts which address different aspects of SMEs as mentioned above. Figure 2 presents an overview of the various legislative frameworks and legal provisions that have been adopted by countries globally to govern and support SMEs.

3.4 GOOD PRACTICES THAT CAN BE DERIVED FROM GLOBAL CONTEXTS TO ENHANCE THE LOCAL SMES

Enhancing the capabilities and competitiveness of Sri Lankan SMEs necessitates a comprehensive approach that incorporates successful strategies and best practices from a variety of global contexts (Gamba, 2019). Given the substantial role of SMEs in fostering economic development, particularly in developing nations, it is essential to address the challenges they encounter and bolster their ability to compete in the global market. (Issau et al., 2022). In order to overcome these obstacles and fully realise the potential of Sri Lankan SMEs, policymakers and business leaders can benefit from the insights gained from international experiences, adapting proven models to meet the specific needs and context of the Sri Lankan economy (Gamba, 2019; Ranadewa et al., 2018).

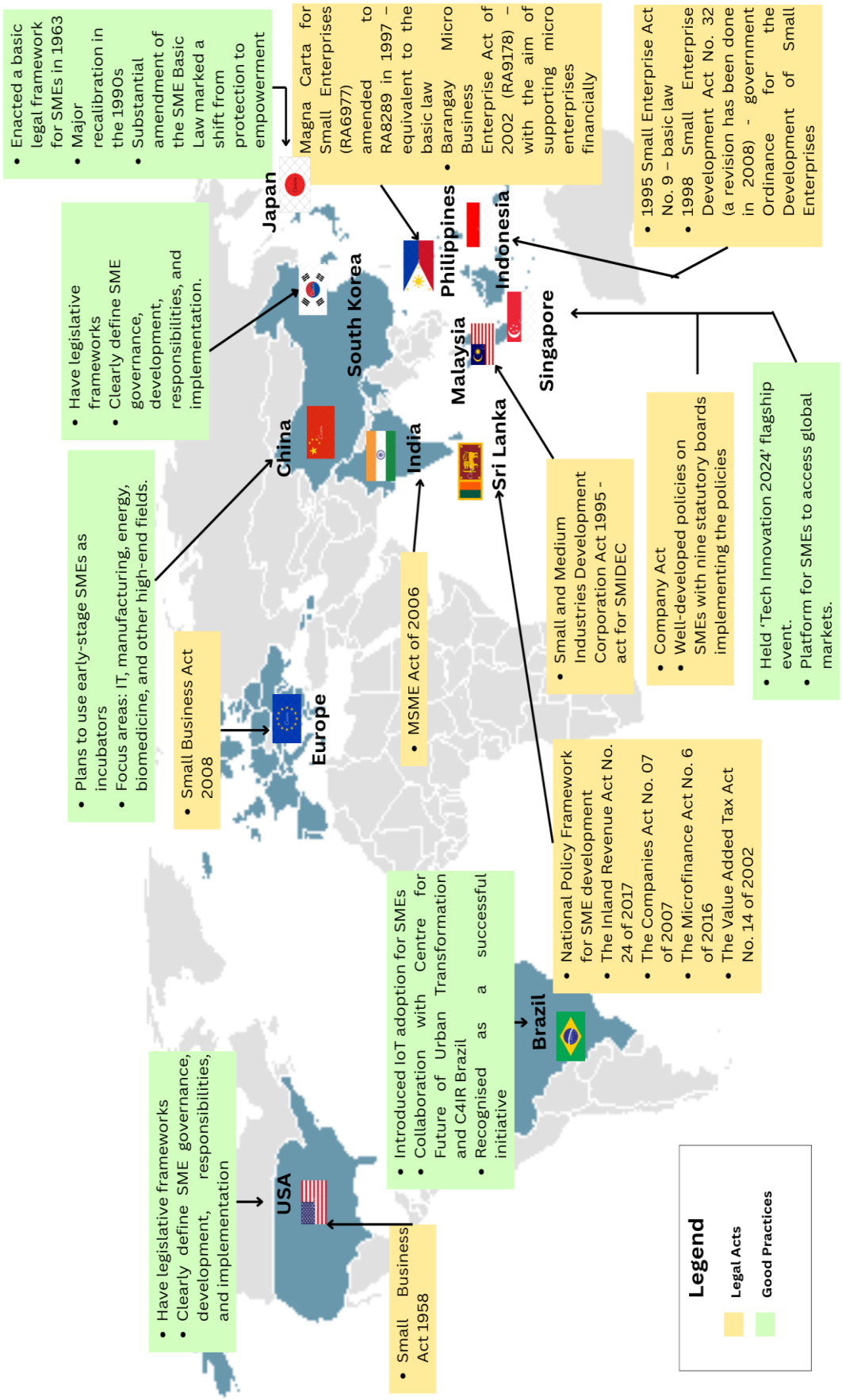


Figure 2: Legal provisions related to SME contractors in global contexts & good practices that can be derived from global contexts to enhance the local SMEs

Figure 2 provides a summary of the best practices that can be adopted from other countries to strengthen Sri Lankan SMEs.

3.4.1 Establishment of Targeted Legal Provisions

Japan and South Korea provide strong examples of SME-focused legislative frameworks, ensuring clarity in governance, development, and policy implementation (Nakagawa, 2012; Knowledge and Research, 2020). The recalibration of Japan's SME Basic Law in the 1990s transformed SMEs into drivers of economic growth rather than passive recipients of protection. Similarly, Sri Lanka requires a dedicated legal framework for SMEs, particularly in the construction sector, to address challenges such as payment paralysis and contract enforcement issues (Rajapakshe et al., 2021; Kaggiah, 2022). Implementing clear legal provisions would create a more supportive business environment and facilitate sustainable SME growth.

3.4.2 Digital Transformation and E-Commerce

The adoption of digital technologies is crucial for enhancing SME productivity and market reach (Patterson-Waites, 2023). Brazil's successful integration of IoT solutions for SMEs demonstrates how digitalisation can significantly improve operational efficiency and return on investment (Aguilar & Salihudin, 2024). However, Sri Lankan SMEs face challenges such as high transaction fees for online payment systems and limited access to digital resources (Gunawardene, 2017). Encouraging affordable digital payment solutions and providing digital literacy training can enhance the participation of SMEs in e-commerce and global trade.

3.4.3 Empowering SMEs to Initiate and Develop Innovations

China has strategically positioned SMEs as incubators for emerging technologies in manufacturing, energy, and biotechnology, integrating them into broader industrial and supply chains (Xinhua, 2021). In Sri Lanka, fostering SME-driven innovation is critical for economic progress. For the construction industry, innovation can be influenced by client demand, procurement arrangements, and collaborative project environments (Hardie & Newell, 2011). Establishing research partnerships and providing financial support for innovation-driven SMEs will strengthen their role in sustainable development.

3.4.4 Improving Linkages to Compete Internationally

Singapore's 'TechInnovation 2024' event facilitates strategic matchmaking among potential business partners where innovators, technology providers, and industry leaders are present. The main goal of IPI, which is the organizer of this event, is to improve the linkage of Singaporean companies with international partners (Asia Research News, 2024). Industry networks heavily impact the innovative capacity of construction industry SMEs as well. Knowledge sharing and joint problem solving through collaboration could enhance each other's capacity. However, there should be opportunities, such as forums by professional associations and research associations in order to provide a proper industry network (Hardie & Newell, 2011).

A thorough and context-sensitive approach is necessary to improve the performance, resilience, and long-term viability of Sri Lankan SMEs, especially in the construction industry, by taking inspiration from these global best practices. First, the creation of a strong and well-defined legal framework based on successful programs in the US, South Korea, and Japan would enhance contract enforcement, create a stable policy

environment, and address systemic problems like poor dispute resolution and late payments. Having such a legal basis is essential for boosting investor trust and promoting SME involvement in official procurement processes, especially for public infrastructure projects. Additionally, SMEs can greatly improve their operational efficiency and market access by adopting digital transformation through the creation of inclusive payment systems, e-commerce platforms, and low-cost digital infrastructure. Smoother transitions to digital operations can be facilitated by strategic relationships with local financial institutions, digital innovation clusters, and international technology providers. Additionally, incorporating digital literacy into national SME development plans will guarantee fair access and lessen the digital divide between urban and rural areas.

In addition, it is critical to cultivate an innovative culture. SME participation in high-value industries can be accelerated via government-led innovation subsidies, tax breaks, and assistance for incubators and accelerators. SMEs in the construction sector might be urged to create digital project management tools, modular construction techniques, and sustainable technology. Enhancing businesses' ability to absorb innovation through upskilling initiatives and promoting knowledge transfer from academic and research institutions are also necessary for integrating innovation into the SME ecosystem. Increasing international connections will help Sri Lankan SMEs better integrate into global value chains and gain knowledge of sustainability standards and global market demands. Targeted networking gatherings, innovation expos, bilateral trade missions, and involvement in regional SME forums like ASEAN SME initiatives can all help achieve this. Additionally, creating cross-border research partnerships and exchange initiatives will support SMEs in maintaining their agility in a rapidly changing and competitive global marketplace. Lastly, it is crucial that these approaches be applied as part of a coordinated, multi-stakeholder approach that involves academic institutions, industrial associations, the private sector, the government, and international development partners. In addition to increasing the productivity and competitiveness of Sri Lankan SMEs, adjusting these techniques to the local environment while maintaining alignment with international standards will also make a substantial contribution to employment creation, national economic growth, and sustainable development. One of the main pillars of Sri Lanka's shift to a more innovative and inclusive economy will be a robust and cohesive SME sector.

4. CONCLUSIONS AND RECOMMENDATIONS

This study aimed to investigate SMEs in both local and global contexts, highlighting their critical role in driving economic growth, innovation, and employment. Although SMEs are widely recognised across nations, a standardised definition remains absent. Countries vary in classification criteria Singapore maintains a broad definition, while Japan and Malaysia apply sector-specific distinctions. Notably, construction SMEs often receive insufficient attention despite their unique operational challenges. In the Sri Lankan context, the lack of a dedicated legal framework for construction SMEs has contributed to persistent issues such as payment delays, limited access to finance, and weak institutional support. Insights drawn from international best practices underline the importance of establishing clear legal and policy structures tailored to the sector’s needs. Global examples also illustrate how digitalisation, e-commerce, innovation support, and international linkages can significantly enhance SME resilience and competitiveness.

To strengthen SME development in Sri Lanka, the introduction of a formal classification system for construction SMEs and the implementation of a targeted legal framework are essential. Complementary measures, including financial incentives, technology adoption, and innovation partnerships, will help bridge gaps between SMEs and larger enterprises. Encouraging global collaboration and knowledge exchange can further position Sri Lankan SMEs to compete in international markets. Theoretically, this study contributes by comparing SME structures across contexts and identifying key lessons for policy development. However, it is limited in its exploration of practical mitigation strategies tailored to construction SMEs. Future research should focus on contextualising international practices and developing actionable implementation plans to address specific local challenges and foster long-term SME growth.

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A STUDY ASSESSING THE APPLICATION OF ARTIFICIAL NEURAL NETWORK FOR PRELIMINARY ESTIMATION IN SRI LANKAN BUILDING PROJECTS

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ABSTRACT

Preliminary estimations are prepared at the early stages of every construction project to determine the project's financial feasibility. The Artificial Neural Network (ANN) method is a machine learning method that could also be utilised in preliminary estimation for forecasting and predicting the cost with higher accuracy at a very early project stage. A mixed research approach was used for this research. In the first stage, an ANN model with 11 input attributes was developed, with an obtained accuracy of 89.56% in the validation process. In the second stage, the suitability and applicability of the ANN method for preliminary estimation within the Sri Lankan context were investigated through 10 semi-structured interviews. The frequent use of traditional methods for preliminary estimation practice is widespread. Furthermore, the preferred accuracy is more than 80% in the context. The increased accuracy, time efficiency and usability of the ANN model emphasise the suitability of ANN in the construction industry. However, the insufficiency of the databases within the firms, the lack of programming knowledge, and people's reluctance to change were identified as challenges. Conversely, initiating a centralised database system within the context, outsourcing the resource requirement to develop the ANN model, and reducing the knowledge gap in the industry regarding modern methods were identified as remedies. Adding location, price fluctuation, and risk uncertainty as input attributes are suggested improvements and modifications for the ANN model, which is the first model with almost 90% accuracy.

Keywords: *Artificial Neural Network (ANN); Cost Estimation Model; Computer-based Estimation; Preliminary Estimation.*

1. INTRODUCTION

Innovative thinking drove society to a modern era where basic human needs and wants are sophisticated (Moses, 2022). Modern civilisation demands more complex, reliable, and aesthetically pleasing buildings and infrastructure to fulfil basic human needs and wants (Ubayi et al., 2024). Preliminary cost estimates are prepared to counsel on the feasibility and profitability of the project. Past project data is used to prepare preliminary estimates with necessary adjustments (Elhegazy et al., 2022). Several methods are

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followed in the industry for early-stage preliminary estimation of projects, such as the gross floor area, functional unit method, cube method, and story enclosure method. These methods are usually quicker to perform but less accurate in most scenarios due to insufficient and unavailability of project information. Meharie et al. (2019) note that, even though there are methods to increase the reliability of conventional methods, the accuracy highly depends on the indices used. It emphasises the requirement and the importance of advanced cost forecasting and estimation methods suited for the current practice in the construction industry.

According to Abiodun et al. (2018), Elmousalami (2019) and Doroshenko (2020) Artificial Neural Network (ANN) could be used as a deep learning method for preliminary estimation in construction projects to overcome the drawbacks of the conventional estimating methods. Further, Hakami and Hassan (2019) mention that this method showed high effectiveness and accuracy with less than 1% error in the preliminary estimation of Yemen Projects. Supporting that, Elmousalami (2019), Kim et al. (2005), and Mohamed (2021) explain that the ANN-based preliminary estimation models have obtained a higher accuracy than conventional methods. Moreover, Hakami and Hassan (2019) and Kim et al. (2005) mentioned that ANN models have a higher accuracy when compared to regression analysis and support vector machine techniques, which have been used with project historical data for preliminary cost estimating. ANN models can be configured to have more accurate results with fewer inputs (Shehatto, 2013). Furthermore, the effects of seasonal changes and trends could be identified by an ANN model, which is more beneficial for increasing the accuracy of the estimate (Karaca et al., 2020; Sanni-Anibire et al., 2021; Tabtabai et al., 1999).

According to Akinradewo et al. (2020) and Jassim et al. (2025), industrial practice for preliminary estimation in Sri Lanka is to use conventional methods. In most scenarios, it causes a less accurate estimate and consumes a significant amount of time to prepare. Gupta & Debnath (2022) declared that existing estimation software in the international market is incompatible with the Sri Lankan context due to limited usage policies and availability. However, ANN-based preliminary estimation has provided promising results in the global context (Al-Tawal et al., 2021; Matel et al., 2022). Therefore, adopting the ANN method for preliminary estimation can be recognised as suitable for the Sri Lankan context. Further, it will assist the parties involved in the project to determine future project decisions more accurately with less information available. The study aims to investigate the applicability of artificial neural network-based methods to enhance the preliminary estimation in Sri Lankan building construction projects. An ANN model is developed, and necessary improvements and modifications relevant to the cost attributes are suggested to enhance the practical implementation of the ANN method within Sri Lanka.

2. LITERATURE REVIEW

2.1 PRELIMINARY COST ESTIMATION FOR BUILDING PROJECTS

Preliminary cost estimates should provide a credible and accurate prediction of the cost at an early stage of a construction project (Kim et al., 2005; Phaobunjong, 2002; Sanni-Anibire et al., 2021; Seeley, 1996; Shehatto, 2013). Gould (2005) explains the preliminary cost estimation as an appraisal, opinion, or approximation of the cost done before the actual construction. Further, Ofori-Boadu (2015) explains preliminary cost estimation as one of the cost estimates prepared in the initial step of developing the budget

for a construction project. Therefore, the task becomes more challenging, especially when a higher accuracy level is required for the estimate at the initial stage of the project (Shehatto, 2013). Holm et al. (2005) describe that preliminary estimations are required to select alternative investment options and design options to determine the funding requirements, conduct feasibility studies, and present bids and tenders. Furthermore, Cheung et al. (2012) note that the employer's requirements for the project must be assessed when preparing a preliminary estimate to perform a reliable estimate based on appropriate data.

According to Phaobunjong (2002) and Oberlender (2000), a specific format or industrial standard is not defined for preparing the preliminary estimate. The required accuracy level is determined according to the stage of the project (Gunaydin & Doğan, 2004).

2.2 ARTIFICIAL NEURAL NETWORK (ANN) FOR PRELIMINARY ESTIMATION

An ANN is a computing technique in computational intelligence that can be used for information processing (Gupta & Debnath, 2022; Kukreja et al., 2016; Rojas, 1996). ANN is inspired by the ideology of the human brain neurons. ANN was developed to easily incorporate human intelligence into computers to perform complicated tasks (Abiodun et al., 2018; Goel et al., 2023). Abiodun et al. (2018) describe that ANN models are compatible with mathematically expressing a real-world phenomenon since an ANN model is a simplified mechanism of brain function. System control, pattern recognition, forecasting, and detection are the main areas where the application of ANN is mainly identified (Kukreja et al., 2016). Matel et al. (2022) stated that ANN can be used in parametric cost estimation as an alternative to statistical methods. Moreover, the same article noted that using ANN models in preliminary estimation is more straightforward than using other evolving methods in computational intelligence.

Elmousalami (2019) was able to represent the use of simulation modelling methods for preliminary estimating in building construction projects by considering 47 studies. The use of ANN and hybrid models was emphasised in the study.

Studies conducted by Arafa and Alqedra (2011), Bayram et al. (2015), Bode (2000), Cheng et al. (2013), Elmousalami (2019), El-Sawah and Moselhi (2014), Emsley et al. (2002), Gunaydin and Doğan (2004), Hakami and Hassan (2019), Kim et al. (2005), Pesko et al. (2013), Petroutsatou et al. (2012), Shehatto (2013) and Wilmot and Mei (2005) signify the applicability of ANN method for preliminary estimation process in the construction industry which results to acquire a higher accuracy than traditional methods.

2.3 IDENTIFYING INPUT VARIABLES FOR THE ANN-BASED PRELIMINARY ESTIMATION MODEL

Identification of the most significant cost parameters of the building is vital when developing the ANN model. The cost relationship between the input variable and the output must be substantial to have more dynamic output from the ANN model and to improve the accuracy with reduced redundancy and noisiness (Arafa & Alqedra, 2011; Elmousalami, 2019; Gunaydin & Doğan, 2004; Shehatto, 2013). Further, Hakami and Hassan (2019) denote that the input variables of the ANN model should expose the client's requirements to increase the model's reliability. Table 1 represents key building

parameters that could be used as input variables for the ANN model, as identified by various authors.

Table 1: Building parameters used as input variables for ANN models in previous research studies

Building Parameter	References
Floor area	(Arafa & Alqedra, 2011; Chandraratne et al., 2019; Geekiyanage & Ramachandra, 2019; Gunaydin & Doğan, 2004; Kim et al., 2005; Shehatto, 2013; Sonmez, 2011; Wang et al., 2012)
Type of the foundation	(Arafa & Alqedra, 2011; Chandraratne et al., 2019; Gunaydin & Doğan, 2004; Kim et al., 2005; Shehatto, 2013; Wang et al., 2012)
Number of floors	(Arafa & Alqedra, 2011; Chandraratne et al., 2019; Geekiyanage & Ramachandra, 2019; Gunaydin & Doğan, 2004; Hakami & Hassan, 2019; Kim et al., 2005; Shehatto, 2013; Sonmez, 2011; Wang et al., 2012)
Number of elevators	(Arafa & Alqedra, 2011; Shehatto, 2013; Sonmez, 2011; Wang et al., 2012)
Building height	(Chandraratne et al., 2019; Geekiyanage & Ramachandra, 2019)
Building type	(Chandraratne et al., 2019; Hakami & Hassan, 2019; Shehatto, 2013)
Project location	(Chandraratne et al., 2019; Gunaydin & Doğan, 2004; Hakami & Hassan, 2019)
Project duration	(Chandraratne et al., 2019)
Type of HVAC	(Hakami & Hassan, 2019; Shehatto, 2013)
Type of electricity	(Shehatto, 2013)
Mechanical services type	(Shehatto, 2013)
Type of external finish	(Hakami & Hassan, 2019; Shehatto, 2013; Sonmez, 2011; Wang et al., 2012)

According to Table 1, floor area, type of foundation and number of floors are significant building parameters for the ANN model. Moreover, the studies conducted by Chandraratne et al. (2019) and Geekiyanage and Ramachandra (2019) additionally, emphasise the significance of building parameters, namely building height, building type, location and project duration, concerning the Sri Lankan context.

3. MATERIAL AND METHODS

This research intends to investigate the suitability and applicability of ANN-based preliminary estimation in Sri Lanka through design science research methodology. Specifically, the suitability and relevance of ANN within the Sri Lankan context were evaluated using a qualitative method. The ANN model development and validation were approached using a quantitative method since it should be performed using numerical figures generated from performance measures as identified in the literature review. This research consisted of two main stages, and the required activities and the sequences of activities for this research study at each stage were identified in Figure 1.

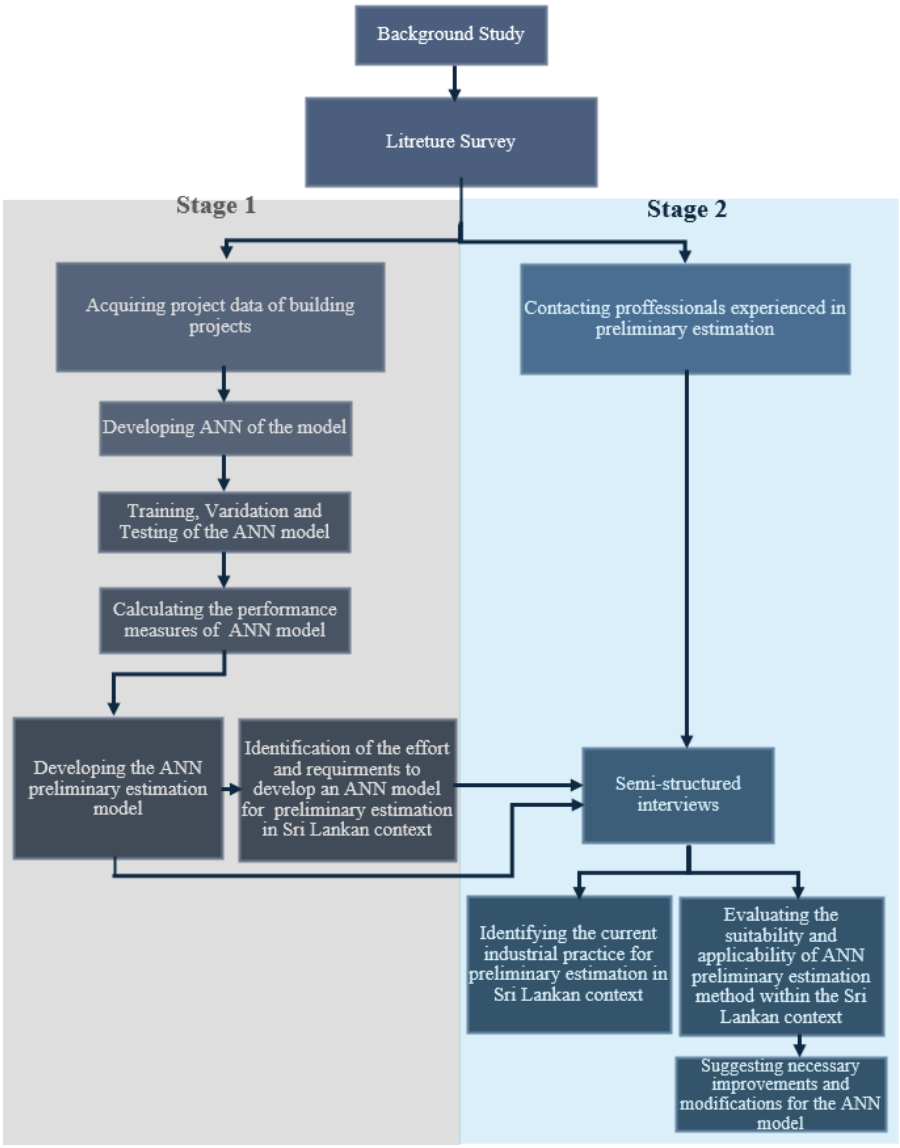


Figure 1: Research process

Fellows and Liu (2015) explain that expert interviews are more beneficial for effective data collection, as they gather data for a relevant matter from someone experienced. Therefore, 10 semi-structured interviews with the building construction sector (Quantity surveyors, Cost consultants, and Project managers) were conducted, since this study should elaborate on the suitability and applicability of ANN for preliminary estimation, which would be a new subject matter for the interviewees. Since the number of experts is unknown in this study area sample size is determined based on the saturation of the information. Snowball sampling is adopted for this study to select suitable experts for the study data collection. Accordingly, data were collected from 10 experts in the building construction sector.

The quantitative analysis report comprises performance measures of the developed ANN preliminary estimation model. The measures can be identified during the ANN model validation process and used for the performance evaluation of the ANN model. An efficient analysis was conducted by adopting qualitative data analysis. Therefore, content

analysis is preferred in this research to perform Stage 2 of this research. As the preliminary estimation model development platform Google Colaboratory platform is used, and its selection has been justified in Subtopic 4.1.3.

4. RESULTS

4.1 STAGE 1: ANN ESTIMATION MODEL DEVELOPMENT

4.1.1 Identification of Input Attributes and Encoding

In this study, categorisation and data encoding were carried out according to the availability of the dataset. The qualitative attributes of the buildings were encoded, and the quantitative attributes were inserted as numerical values. The relation of each input attribute to the cost was identified through Figure 2, generated using Python coding libraries in the Google Colaboratory platform, where the calculation is processed statistically within the model.

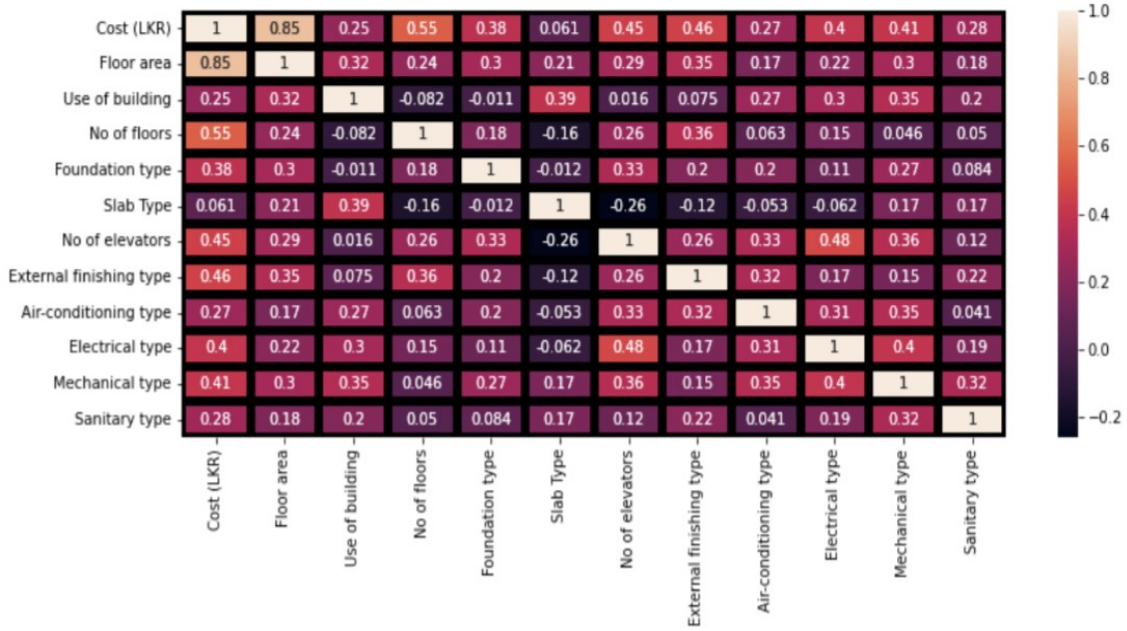


Figure 2: Correlation of cost to each input attribute

Figure 2 shows that the floor area is the most significant input attribute to the cost, and the slab type is the least affecting input attribute. Therefore, it can be stated that various input attributes can be considered when preparing the database as per the ANN model developer's desire. The correlation figure could be generated from Google Colaboratory to identify the model's most significant and suitable input attributes. Then the ANN model was developed using a database related to the UAE with 169 building projects.

4.1.2 Evaluation of the Data Distribution of the Database

Evaluation of the data distribution is mandatory to develop a reliable ANN model. The review of the data distribution was conducted through the Google Colaboratory platform. The data is preferred to be generally distributed within the expected range. Therefore, the data distribution of the most significant input attributes identified in Figure 2, and the model output attribute must be studied before the model development. This data set evaluation would be more beneficial in generating a model with higher accuracy. Figure

3 displays the data distribution of the most cost-significant input attribute (floor area) and the output attribute (building cost) specified in this ANN model.

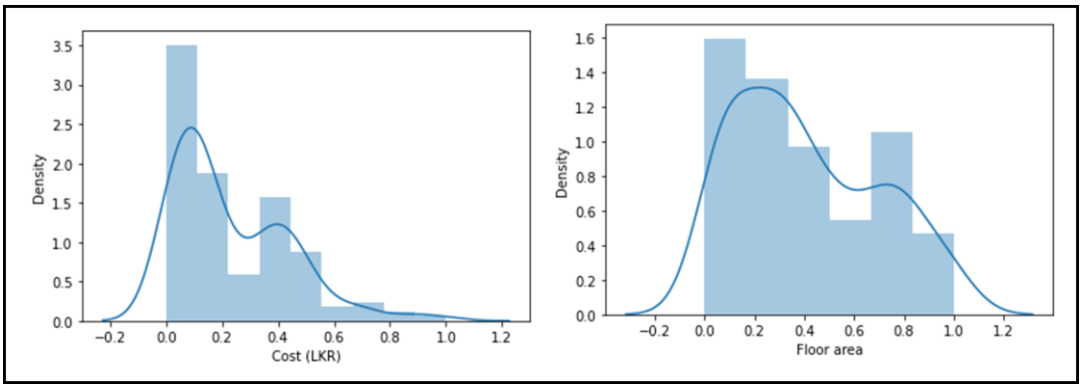


Figure 3: Data distribution of building cost and the floor area in the dataset

According to Figure 3, the selected dataset represents a bimodal distribution of data rather than a normal distribution. It emphasised the need for more mid-range cost data within the chosen dataset so that the ANN model could be more accurate in estimation.

4.1.3 Developing the ANN Preliminary Estimation Model

Three ANN preliminary estimation models were developed using the Google Colaboratory platform, MATLAB Software and Neural Designer Software. The Google Colaboratory platform enabled the development of models from scratch with Python coding online. At the same time, MATLAB and Neural Designer software were capable of developing ANN models without coding knowledge.

The models' ANN architecture, training, and testing processes were substantially similar, although the sequential model is significantly different from the Google Colaboratory model. The Google Colaboratory model is highly customisable compared to the MATLAB and Neural Designer models. (Ray et al., 2021; Sukhdeve & Sukhdeve, 2023). The architecture of the ANN model can be changed as the developer desires. The ANN models developed using MATLAB and neural designer software took less time to create, but a cost was incurred for the purchase of the software. In contrast, the Google Collaboratory platform was available free of cost. When considering the performance measures of each model, the correlation and validation performance of the Google Colaboratory and MATLAB models are shown in Figure 4.

Both models were able to achieve a correlation of more than 0.96 and were able to obtain a validation performance within the respective range of epochs. The ANN model developed in Neural Designer software validated a lower accuracy than the other two ANN models.

4.1.4 Validation of the ANN Models

The ANN model was developed using three methods to identify the resource requirement critically. The best ANN model was the Google Colaboratory model, developed using Python. It showed an accuracy of 89.56% and was prioritised for presentation in the interviews. The higher accuracy of the ANN model supports the sound examination with a minimised margin for errors. It benefits the contractor to obtain higher profits and gain customer satisfaction and trust. Meanwhile, accurate estimation avoids the requirements of price adjustments for the client, creating price certainty in the projects.

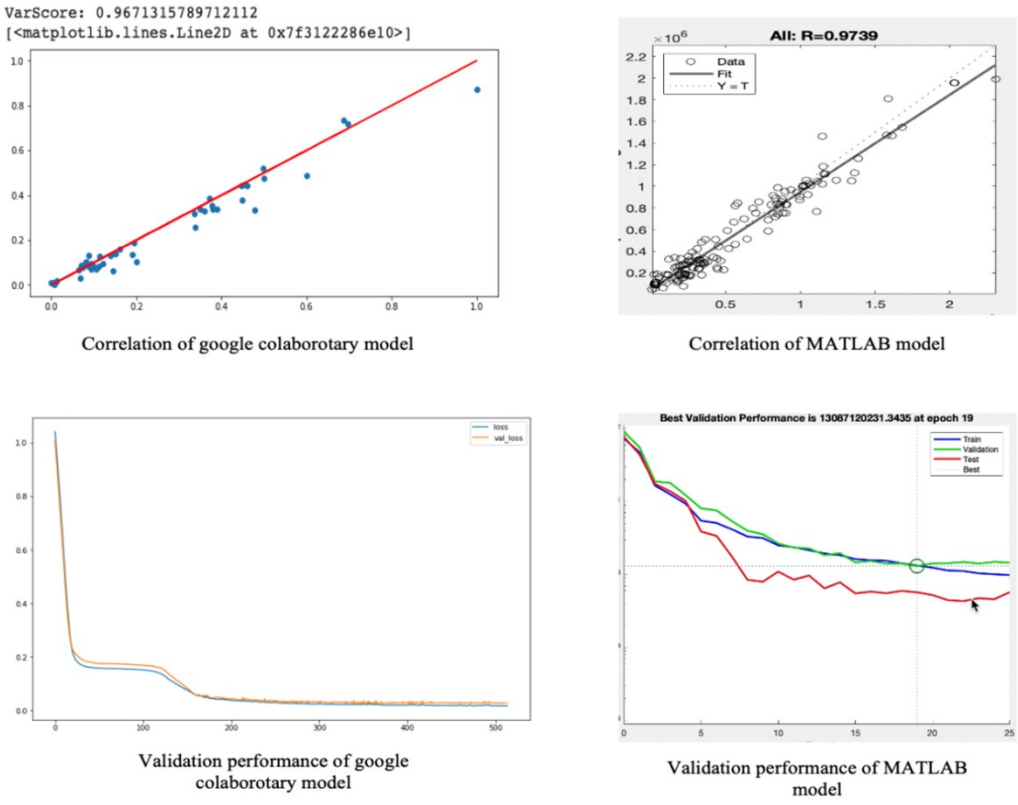


Figure 4: The correlation and validation performance of ANN models

4.2 STAGE 2: SEMI-STRUCTURED INTERVIEWS

4.2.1 SWOT Analysis of ANN Model Applicability within a Firm

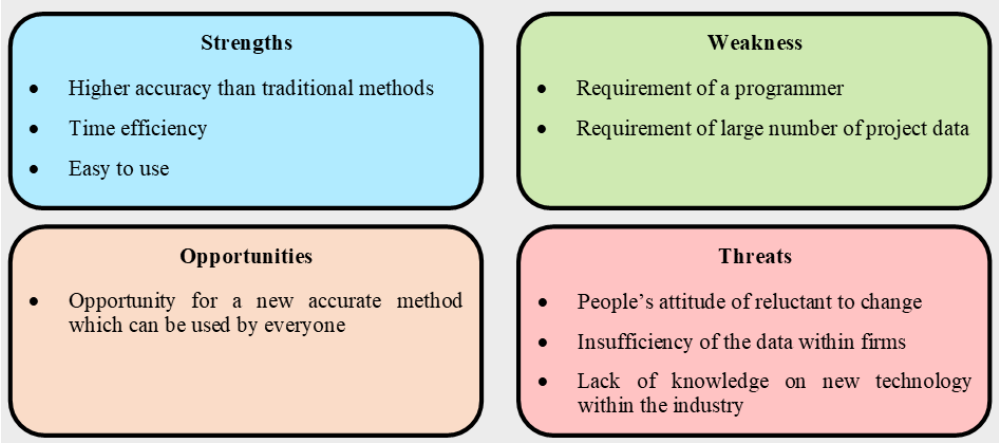


Figure 5: SWOT analysis of ANN model applicability within a firm

Figure 5 demonstrates the SWOT analysis by referring to the interviewees' responses regarding using an ANN model for preliminary estimation within the Sri Lankan context.

4.2.2 Driving and Resisting Factors for ANN-based Preliminary Estimation Model

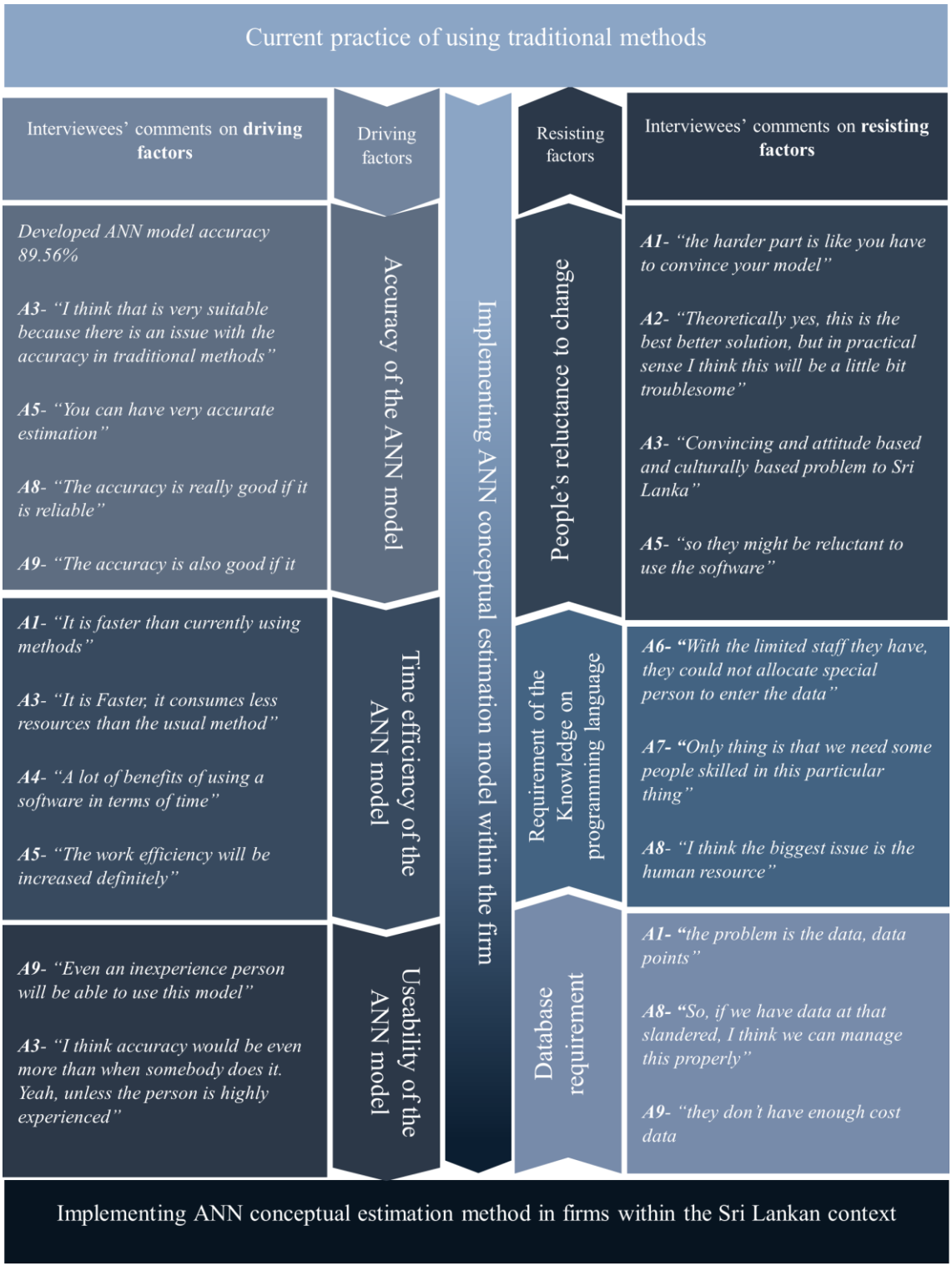


Figure 6: Identified driving and resisting factors in ANN model applicability

Further, according to the interviewees' responses, Figure 6 was developed to identify the driving and resisting factors for applying the ANN-based preliminary estimation model in the Sri Lankan context.

The interviewees strongly identified the time efficiency and the accuracy of the ANN preliminary estimation model, which will be more advantageous in overcoming the issues of the existing industrial practice of using traditional methods for preliminary estimation.

4.2.3 Suggested Improvements and Modifications for the ANN Model to Optimise its Use in the Sri Lankan Context

According to the research objectives, necessary improvements and modifications for the ANN model have been suggested to optimise the practical application within the industry. Interviewees A1, A4, A7, and A8 have identified that the model should be competent in estimating the different site conditions and settings, and interviewees A9 and A10 identified it as considering the location factor for estimation. Further, the interviewees A2, A6, A7, A9, and A10 emphasised that the model should be capable of being used for a preliminary analysis of the price fluctuations in the industry. Specifically, the interviewees A2, A6 and A7 questioned how the use of CIDA indices could be performed when using the model.

The next improvement identified was having a user interface for the model, where the efficient and effective interaction between the model and the user can be improved. The interviewees A1, A3, A5 and A6 denoted the need for a user interface for the model.

As a further improvement, the interviewees A4, A5, A6 and A7 denoted the importance of the model and whether it can be developed to prepare elemental cost planning. Furthermore, interviewees noted that the model would be more useful since the firms are primarily concerned about the elemental cost plan rather than the preliminary estimate.

Concerning the expected modifications, being location-specific, adjustments to price fluctuations and identifying the risk and uncertainty were identified by the interviewees as recommended modifications. Further, improvements in developing a user interface and compatibility with the model in elemental cost planning were emphasised.

5. DISCUSSION

The ANN model developed by Chandraratne et al. (2019), Dissanayake et al. (2015) and Geekiyanage and Ramachandra (2019) was developed using supplementary software, which was made to establish ANN models. Therefore, customizability is low compared to developing an ANN by using Python coding. There should be knowledge regarding ANN to develop an ANN model within a firm. Further, the ANN model developed for this research is a solitary model developed using only ANN, and it was able to perform with an accuracy of 89.56%. Therefore, it can be identified that the ANN is suitable for predicting the costs of building projects at the conceptual stage, as similarly identified in the literature review.

According to the interviews, the Sri Lankan preliminary estimation process still relies on traditional methods. Chandraratne et al. (2019), Dissanayake et al. (2015), Geekiyanage and Ramachandra (2019) and Rathnayake et al. (2018) also mentioned that traditional methods are still in practice in almost all preliminary estimations. According to the interviewees, the reason for using the conventional method in the industry is the simplicity of those methods. People mostly use their experience to prepare estimates (Britto et al., 2013; Dissanayake et al., 2015; Ganeshu et al., 2015). However, traditional and non-traditional methods are being replaced globally by hybrid intelligent models (Elmousalami, 2019; Sanni-Anibire et al., 2021).

Regarding preliminary estimation within the context, it is recognised that the consultant interacts with the client to gather as much information regarding the project as possible. The assumptions are made for the deficiency of information, mostly on building specifications, duration, and price fluctuations. Further, the consultants identify the client's requirements. Bley (1990) and Phaobunjong (2002) also identified the preliminary estimation process similar to the existing practice in Sri Lanka.

With the existing practice, it will take several days to analyse the data and provide a figure to the client. However, using ANN, time consumption can be drastically reduced when providing such a figure to a client. In contrast, Arafa and Alqedra (2011), Hakami and Hassan (2019) and Kim et al. (2005) have also signified the time efficiency of the ANN-based preliminary estimation.

According to the findings, database management within the firms shows a trend to use software-based data collection methods rather than Excel. The use of ERP software could be identified as a trend within the industry, and previous studies have shown a trend to use traditional Excel for data keeping and management (Rathnayake et al., 2018).

Another aspect identified through the interviews was the expected accuracy of a preliminary estimate of more than 80%. Accordingly, ANN preliminary estimation could be identified as a solution where any person within the firm can use the model to get a figure after inserting the project data into the respective input attributes.

In terms of suitability, most interviewees identified that ANN is suitable for preliminary estimation, even though ANN is not familiar to interviewees. The time effectiveness and the increased accuracy were the main advantages identified by the interviewees. It is aligned with the existing research studies of Arafa and Alqedra (2011), Sanni-Anibire et al. (2021) and Shehatto (2013), where the higher accuracy and time efficiency of ANN models were elaborated.

Therefore, according to the findings, even though the ANN is suitable for the preliminary estimation, some challenges should be addressed and rectified. The interviewees noted that the centralised database system will be beneficial in these situations, and the professional bodies related to construction can be initiated to introduce these kinds of methods to the industry to address the issue of resistance to change among people in the industry.

Furthermore, necessary improvements and modifications have been suggested according to the responses of the interviews, which were mainly focused on having a user interface and inserting input parameters to the model regarding the location and site condition of the project, price fluctuations, risk, and uncertainty. These aspects can be inserted into the model as input attributes using the location indices, CIDA price indices and the inflation rate. Along with that, the data set should be updated accurately with each project's relative location indices, CIDA indices and the inflation rate.

Figure 7 elaborates on the cognitive map regarding the applicability of the ANN preliminary estimation model within the Sri Lankan context.

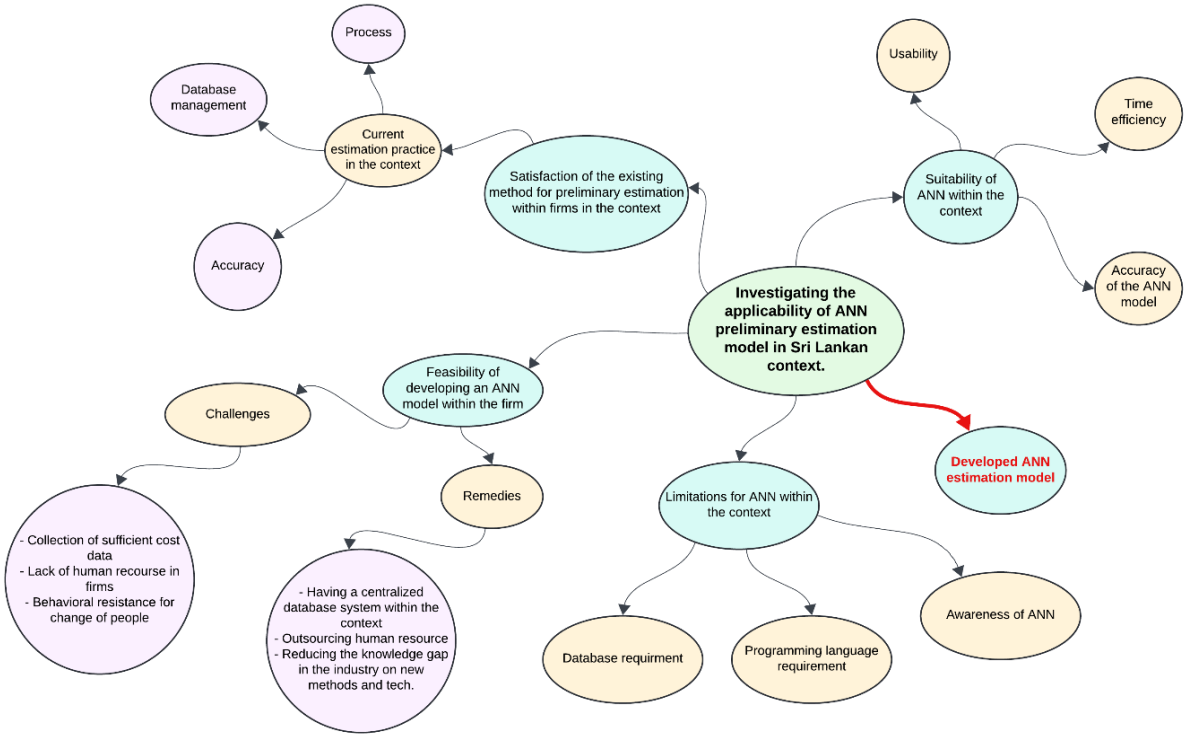


Figure 7: Cognitive map for ANN model applicability in Sri Lanka

The use of ANN for preliminary estimation is identified globally as a more accurate and easier method than the traditional method. The suitability and applicability of the ANN preliminary estimation model were critically analysed within the study. The ANN model was developed, validated, and modified according to the interviewees' responses, which were provided as improvements to the ANN model. The interviewees provided a positive impression of the applicability of ANN within the context while identifying specific challenges which can be overcome with effort within the firm.

6. CONCLUSIONS

Hybrid intelligent models are more advanced than even non-traditional methods such as MRA since hybrid intelligent models may combine several machine learning techniques, namely, evolutionary computing, ANN, SVM, CBR and fuzzy logic. Regarding the Sri Lankan context, the practice uses traditional methods and maintains the required accuracy through the estimator's experience.

Preparing a preliminary estimate within the context includes identifying project characteristics through available drawings, the client's brief, and discussions with the client. After that, the estimator prepares the estimate using past project data. The experience of the estimator mainly produces the necessary assumptions and adjustments. Further, it can be identified that several experienced estimators are using a combination of traditional methods as a customised method that suits the firm to maintain the accuracy and reliability of the estimate.

The model can be developed within the firm using an appropriate database and the necessary human resources. Further, the investors can make reliable decisions on the project at the initial stage by using ANN models for preliminary estimations. Also, the

higher accuracy and time efficiency are the most significant benefits of using ANN for preliminary estimations. A manual validation process was carried out to identify the accuracy of the developed ANN model. The best model was the Google Colaborotary model, which had the highest accuracy of 89.56%. Furthermore, the study used a comprehensive data set along with the expert review on the parameters, ensuring the reliability of the outcome of the study.

The outcome highlighted the requirements for input attributes related to location, price fluctuations, risk, and uncertainty to improve the accuracy of the preliminary estimation model as the limitations of this study. Location and price fluctuation changes can be included in the model using location indices, CIDA indices and inflation rates as the future research direction of this study.

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ADDRESSING DATA MANAGEMENT CHALLENGES IN SRI LANKAN CONSTRUCTION INDUSTRY THROUGH BLOCKCHAIN INTEGRATION

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ABSTRACT

The construction industry in Sri Lanka continues to face critical data management challenges due to fragmented systems, manual processes, and a lack of interoperability among digital platforms. These inefficiencies lead to delayed decision-making, data duplication, and reduced stakeholder trust. In response, blockchain technology has gained attention as a transformative digital solution capable of enhancing transparency, traceability, and security in construction data workflows. This study first explores the DM challenges in construction and then investigates the potential of integrating BC technology to address these DM challenges within the Sri Lankan construction sector. A mixed-method research approach was employed, comprising 35 quantitative questionnaires and 13 qualitative expert interviews with industry professionals. The findings identified several persistent DM challenges, including poor real-time data access, data ownership ambiguity, and cybersecurity risks, and such challenges were mapped against the core features BC such as decentralisation, immutability, auditability, and smart contracts. While practical deployment was not undertaken, the study presents a conceptual foundation for how BC can enhance construction DM. The research contributes to the broader discourse on digital transformation in construction by offering context-specific insights and strategic recommendations for future adoption of BC in Sri Lankan built environment.

Keywords: *Blockchain; Construction Industry; Data Management; Digital Transformation; Sri Lanka.*

1. INTRODUCTION

The construction industry is widely acknowledged as one of the most data-intensive sectors, relying heavily on consistent, accurate, and timely information exchange across the entire project lifecycle from initial conceptualisation, design, and procurement to construction, handover, and facilities management (Dauda et al., 2024; Tsay et al., 2022). Thus, efficient data management (DM) is essential to ensure that critical information is accessible, accurate, and timely to support planning, execution, monitoring, and control

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of construction activities (Dauda et al., 2024; Antunes & Gonzalez, 2015). However, poorly managed data can result in significant inefficiencies such as delayed decisions, duplicated work, rework, budget overruns, and contractual disputes (Love et al., 2013).

In the context of Sri Lanka, the construction sector continues to rely heavily on fragmented and predominantly manual DM processes (Dilaksha et al., 2024). Although digital tools such as Building Information Modelling (BIM), Enterprise Resource Planning (ERP), and cloud-based storage platforms have been introduced in some projects, these are not uniformly adopted or fully integrated into everyday workflows (Hewavitharana et al., 2025; Mohanaraj et al., 2022). The sector's digital transformation is hindered by technological inertia, inconsistent adoption across departments, lack of skills, and insufficient regulatory and organisational frameworks (Bandara et al., 2024). These issues are compounded by concerns about data ownership, version control, interoperability, and the trustworthiness of shared project information (Turk, 2020). Systemic DM limitations necessitate innovative technological interventions that can address the root causes of inefficiency, fragmentation, and lack of transparency (Nawi et al., 2014). While advanced economies have increasingly adopted integrated digital platforms (Bandara et al., 2024) Sri Lanka's construction industry remains largely reliant on manual documentation, disconnected digital systems, and paper-based approvals. This disparity necessitates a context-sensitive evaluation of blockchain, which may offer different implementation pathways and benefits than in global settings (Elghaish et al., 2023).

Blockchain (BC) technology has recently gained attention as a potential game-changer in this regard. Initially developed for financial transactions, BC is now recognised across industries for its capabilities in ensuring secure, decentralised, and tamper-proof data environments (Perera et al., 2020; Punia et al., 2024; Shishehgarkhaneh et al., 2023). Features such as immutability, consensus verification, cryptographic encryption, and smart contract automation can significantly enhance data reliability, stakeholder trust, and process integrity in construction settings (Dauda et al., 2024; Shojaei, 2019; Nawari & Ravindran, 2019). However, the practical integration of BC into construction DM particularly in developing countries such as Sri Lanka remains underexplored. A critical gap exists in understanding how BC's capabilities can be aligned with local DM challenges, industry constraints, and stakeholder readiness (Perera et al., 2020; Gamage et al., 2024).

Given this context, this paper addresses two research objectives: 1) To identify challenges within current DM systems in Sri Lankan construction sector, 2) To assess the potential of BC technology as a solution to those challenges. This study provides strategic insights for leveraging BC to overcome Sri Lankan construction DM inefficiencies through targeted technological integration.

2. LITERATURE REVIEW

2.1 DATA MANAGEMENT CHALLENGES IN CONSTRUCTION INDUSTRY

The construction industry is a complex, fragmented, and multidisciplinary domain involving various stakeholders such as clients, contractors, consultants, subcontractors, suppliers, and regulatory agencies working across distinct project phases (Nawi et al., 2014). This collaborative environment generates diverse data types such as architectural

plans, structural designs, cost estimates, contracts, and maintenance logs, which must be effectively managed in real time (Yousif et al., 2021).

In recent years, the construction industry has transitioned from manual DM to digital platforms such as BIM, ERP systems, and cloud databases to improve data integration and access (Vararean-Cochisa & Crisan, 2024). However, in developing countries like Sri Lanka, adoption remains inconsistent due to infrastructural limitations, skills gaps, and resistance to change (Jaiswal et al., 2024). While advanced economies such as the UK, Singapore, and China have successfully integrated BC with digital systems, Sri Lanka continues to face low ICT penetration and weak regulatory support (Gamage et al., 2024; Bandara et al., 2024). These disparities affect BC's practical applicability. Despite digital tools' potential to improve productivity and transparency, persistent challenges such as poor interoperability, limited real-time access, cybersecurity risks, and ambiguous data ownership undermine efficient DM (Dauda et al., 2024; Chaganti et al., 2022). These issues highlight the need for secure, decentralised solutions tailored to the local context (Hua et al., 2025).

Table 1 outlines the key DM challenges identified in the literature, which form the basis for assessing BC's potential as a strategic response in addressing such challenges.

Table 1: Key DM challenges in the construction industry

Challenge	Description	Citation
Real-Time Data Access	Disconnected systems delay updates on-site and off-site, resulting in outdated decisions, rework, and project delays.	[1], [3], [11]
Data Sharing and Collaboration	Fragmented stakeholder networks and proprietary data formats hinder smooth collaboration, limiting efficiency in multi-party coordination.	[2], [7], [9], [11]
Data Security and Cyber Threats	Increasing reliance on digital systems exposes projects to phishing, ransomware, and data leaks due to inadequate cybersecurity practices.	[3], [7], [14]
Data Ownership and Responsibility	Ambiguity in contracts regarding who controls or updates data creates accountability gaps and potential legal conflicts.	[2], [3], [7]
Data Quality and Accuracy	Manual entries, lack of validation processes, and poor integration lead to inaccurate data, which affects scheduling, budgeting, and claims.	[3], [4], [7], [13], [9]
Adopting and Implementing Technology	Resistance to change, insufficient digital skills, and unclear ROI slow down the implementation of integrated DM systems.	[8], [12]
Data Collection and Integration	Data is often collected through isolated tools or paper-based methods, leading to inconsistencies and duplication across the lifecycle.	[4], [10], [15]
Cost Management	Disparate data sources and delayed reporting lead to budget overruns, inaccurate estimates, and delayed payments.	[2], [5]
Compliance with Regulations	Without tamper-proof records or audit trails, firms face challenges in meeting regulatory, contractual, and sustainability reporting requirements.	[2], [9], [13]

Challenge	Description	Citation
Interoperability of Systems	Use of non-standard software and platforms causes integration issues, requiring manual data transfers between incompatible systems.	[3], [8]
Version Control and Document Management	Poorly managed document versions result in miscommunication, outdated approvals, and project disputes.	[1], [2], [10], [12]
Training & Skills Gaps	Many professionals lack the skills to adopt emerging digital tools, including BIM and BC, limiting their practical implementation.	[1], [2], [11]

[1]-(Abu-Reishah & Hiyassat, 2021), [2]-(Bhavsar et al., 2018), [3]-(Dauda et al., 2024), [4]-(de Bruijn & Janssen, 2017), [5]-(Halttula et al. 2020), [6]-(Jaiswal et al., 2024), [7]-(Luo, 2022), [8]-(Nawari & Ravindran, 2019), [9]-(Pham et al., 2023), , [10]-Shojaei, 2019 [11]-(Tanga et al., 2021), [12]-(Turk, 2020), [13]-(Vararean-Cochisa & Crisan, 2024), [14]- (Yao & De Soto, 2024), [15]- (Zhang et al., 2017)

The challenges prove persistent and multi-dimensional, cutting across technical, organisational, and cultural domains. The identification of these challenges by academic researchers enables an assessment of how BC can be applied for their resolution.

2.2 POTENTIAL OF BLOCKCHAIN TO ADDRESS DATA MANAGEMENT CHALLENGES

BC, originally conceptualised by Nakamoto (2008) for peer-to-peer financial transactions, has evolved into a versatile digital infrastructure applicable across various sectors. It operates as a decentralised, distributed ledger that records transactions in cryptographically linked blocks. Each block is time-stamped and validated through consensus algorithms, which ensures data integrity, transparency, and immutability (Christidis & Devetsikiotis, 2016). Within the construction industry where project success hinges on real-time, accurate, and trustworthy data exchanges BC offers a set of technological features that directly respond to the sector's persistent DM challenges. The following sub-sections outline how these core features can provide targeted solutions aligned with construction project workflows:

- Decentralisation: BC reduces single points of failure by distributing data storage and validation across a peer-to-peer network. Consensus mechanisms replace central authority, enhancing traceability and system reliability (Karafiloski & Mishev, 2017; Singh et al., 2023; Sood et al., 2024).
- Transparency: BC promotes stakeholder accountability by providing real-time, tamper-evident access to transaction records. This is particularly valuable in public construction projects, reducing corruption and fostering trust (Awaysheh & Klassen, 2010; Perera et al., 2021).
- Performance and scalability: Permissioned platforms like Hyperledger Fabric support high transaction throughput. Smart contracts automate key processes tendering, procurement, payments streamlining construction workflows and reducing delays (Alharby & Van Moorsel, 2017; Bondi, 2000).
- Trust: Built through decentralised consensus, which ensures that no data entry is accepted without validation by a network majority. This process reduces

misinformation, reinforces mutual credibility among project parties, and enhances cooperative decision-making (Tanga et al., 2022).

- Security: Enhanced via cryptographic protocols, such as SHA-256, which protect sensitive project documents from tampering and unauthorised access. Peer-to-peer validation further ensures that only verified entries become part of the immutable record (Sood et al., 2024).
- Immutability: Guarantees that once information is entered into the BC, it cannot be modified without collective agreement. This feature is critical for managing design revisions, procurement logs, and change orders, as it preserves the integrity of historical data (Underwood, 2016; Wu et al., 2019).
- Auditability: Achieved through time-stamped, sequential data blocks that enable easy tracking of activities such as inspection reports, delivery schedules, and contractual milestones. This feature enhances regulatory compliance and internal project governance (Selvanesan & Satanarachchi, 2023; Collinge et al. 2009).

Overall, BC's technological enablers provide a transformative framework for solving critical DM issues in construction, offering improved real-time access, interoperability, security, and stakeholder collaboration.

3. METHODOLOGY

This study adopted a mixed methods design to investigate the potential of BC in addressing DM challenges identified within Sri Lanka's construction industry. As such both structured questionnaires and semi-structured interviews were used to collect quantitative and qualitative data, respectively. Structured questionnaires distributed to 55 professionals, with 35 valid responses were analysed using the Relative Importance Index (RII) method to rank key DM challenges identified using the comprehensive literature review. While the sample size is modest, it is considered adequate for exploratory research in construction studies where respondents are purposefully selected based on their domain knowledge (Vasileiou et al., 2018). Similar studies in Sri Lanka have also employed comparable sample sizes to examine digitalisation in construction (Gamage et al., 2024). A non-probabilistic purposive sampling method was used to ensure participants had experience in digital tools and DM processes. The sample included professionals actively involved in data-driven decision-making, making the responses highly relevant. Additionally, as younger professionals tend to engage more with digital platforms, the selection did not limit based on years of experience. Table 2 presents the experience breakdown and response rates, showing that a majority of respondents had less than five years of experience.

Table 2: Experience and response rate of respondents for the questionnaire

Experience (Years)	Distributed	Valid responses	Response rate (%)
0–5 years	25	20	80%
6–10 years	15	8	53%
11–15 years	10	4	40%
Over 15 years	5	3	60%
Total	55	35	63.64%

To complement the survey findings and add more richness to the identified challenges, 13 expert interviews were conducted using a semi-structured format. The experts included construction professionals familiar with DM processes and IT experts with BC knowledge. The construction professionals have comparatively limited knowledge about BC technology in Sri Lanka, as those technologies are not adopted to the construction. Due to their limited knowledge, they are unable to see the full potential a BC can bring to improve DM challenges. To address this limitation the authors also interviewed IT experts who had provided the technical insights on BC in addressing DM challenges. The researcher has played a key role during the interview in terms of bridging the knowledge gap about BC and DM in construction to both construction and IT experts, respectively. The interviews offered qualitative insights into the feasibility, barriers, and strategic integration of BC in the local context. Manual content analysis was used to analyse the qualitative data. The respondent profile in terms of years of experience and the knowledge / experience on the key areas of the research, i.e., BC, DM, construction are summarised in Table 3.

Table3: Profile of interviewees

Respondent	Total work experience (Years)	Knowledge and Experience on the key areas related of the research
CI1	6+	Construction, BC technology, and DM
CI2	6+	Construction and DM
CI3	9+	PhD in BC for DM in construction
CI4	5-10	Experience in both BC and DM in construction
CI5	5+	BC for Sri Lankan tendering processes
CI6	15+	Construction industry and DM experience, PhD research in BC
CI7	8+	PhD in BC
CI8	6+	Experience in both DM and BC
IT1	7+	Construction-based IT products, BC experience
IT2	5+	Construction data analyst, AI solutions for DM
IT3	7+	BC technology
IT4	3-4	Supply chain BC solutions
IT5	5+	Web-based application development

4. FINDINGS AND DISCUSSION

4.1 CURRENT DATA MANAGEMENT CHALLENGES

The critical DM challenges identified in the literature were contextualised to Sri Lankan construction using both quantitative RII analysis and qualitative content analysis. Table 4 outlines these challenges, combining quantitative rankings with qualitative validation to highlight key problem areas affecting efficiency, accuracy, integration, and decision-making in construction projects in Sri Lanka.

Table 4: Challenges in DM with RII and interview validation

DM Challenge	RII	CI1	CI2	CI3	CI4	CI5	CI6	CI7	CI8	IT1	IT2	IT3	IT4	IT5
Cost Management	0.794	✓	✓	✓		✓	✓	✓	✓				✓	
Data Security and Cyber Threats	0.761			✓	✓						✓			
Version Control and Document Management	0.761		✓											✓
Interoperability of Systems	0.755	✓	✓	✓		✓	✓	✓	✓	✓				
Real-Time Data Access	0.729	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	
Training and Skills Gaps	0.729						✓							
Adopting and Implementing Technology	0.723		✓			✓		✓	✓		✓	✓	✓	✓
Data Collection and Integration	0.716	✓	✓				✓			✓			✓	
Data Quality and Accuracy	0.703	✓	✓	✓	✓			✓	✓	✓		✓	✓	✓
Compliance with Regulations	0.703		✓		✓	✓	✓	✓		✓	✓	✓		
Data Sharing and Collaboration	0.690	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	
Data Ownership and Responsibility	0.684		✓	✓	✓	✓	✓		✓		✓	✓	✓	✓

These findings provide a structured foundation for deeper analysis of each significant challenge which are discussed below.

Among all, the cost management has been ranked as the most significant challenge which was also agreed by the experts to a certain extent. It is a leading challenge due to poor real-time tracking and budget visibility. CI6 stated, *"delays happen because of unclear cost tracking and improper budget allocation."* IT4 noted, *"BC can improve real-time cost updates,"* while CI8 warned that *"high implementation costs may deter smaller firms,"* highlighting both the promise and the barrier of adopting BC solutions.

In close alignment, cybersecurity emerged as another serious concern, where firms are increasingly storing sensitive project data on cloud platforms without adequate safeguards. IT1 stated, *"security breaches are not rare anymore… but most local firms don't have dedicated cybersecurity teams."* These insights reveal critical vulnerabilities that not only threaten data integrity but also expose firms to compliance failures and reputational harm.

Equally critical is the issue of version control and document management, with teams often working on outdated documents, leading to conflicts and added costs. CI2 noted, *"multiple document revisions between systems create chaos,"* while IT1 stated, *"BC enables transparent monitoring of updates,"* ensuring version accuracy. The lack of unified tracking systems poses operational and legal risks across project environments.

Interoperability was also highlighted as a major barrier to digital transformation in the Sri Lankan construction sector. Respondents noted that many existing digital platforms, including BIM and ERP systems, operate in isolation due to a lack of integration standards and APIs. CI6 explained, *"our BIM model can't talk to the procurement system,*

we end up duplicating everything manually." IT3 reinforced this issue, stating, *"without integration tools, digital systems just become digital islands."* These silos lead to inefficiencies in communication, data duplication, and an overall disjointed workflow that slows down collaboration.

Another pressing challenge is real-time data access. In Sri Lankan construction projects, delays in accessing up-to-date information frequently interrupt workflows, delay procurement, and cause billing inconsistencies. Survey findings confirmed this as a major issue.CI3 noted, *"we face major delays because the site team and consultants often work with different versions of data,"* while CI6 added, *"even printing outdated drawings has caused rework."* These inconsistencies not only increase the risk of errors and miscommunication but also lead to duplicated work, claims disputes, and reduced stakeholder confidence in project documentation.

Furthermore, digital literacy and skills gaps emerged as a recurring theme in both survey and interview data. CI2 mentioned, *"we invested in ERP, but staff still rely on Excel. They don't trust the new system."* IT3 reinforced this, stating, *"many project managers are afraid of making mistakes, they avoid digital platforms altogether."* Without structured training and change management, firms struggle to shift from traditional practices to efficient digital workflows.

These findings confirm the complex, interrelated nature of DM challenges in Sri Lanka's construction industry.

4.2 THE POTENTIAL OF BLOCKCHAIN TO ADDRESS DATA MANAGEMENT CHALLENGES

Survey and interview findings show strong optimism for BC in addressing construction DM issues. With 65.9% rating BC as "likely" or "extremely likely" to help, no respondents found it ineffective (Figure 1).

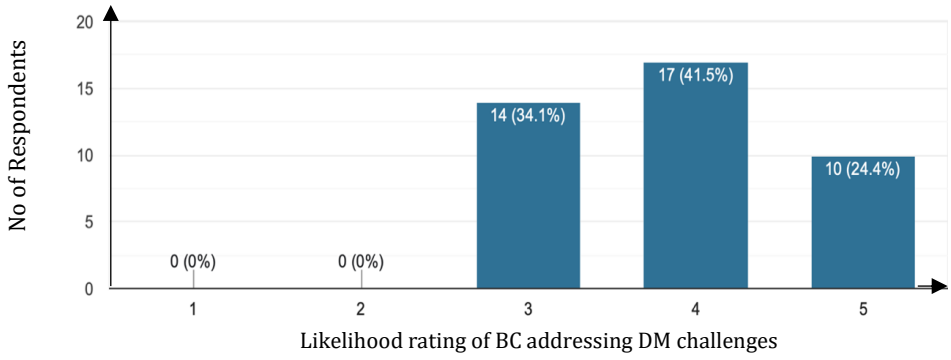


Figure 1: Likelihood rating of BC addressing DM challenges from questionnaire analysis

These findings form the foundation for evaluating specific BC features and their alignment with the critical challenges identified earlier. This subsection further investigates key features of BC such as security, auditability, transparency, decentralisation, performance & scalability, immutability, trust and disintermediation to directly map with construction DM.

To begin with, security was highlighted as a significant challenge, BC can address this through advanced cryptographic protocols, such as SHA-256 and asymmetric encryption,

to authenticate access and detect tampering. IT1 emphasised, *"once a file is in the chain, nobody can alter it without permission. That's the kind of integrity we need for compliance and audits."* CI4 added, *"without real encryption, it's just a data dump, BC gives structure and defense."* These features are critical for safeguarding procurement records, site data, and sensitive communications.

In addition to security, auditability is a core benefit of BC. BC's timestamped entries and full historical traceability support compliance with legal, regulatory, and quality standards. CI7 remarked, *"the audit trail in BC can reduce the effort needed for dispute resolution or compliance reviews."* By maintaining unalterable records of contracts, transactions, and communications, BC offers greater certainty in audits and builds confidence among clients and government agencies.

Closely linked to auditability is transparency, which directly impacts collaboration and accountability. BC allows all participants to trace data origins, monitor alterations, and verify user access through immutable logs. As CI5 noted, *"when people can see exactly who changed what and when, trust builds naturally. BC can offer that."* IT2 echoed, *"visibility builds confidence, when data access is logged, people stop hiding updates."* In collaborative, multi-party environments, BC thus fosters accountability and encourages proactive data sharing and improved coordination.

Equally important is decentralisation, a foundational attribute of BC. Its decentralised nature ensures that data is stored and updated across multiple nodes, allowing all authorised users to access synchronised, real-time information. This feature directly addresses the challenge of outdated or inconsistent data. CI3 explained, *"BC's structure means everyone works off the same real-time ledger, reducing delays caused by outdated files."* CI6 added, *"the data flows immediately once verified; you don't need to chase it across departments."* This systemic improvement enhances workflow continuity, particularly during procurement and billing milestones.

Moreover, BC offers high performance and scalability, especially through API-based interoperability. This capability is crucial in resolving challenges around fragmented software ecosystems. Interoperability issues affect nearly every construction firm surveyed, with disparate tools such as BIM, ERP, and project management software often functioning in isolation. IT5 highlighted, *"with smart contracts, you can link milestones in BIM to payment releases in ERP. It's like getting everything to finally speak the same language."* The flexible architecture of BC allows tailored implementation, making cross-platform automation more achievable than with traditional systems.

When it comes to immutability, BC plays a vital role in addressing version control issues. Once data is entered into the BC, it cannot be altered without consensus, effectively protecting records from unauthorised edits. CI6 commented, *"the immutability of BC means we can trace every step of a design change, every update to a BOQ, without confusion."*

Furthermore, trust is a central factor in any data-sharing environment, and BC enhances this through verifiable, tamper-proof records and transparent workflows. CI5 mentioned that transparency naturally builds trust, while CI2 reflected, *"yes, training is needed, but once teams see the system protecting their input and giving credit, adoption becomes easier."* Trust increases when team members can independently verify data without relying on intermediaries, fostering a sense of ownership and accountability.

Finally, BC facilitates disintermediation by eliminating unnecessary intermediaries in data validation and approvals. This is especially relevant in projects involving multiple tiers of subcontractors and consultants. IT2 and CI6 emphasised that disintermediation not only cuts costs but also enhances transparency and decision-making speed across the value chain.

In summary, BC's unique features directly respond to longstanding challenges in construction DM, offering a structured and secure pathway for digital transformation.

4.3 MAPPING THE BC FEATURES WITH DATA MANAGEMENT CHALLENGES

The Figure 2 visually represents summary of the analysis discussed above about BC features and DM challenges in the construction industry. The color-coded cells indicate the level of endorsement from respondents, showing which BC features are widely recommended, highly rated, strongly agreed upon, or mentioned by the respondents, reinforcing the survey findings that BC can significantly enhance DM in construction projects.

DM Challenges \ BC Feature	Security	Auditability	Transparency	Decentralisation	Performance & Scalability	Immutability	Trust	Disintermediation
Cost Management								
Data Security and Cyber Threats								
Version Control and Document Management								
Interoperability of Systems								
Real-Time Data Access								
Training and Skills Gaps								
Adopting and Implementing Technology								
Data Collection and Integration								
Data Quality and Accuracy								
Compliance with Regulations								
Data Sharing and Collaboration								
Data Ownership and Responsibility								

Minimally recommended- Chosen by 4 or fewer respondents	
Moderately recommended - Chosen by 5–9 respondents	
Mostly recommended - Chosen by 10 or more respondents	

Figure 2: Correlation between BC features and DM challenges in Sri Lankan construction industry

Figure 2 indicates that BC features are contributing to address the DM challenges, though the extent of contribution from each feature varies from challenge to challenge. It is also observable that each DM challenge can be addressed by using at least one of the BC features. This clearly indicates the potential of integrating BC technology to address these DM challenges within the Sri Lankan construction sector.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper explored the DM related challenges in Sri Lankan construction sector and assessed how BC technology could help address key challenges. Findings from both questionnaire survey and expert interviews confirmed most of the critical DM challenges identified in the literature, that include lack of real-time data access, poor system interoperability, cybersecurity risks, and document version inconsistencies. These inefficiencies significantly undermine project performance, collaboration, and trust among stakeholders.

BC technology demonstrates strong potential in mitigating these challenges through its core features such as security, auditability, transparency, decentralisation, performance & scalability, immutability, trust and disintermediation. The study highlighted that BC could ensure synchronised access to real-time data, secure information exchange, and enhance traceability across project phases. It also provides a robust mechanism for document management, reducing version conflicts and ensuring accountability through immutable records.

Although the implementation of BC was not explored in depth, the study concludes that BC is a promising technological intervention with high potential and capability of addressing fundamental DM challenges in the construction industry. Future research should explore real-world pilot projects, implementation strategies, and the regulatory and organisational support needed to operationalise BC solutions within Sri Lankan construction context.

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AN INVESTIGATION INTO EFFECTIVE ENERGY BEHAVIOR CONTROL STRATEGIES IN THE APPAREL MANUFACTURING SECTOR

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ABSTRACT

Energy consumption in the apparel industry is high, driven by intense usage of Heating, Ventilation, and Air Conditioning (HVAC) systems, lighting, and machines. Given its intensive nature and high carbon footprint, implementing efficient energy behavioural control strategies is crucial for advancing sustainability goals. This study identifies, evaluates, and rates thirteen strategies spanning technological, managerial, legal, and social domains through a comprehensive literature analysis and expert validation using the Relative Importance Index (RII) technique. Findings demonstrate a high preference for technologically driven interventions such as Artificial Intelligence (AI) and machine learning based predictive control, automation and smart controls, and smart metering systems, which enable precision, scalability, and real-time adaptability. Mid-tier tactics like incentive programs, dashboards, and training were regarded vital, while behaviour focused, legal, and social initiatives were ranked less effective due to perceived complexity, longer return scopes, and lower direct impact. The study underlines the necessity of a hybrid implementation approach that combines high impact technology with structured behavioural support mechanisms to foster sustainable energy practices. Limitations include potential sample bias in expert replies and a focus on large-scale manufacturing contexts, which may not completely represent issues experienced by small and medium enterprises (SMEs). Future studies should explore contextual barriers to strategy adoption across different organizational sizes and cultures and analyse the long-term performance of integrated technical behavioural models.

Keywords: *Apparel manufacturing; Energy efficiency; Energy behaviour control strategies; Sustainability.*

1. INTRODUCTION

The building sector is a dominant contributor to global energy consumption, accounting for approximately 40% of total energy use and 30% of carbon dioxide (CO_2) emissions (Schito & Lucchi, 2023). Substantial energy demand stems primarily from heating, cooling, lighting, and other operational activities powered by fossil fuels (Bodziacki et al., 2024). Due to urbanization and economic growth accelerating energy demand, policymakers worldwide are prioritizing energy efficiency measures in urban planning to

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mitigate climate change and reduce ecological footprints (Umoh et al., 2024). Despite advancements in energy efficient technologies such as high-performance Heating, Ventilation, and Air Conditioning (HVAC) systems, Light emitting diode (LED) lighting, and smart building automation, a persistent gap remains between projected and actual energy performance due to human behaviour (Kovalchuk & Shcherbakova, 2024; Ekim et al., 2023).

While technological innovations like improved insulation, airtight construction, and solar panels enhance energy efficiency, their full potential is often undermined by occupant behaviour (Amasyali & El-Gohary, 2021). Studies indicate that fluctuating behaviour, such as not turning off the lights, adjusting thermostats too much, or switching off automated devices, is likely to discredit energy saving potential (Xu et al., 2023). Hence, the discrepancy is known as the "energy performance gap," as it focuses on the implementation of a combined approach that involves technological advancements and behaviour (Bäcklund et al., 2023).

As per that research suggests that psychological factors and behaviour have the greatest contribution to energy consumption patterns (Ekim et al., 2023). As per that, activities of end users with lighting, HVAC, and appliances contribute significantly to total energy consumption and habits, awareness, and incentives must be considered along with technical measures (Maghsoudi Nia et al., 2022). For instance, energy feedback systems with real-time energy feedback were identified to reduce usage by 14.8%, demonstrating the effectiveness of data informed, individual specific interventions (Vijlbrief et al., 2022). Similarly, gamification, nudging behaviour like reminders and incentives, and reward schemes can instil long-term energy-saving habits (Li et al., 2024; Maghsoudi Nia et al., 2022).

The apparel industry is one of the most energy-consuming sectors, where air conditioning alone accounts for 46% of the energy used in manufacturing plants (Jananthan et al., 2006). In addition, textile processing requires enormous water, fuel, and electricity consumption, thus posing a massive industrial carbon footprint (Garg & Bhardwaj, 2024).

This study aims to bridge the gap between theoretical energy saving models and real-world applications by developing and assessing viable energy behavioural control strategies within the apparel manufacturing sector. The paper provides a review of relevant literature, followed by a full discussion of the research methods. It then provides the findings and includes a discussion on their implications, closing with practical insights and recommendations for further implementation and study.

2. LITERATURE REVIEW

2.1 ENERGY CONSUMPTION IN APPAREL MANUFACTURING

The apparel manufacturing business is a major industry in world economies but is also famously energy intensive, as it directly impacts production costs, ecological sustainability, and company effectiveness (Yılmaz et al., 2024). The apparel industry is renowned for having multifarious operational processes that include spinning, weaving, dyeing, finishing, cutting, sewing, and pressing and wet processing, particularly dyeing and finishing, which constitutes a major energy intensive industry, using a considerable portion of the industry's total energy consumption (Ajam & Khoshgoftar Manesh, 2025).

In extensive apparel manufacturing facilities, producers typically employ energy efficient technology, automation, and renewable energy sources to enhance consumption efficiency, whereas small and medium sized enterprises encounter challenges in adopting these strategies due to financial and technical constraints (Ketenci & Wolf, 2024).

As sustainability gains popularity, factories are increasingly using energy behaviour control tactics and data-driven energy management systems to boost efficiency and comply with environmental standards, and these approaches employ sophisticated technology, such as Artificial Intelligence (AI) and Internet of Things (IoT), to optimize energy consumption and eliminate waste, eventually supporting sustainability goals.

2.2 SIGNIFICANCE OF ENERGY BEHAVIOUR CONTROL STRATEGIES

Energy behaviour control strategies offer significant economic benefits by optimizing industrial processes, reducing energy costs, and enhancing productivity. Businesses that adopt these strategies improve resource efficiency, mitigate market risks, and strengthen competitiveness (Gitelman et al., 2019). Non-price interventions, such as energy use labelling and feedback systems, further encourage energy efficient behaviors, yielding long term economic returns (Zheng et al., 2022).

As for environmental impact, integrating psychological variables such as behavioural changes and persuasive technology (IoT, Smart metering and AI) promotes user engagement, ultimately promoting environmentally friendly behaviours and contributing to sustainable development (Chiu et al., 2020). Moreover, energy behaviour management measures are crucial for sustainable energy consumption, reducing environmental impact, and fostering conservation, ultimately reducing carbon emissions, helping ameliorate climate change and enhancing ecological health (Sweeney et al., 2018).

Practicing energy behaviour control strategies is significant because it improves building practitioners' sense of behavioural control, which positively impacts their intent of complying with energy performance standards, ultimately leading to better compliance outcomes than the minimum requirements in building design (Lu et al., 2024). Integrating energy behaviour management strategies, such as noise reduction techniques for Battery, Energy Storage Systems are vital for achieving regulatory compliance requirements while guaranteeing community acceptability and limiting the impact on residential areas (Martinez et al., 2013).

2.3 ENERGY BEHAVIOUR CONTROL STRATEGIES

2.3.1 Technological Strategies

Recent improvements in smart metering and IoT based systems have enabled real-time energy tracking, automated alarms, and comparative usage analysis, which are often attributed with boosting industrial energy efficiency (Mirani et al., 2024). While these technologies outperform traditional human monitoring in scalability and data precision, their performance strongly depends on organizational capability to act on the insights generated. In SMEs, the lack of competent individuals or integration frameworks sometimes limits their impact, a topic underexplored in current literature (Hattori et al., 2019). Automation solutions such as variable speed drives are also commonly referenced for optimizing motor and pump operations, eliminating unnecessary energy waste (Singhal & TR, 2023). However, most studies focus on their implementation in developed nations or highly mechanized industries, with scant investigation of their performance in

labour intensive sectors like clothing manufacture. This is an important research gap, as the operational context can considerably influence system performance (Hattori et al., 2019).

Behavioural nudging using apps and digital notifications is another new method, leveraging psychological triggers to induce change (Cellina et al., 2024). Although studies highlight positive short-term effects, others point to uneven engagement and user fatigue, suggesting that these technologies may lack sustainability if not linked with management reinforcement or tangible incentives (Ubachukwu et al., 2023). These discrepancies underscore the necessity for hybrid approaches that mix digital interventions with organizational support structures (Zhao, 2024).

2.3.2 Managerial Strategies

Employee training programs are crucial for fostering energy conscious behaviours in the workplace (Kotsopoulos et al., 2023). Effective training integrates behavioural psychology principles to overcome cognitive biases and reinforce energy saving habits (Canova & Manganelli, 2020). Performance monitoring and feedback systems, when combined with smart metering, sustain energy reductions of approximately 5% (Schleich et al., 2017). Energy conservation is further encouraged via incentive-based programs, which include monetary awards as well as nonmonetary motivators like environmental awareness campaigns (Asensio & Delmas, 2015).

2.3.3 Legal and Social Strategies

Energy conservation agreements between governments and industries facilitate negotiated efficiency targets, offering flexibility and cost-effective compliance (Dernbach et al., 2011). Policy enforcement, when combined with behavioural insights, enhances regulatory adherence and promotes sustainable practices (Hajialigol et al., 2023). Social strategies, such as recognition programs and community engagement, leverage social norms to motivate energy saving behaviours (Bonan et al., 2020). As well as collaborative goal setting initiatives in residential and organizational settings have achieved energy savings exceeding 20% (Iweka et al., 2019).

2.4 IMPLEMENTATION BARRIERS AND CHALLENGES

2.4.1 Technical Barriers

The deployment of energy behavioural control systems confronts various technological hurdles, including infrastructure limits due to incompatible data formats, security and privacy concerns, and the necessity for robust communication networks (Chillayil et al., 2022; Reynolds et al., 2017). Integration with existing systems is challenged by legacy technologies, rigid operational models, and the difficulties of adding predictive control algorithms (Huckebrink & Bertsch, 2021). Additionally, a lack of technical skills inhibits deployment, notably in installing and maintaining data from devices like submeters and building automation systems (Adu-Kankam & Camarinha-Matos, 2020; Barido et al., 2020). Maintenance and upgrades further complicate implementation, as malfunctioning systems and complex controls annoy building workers, diminishing the efficiency of energy saving measures (Yılmaz et al., 2024).

2.4.2 Organizational Barriers

Organizational obstacles include high initial investment costs, which dissuade stakeholders owing to unclear financial returns and a propensity for limiting capital expenses over long term efficiency (Bensouda & Benali, 2022). Resistance to change among employees, coming from psychological and social issues, also obstructs adoption, requiring appropriate communication and support to overcome (Bäcklund et al., 2023). A lack of management commitment increases these challenges, resulting in poor resource allocation and insufficient strategic planning for energy saving programs (Khafiso et al., 2024; Russell et al., 2020). Additionally, restricted resources and time limits hinder decision making, requiring supportive policies and accessible information to induce behavioural shifts (Bensouda & Benali, 2022).

2.4.3 Long term Sustainability Challenges

Sustaining behavioral improvements over time remains difficult due to psychological resistance, motivational gaps, and the need for constant assistance (Tsuda et al., 2017; Cash et al., 2023). Continuous monitoring is crucial but problematic due to data disparities and the complexity of tracking energy conservation outcomes (Chen & Nunes, 2023). Rapidly emerging technologies present acceptance barriers, particularly for smaller enterprises with limited resources, while knowledge gaps among consumers inhibit proactive engagement (Borowski, 2020). Staff turnover further undermines long term sustainability, as organizational culture and training efficacy influence the retention of energy management techniques (Brabson et al., 2019).

3. RESEARCH METHODOLOGY

This study adopted a quantitative approach, sequential exploratory, grounded in a quantitative dominant approach, to identify and prioritize behavioural energy management strategies within the apparel manufacturing industry (Levitt et al., 2018).

The methodology had three essential phases: strategy identification from literature review, validation through peer review by experts, and a quantitative ranking procedure. A thorough literature analysis was undertaken to compile a diverse array of energy behaviour management strategies applicable to industrial contexts, namely in apparel manufacturing. The review concentrated on peer-reviewed academic journals, industrial case studies, government publications, and best practice manuals released in the past decade. The review yielded 13 distinct strategies, which were then categorized into four thematic domains: technological, managerial, legal, and societal. The use of classification was intended to facilitate a holistic understanding of behavioural influences on energy efficiency (Thollander & Palm, 2018).

Further to the literature review, the identified strategies were corroborated and evaluated by expert opinion. A systematic questionnaire was prepared and disseminated among a selected group of energy professionals, including energy managers, engineers, facilities managers, and university scholars focusing on sustainability and industrial energy efficiency. A total of 40 specialists were recruited to participate in the study. The participants were chosen by purposive sampling, ensuring the inclusion solely of individuals with direct experience in energy management in industrial or commercial environments (Etikan, 2016). This selection method yielded a wide range of findings, enabling the research to encompass many views within the sector.

The questionnaire offered experts to score the 13 techniques based on their perceived effectiveness in real-world apparel manufacturing scenarios. Each participant was asked to assign a rank from 1 to 13, with 1 being the most effective method and 13 being the least effective, which is suitable for decision making and priority setting studies in energy research (Kassem et al., 2020). The purpose was to reflect on the practical prioritization of solutions as observed by individuals actively involved in energy related decision making and implementation.

To assess the responses, the Relative Importance Index (RII) approach was applied. This technique is widely used in construction and behavioural energy research to determine relative significance based on expert input (Kassem et al., 2020). The RII was determined using the formula:

$$RII = \frac{\sum W}{A \times N} \qquad Equation\ (1)$$

Where, W = constant expressing the weighting given to each response, A = highest weighting and N = total number in the responses.

Where W is the weight provided to each approach by respondents, A is the highest possible weight (in this case, 13), and N is the total number of respondents. The resulting RII scores were used to rank the solutions from most to least effective, presenting a clear indication of industry consensus on priority activities for behavioural energy control.

Ethical considerations were thoroughly addressed throughout the research process. Participation was entirely voluntary, and all respondents were informed of the study's goal and use of their responses. No personal or sensitive information was collected, and all replies were kept anonymous to maintain confidentiality. These processes guaranteed that the research was done in a manner that respects both academic integrity and the rights of the participants.

4. RESEARCH FINDINGS AND ANALYSIS

Through a comprehensive literature analysis, various energy behaviour control strategies have been identified and divided into four primary domains as technological, managerial, legal, and social strategies. Technological strategies include smart metering and monitoring systems, automation and smart controls, behavioural nudges through apps and notifications, energy dashboards and visualization tools, and AI and machine learning based predictive control, which leverage real-time data and automation to optimize energy efficiency. Managerial solutions focus on organizational interventions such as employee training programs, performance monitoring and feedback systems, and incentive-based programs to develop energy conscious behaviours. Legal strategies comprise energy conservation agreements and policy enforcement, which establish legislative frameworks to ensure compliance with energy saving initiatives. Lastly, social tactics encompass social recognition programs, community participation and education, and joint goal formulation, attempting to develop a culture of sustainability through collective action and awareness. These solutions jointly target both technological and human centric aspects of energy management, offering a holistic approach to reducing energy usage in industrial settings.

In the next step of the analysis, the identified energy behaviour control strategies were subjected to expert validation to assess their real-world effectiveness. According to that, the rankings were used to calculate the RII value of the strategies.

$$RII = \frac{\sum W}{A \times N} \qquad Equation\ (2)$$

Σ Scores for a Factor, this symbol (Sigma) represents the sum of all ranking that given to a specific strategy by all respondents. Higher ranking shows higher efficiency in normal context. Since lower original ranks (1, 2, 3...) indicate higher efficiency**,** invert the ranks.

For each strategy (1 to 13),

Inverted Score (W) = 14 - Original Rank

So, for AI ΣW = (14-7) +(14-7) +(14-13) +(14-2) +(14-9) +(14-13) +……+(14-3)

= 394

Based on the calculation of RII, Table 1 shows the RII rate of energy behaviour control strategies.

Table 1: RII rate of energy behaviour control strategies

Strategies	Highest Rank	Number of Responses	Weight of Strategy	RII	Rank
AI and Machine Learning Based Predictive Control	13	40	464	0.892	1
Automation and Smart Controls	13	40	423	0.813	2
Smart Metering and Monitoring Systems	13	40	394	0.758	3
Incentive based programs	13	40	370	0.712	4
Energy Dashboards and Visualization Tools	13	40	340	0.654	5
Employee training programs	13	40	324	0.623	6
Performance monitoring and feedback systems	13	40	306	0.588	7
Behavioural Nudges Through Apps and Notifications	13	40	286	0.550	8
Policy Enforcement	13	40	256	0.492	9
Energy Conservation Agreements	13	40	234	0.450	10
Social Recognition Programs	13	40	200	0.385	11
Community Engagement and Education	13	40	164	0.315	12
Collaborative Goal Setting	13	40	70	0.150	13

The strategy with the highest RII is AI and Machine Learning Based Predictive Control (0.892), signifying its considerable importance in contemporary energy optimisation initiatives. Subsequently, Automation and Smart Controls (0.813) and Smart Metering and Monitoring Systems (0.758) underscore the increasing focus on technology driven

solutions. Incentive Based Programs (0.712) and Energy Dashboards and Visualisation Tools (0.654) are highly ranked strategies, indicating that both motivation and visibility are crucial in promoting energy efficiency. Mid-level tactics encompass Employee Training Programs, Performance Monitoring, and Behavioural Nudges, highlighting the significance of human elements in conjunction with technical instruments. Policy Enforcement, Energy Conservation Agreements, and Social Recognition Programs rank lower on the list, whereas Community Engagement and Education and Collaborative Goal Setting are seen as the least impactful, with RIIs of 0.315 and 0.150, respectively.

For the classification of these strategies, the RII classification has been used based on Buertey et al. (2024) (Table 2).

Table 2: RII classification

RII Values	Importance Level
$0.90 \leq RII \leq 1$	Strongly Important
$0.75 \leq RII \leq 0.89$	Very Important
$0.60 \leq RII \leq 0.74$	Important
$0.45 \leq RII \leq 0.59$	Moderately Important
$0.30 \leq RII \leq 0.44$	Unimportant
$0.15 \leq RII \leq 0.29$	Very Unimportant
$0 \leq RII \leq 0.14$	Strongly Unimportant

The ranking of energy management strategies, according to the Relative Importance Index (RII) classification, illustrates the impact of technical advancements and organisational preferences on energy efficiency and conservation. AI and Machine Learning Based Predictive Control (0.892), Automation and Smart Controls (0.813), and Smart Metering and Monitoring Systems (0.758) are classified as "Very Important." These tactics are esteemed for embodying innovative, data driven methodologies that facilitate real-time energy optimisation, problem identification, and predictive maintenance. The incorporation of AI facilitates adaptive and anticipatory control systems, minimising energy waste and improving operational efficiency. Automation and smart systems decrease human error and assure constant performance, while smart metering provides granular visibility into energy usage trends, which is crucial for informed decision making and accountability.

In the "Important" category, Incentive Based Programs (0.712), Energy Dashboards and Visualization Tools (0.654), and Employee Training Programs (0.623) are acknowledged for their supportive and enabling roles. Incentives are robust motivators that encourage compliance and involvement in energy saving measures. They integrate individual or departmental interests with organizational sustainability goals. Dashboards and visualization tools can make energy data more accessible and actionable, enabling transparency and fostering a culture of awareness. Meanwhile, employee training programs are crucial for strengthening internal capabilities, fostering responsible conduct, and assuring optimal use of the established systems and technology.

Strategies ranked as "Moderately Important", such as Performance Monitoring and Feedback Systems (0.588), Behavioural Nudges Through Apps and Notifications (0.550), Policy Enforcement (0.492), and Energy Conservation Agreements (0.450), demonstrate attempts to support long-term engagement and compliance. These strategies are regarded

as somewhat effective because their effectiveness frequently depends on consistent implementation, user responsiveness, and cultural factors. For instance, feedback methods can improve performance only if users are motivated to act on the data. Similarly, behavioural nudges rely on psychological triggers, which may not consistently deliver sustained behaviour change. Policy enforcement and conservation agreements are crucial for formal accountability but may be regarded as top-down measures with limited flexibility or intrinsic incentive.

In the "Unimportant" category, Social Recognition Programs (0.385) and Community Engagement and Education (0.315) are considered to have less influence on energy results in business environments. This may be owing to the indirect nature of their impact, since they generally try to shift cultural norms or public awareness rather than offer instant, verifiable benefits. Their effectiveness may also be lessened in corporate organisations where quantifiable goals and returns on investment are stressed.

Finally, Collaborative Goal Setting (0.150) is classed as "Very Unimportant", probably because it demands significant work and coordination across departments, frequently without quick or evident energy savings. In practice, collaborative initiatives can confront obstacles linked to conflicting priorities, lack of engagement, or ambiguous accountability, making them less attractive compared to more direct or automated treatments.

Overall, this classification demonstrates a strong preference for technologically advanced, results oriented techniques that offer measurable and scalable energy reductions. It also emphasises a weaker emphasis on softer, community based, or participatory strategies, presumably due to their perceived lower impact and longer deadlines for effect.

Table 3: Classification on strategies

Classification	Strategies	RII
Very Important	AI and Machine Learning Based Predictive Control	0.892
	Automation and Smart Controls	0.813
	Smart Metering and Monitoring Systems	0.758
Important	Incentive based programs	0.712
	Energy Dashboards and Visualization Tools	0.654
	Employee training programs	0.623
Moderately Important	Performance monitoring and feedback systems	0.588
	Behavioural Nudges Through Apps and Notifications	0.550
	Policy Enforcement	0.492
	Energy Conservation Agreements	0.450
Unimportant	Social Recognition Programs	0.385
	Community Engagement and Education	0.315
Very Unimportant	Collaborative Goal Setting	0.150

5. DISCUSSION

This study's findings indicate an apparent trend in the apparel manufacturing sector towards the adoption of technologically advanced energy behaviour management measures. Amongst the thirteen techniques assessed, AI and Machine Learning Based Predictive Control obtained the highest Relative Importance Index (RII), closely followed by Automation and Smart Controls, as well as Smart Metering and Monitoring Systems. This pattern highlights a distinct industrial inclination towards data driven, real-time, and precision focused interventions capable of producing quantifiable results with less human involvement.

These top ranked techniques not only offer exceptional scalability but also align with the expanding digitalization trends in manufacturing. The strong RII values reflect credibility in these systems' ability to forecast consumption patterns, discover inefficiencies, and self-correct processes without the need for considerable user input. The introduction of such smart devices helps bridge the "energy performance gap" by decreasing the mismatch between expected and actual energy consumption levels, a recurrent challenge in energy saving programs.

Managerial and motivational initiatives such as Incentive Based Programs, Energy Dashboards, and Employee Training Programs also obtained significant attention, falling inside the "Important" category. These methods are crucial facilitators that promote technological interventions by encouraging awareness, engagement, and accountability among employees. Incentive schemes aim to integrate individual behaviours with organizational sustainability objectives, therefore improving the adoption and continued usage of new technology.

Conversely, methods relying on legal and social frameworks, including Policy Enforcement, Community Engagement, and Collaborative Goal Setting, turned out substantially lower. This trend reflects the corporate sector's preference for bottom line-oriented solutions over regulatory or socially motivated initiatives, which may be regarded as slower or less directly influential. Particularly, Collaborative Goal Setting being ranked as "Very Unimportant" shows that techniques involving substantial coordination and abstract results are commonly deprioritized in fast paced industrial environments.

Interestingly, behavioural and psychological methods like Behavioural Nudges and Recognition Programs also obtained low to moderate relevance ratings. This may reflect the problem of maintaining long-term involvement in behaviourally driven interventions without constant reward, monitoring, or integration with technology. The effectiveness of these tactics may also be context dependent, necessitating cultural transformations and leadership commitment that are sometimes difficult to maintain in changing manufacturing environments.

These observations emphasize the requirement of a hybrid approach that utilizes the precision and efficiency of sophisticated technologies while embedding behavioural and organizational enables them to ensure lasting impact. Despite the lower rankings of social and behavioural interventions, their synergistic integration with technological solutions may be vital for generating deeper and more sustainable improvements in energy use behaviour.

6. CONCLUSION

The paper offers a detailed investigation of energy behaviour control strategies within the apparel manufacturing sector, offering empirical evidence of their relative effectiveness through expert validation and Relative Importance Index (RII) analysis. The results suggest a strong industry preference for technologically driven initiatives, especially AI and machine learning based predictive control, automation, and smart metering systems. These solutions are prized for their capacity to deliver real-time, adaptive, and scalable energy optimizations that decrease waste and meet sustainability targets.

While managerial tactics such as training programs, incentive mechanisms, and performance monitoring have notable importance, they serve primarily as facilitators for the more impactful technical initiatives. Conversely, legal and social tactics, though potentially valuable, are sometimes deprioritized due to perceived complexity, slower return on investment, or mismatch with corporate priorities.

A critical recommendation resulting from this research is the adoption of a quantitative framework, one that mixes high impact technologies with structured behavioural and organizational components. Such a hybrid strategy targets not only operational efficiency but also the human components of energy use, delivering more robust and sustainable outcomes.

For governments and business leaders, these findings give a realistic roadmap to identify actions that balance cost effectiveness with long-term sustainability. Future studies might further explore the contextual factors driving the adoption of lower ranked methods, particularly in apparel, and analyse the long-term implications of integrated behavioural and technical solutions.

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APPLICABILITY OF ARTIFICIAL INTELLIGENCE MODELS FOR SELECTION OF ADR METHODS TO THE SETTLEMENT OF CONTRACTOR-RELATED VARIATION DISPUTES IN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA

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ABSTRACT

Construction disputes in Sri Lanka are highly technical in nature and differ significantly from general commercial disputes, necessitating fast and cost-effective resolution methods. Due to the drawbacks of litigation such as high cost, delays, and complexity, Alternative Dispute Resolution (ADR) methods have become increasingly important, offering advantages like speed, affordability, fairness, simplicity, flexibility, confidentiality, and minimal delays. In building construction projects, variations are common and often lead to disputes, with contractor-related variation disputes being particularly prevalent and impactful. Effective resolution of these disputes is essential for successful project completion. This research aims to propose a guideline that utilizes Artificial Intelligence (AI), including machine learning and deep learning techniques, to select the most suitable ADR method for settling contractor-related variation disputes in building construction projects in Sri Lanka. The study adopted a qualitative approach, conducting expert interviews with ten professionals selected through purposive sampling, all of whom had experience in ADR and construction variations. Data were analysed using code-based content analysis to identify appropriate ADR methods. The research findings led to the development of a guideline integrating AI tools to support decision-making in ADR method selection. This guideline provides valuable insights for industry practitioners, enabling more efficient and effective resolution of contractor-related variation disputes within Sri Lanka's building construction sector.

Keywords: *ADR Methods, Artificial Intelligence, Construction Industry, Contractor-Related Variation Dispute*

1. INTRODUCTION

The construction industry is one of the major industries which plays a vital role in the economy of any country (Illankoon et al., 2019). It has become more competitive and

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complex due to the increasing demands of employers and the global economic downturn (Farooqui et al., 2022). Consequently, variations are inevitable in those building construction projects, and it may escalate up to variation disputes (Perera et al., 2019). Cakmak and Cakmak (2014) described that contractor-related variation disputes are distinctive among variation disputes and, consequently, effective settlement procedures of contractor-related variation disputes are valuable to the successful completion of the building construction project. If the resolution of contractor-related variation raised disputes not focused properly, the proper sequence of the project may often be lost (Cheung et al., 2002) Various types of ADR methods can be used to resolve various building construction related disputes. The previous researchers have highlighted only the common disputes in building construction. According to this research, endeavour to establish a strategic guideline to settlement of contractor related variation raised disputes by using ADR methods. A detailed study to investigate the contractor-related variation disputes and how Alternative Dispute Resolution methods can apply for those disputes in the context of Sri Lankan building construction projects has not been done yet. Since the contractor-related variation disputes in the Sri Lankan building construction projects are different from other countries, carrying out a study to provide guideline to settlement of contractor related variation disputes by using ADR in building construction industry in Sri Lanka will be very important to the success of future construction industry in Sri Lanka.

Today, more than ever, it is clear that claims and disputes in the construction industry have become endemic, particularly those resulting from variations. Furthermore, Latham (1994) revealed that, one of the key issues in the building construction industry was variation and its impact on productivity. Similarly, variations are a key source of delays and cost overruns in building projects, and they are the source of many conflicts in construction contracts. In practice, the time and cost impact on the project is a contested topic when valuing a variation (Mustapha et al., 2018). According to Asamaoh and Offei-Nyako (2013), variations in the construction process at all stages have an impact on project administration. Time overrun and cost overrun are revealed as the leading effects of variation order (Asamaoh & Offei-Nyako, 2013). Furthermore Keane et al. (2010) also identified cost overrun, time overrun and contract disagreements between parties in contract are major impacts of variation. Arain and Pheng (2006) summarized the impacts of variations to building construction projects as follows: rising the project cost, need of hiring new professionals, procurement delay, increase in overhead expenses, and payment delays, quality reduction, productivity reduction, demolition and reworks, logistics delays, additional payments for contractor, conflicts among professionals and delay in the completion schedule.

Integrating Artificial Intelligence (AI) into the ADR process can improve the selection and application of resolution methods by providing data-driven insights, reducing time and costs, and enhancing decision-making. AI can analyse project data like contracts and designs to identify potential disputes early on. Using machine learning, AI can recommend the most suitable ADR method based on the nature of the dispute and its financial impact. AI can also streamline communication by automating document exchanges, speeding up negotiations, and ensuring transparency. Additionally, AI platforms can provide real-time insights, helping make better decisions during dispute resolution (Goh & Zhang, 2020). By using AI, the dispute resolution process becomes

faster, more accurate, and cost-effective, improving overall efficiency in Sri Lanka's construction sector.

2. METHODOLOGY

This study employed a qualitative research methodology combined with the development of Artificial Intelligence (AI) models to explore the applicability of AI in selecting appropriate Alternative Dispute Resolution (ADR) methods for contractor-related variation disputes in building construction projects in Sri Lanka. The research began with an in-depth literature review was conducted to critically examine existing ADR practices in the Sri Lankan construction context. This was essential to understand the local legal, procedural, and cultural aspects of dispute resolution, identify limitations in current methods, and ensure that any proposed AI application would be contextually relevant and practically viable. Moreover, the review helped define the research problem, identify knowledge gaps, and design the data collection framework. This review helped define the research problem and design the data collection framework.

To gather context-specific insights, semi-structured interviews were conducted with a purposively selected group of industry professionals, including project managers, contract administrators, dispute resolution experts, and consultants. The experts were selected based on their substantial professional experience, each having a minimum of 10 years in the Sri Lankan construction industry with direct involvement in managing contractor-related variations and dispute resolution. Inclusion criteria required that participants had (1) practical experience handling building construction projects under standard forms of contract, (2) prior involvement in variation-related disputes as a contracting party, consultant, or neutral third party, and (3) familiarity with at least one form of ADR method (e.g., adjudication, mediation, or arbitration). This ensured that their perspectives were grounded in both contractual and dispute resolution practice. A total of 10 experts, comprising 3 project managers, 2 contract administrators, 3 dispute resolution practitioners (including arbitrators and adjudicators), and 2 senior consultants, were interviewed. The sample size was determined based on the principle of data saturation, where additional interviews no longer yielded new themes or insights, and was considered sufficient to capture diverse yet deeply informed professional perspectives. The interviews focused on collecting qualitative data regarding the common causes and impacts of contractor-related variations, existing ADR practices, challenges in current dispute resolution processes, and key factors influencing the selection of ADR methods. Furthermore, participants were asked to reflect on the potential role of AI in enhancing ADR decision-making. While it was evident from the interviews that AI is not currently applied in real-world ADR processes within the local context, the insights obtained were systematically analysed and later used to identify relevant decision variables, which formed the basis for developing and training AI models for ADR method selection.

Following data collection, the interview responses were transcribed and analysed manually using thematic analysis. Key variables, decision factors, and common patterns were extracted and structured. These refined data points were then used as input to develop and train AI models aimed at predicting or recommending suitable ADR methods for specific dispute scenarios. Thus, although the study is grounded in qualitative research, it also incorporates a data-driven component by utilizing expert-derived knowledge to simulate the potential of AI-assisted decision-making tools.

This integrated methodological approach combining qualitative inquiry with AI model training allowed for both a deep understanding of industry challenges and a forward-looking evaluation of how AI could enhance dispute resolution processes in Sri Lanka's construction sector, despite its current lack of practical adoption.

3. DATA ANALYSIS

3.1 CAUSES OF DISPUTES ON VARIATIONS IN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA

Various research have been conducted by the researchers along the different types of variation disputes (Bello & Saka, 2017). However, according to Keane et al. (2010), the most effective way to classify variation disputes is to classify them according to the cause. The following Table 1 presents the classification and related causes of variation disputes.

Table 1: Classification of variation disputes and causes

Client-related	Consultant-related
Change of plans or scope	Change in design
Insufficient planning at the project definition stage	Errors and omissions
Owners' financial problems	Poor coordination
Inadequate project objectives	Technology change
Replacement of materials/procedures	Value engineering
Impediment of prompt decision-making process	Conflicts among contract documents
Change in specifications by owner	Design complexity
Lack of involvement of the owner in design phase	Poor working drawing details
	Change in specifications

Cakmak and Cakmak (2014) described that contractor-related variation disputes are distinctive among variation disputes and consequently, effective settlement procedures of contractor-related variations disputes are valuable to the successful completion of the building construction project.

3.1.1 Settlement of Disputes through ADR Methods

According to the above mechanism both parties were responsible for resolving their own problems due to its voluntary character (Wimalachndra, 2007). This old system of ADR procedures encouraged peace and harmony, facilitated economic growth at the village level, and promoted social stability by bringing people together (Abeynayake, 2015). According to Abeynayake (2015) different ADR methods have been identified and utilized by stakeholders in the construction and commercial sectors in Sri Lanka at the modern era. In the construction industry, negotiation, mediation, conciliation, adjudication, and arbitration are known as widely used ADR methods (Abeynayake & Weddikkara, 2012).

3.1.2 Negotiation

Negotiation occurs whenever people discuss or share ideas in order to define or redefine the terms and conditions of their relationship. Further negotiation is a voluntary and usually informal procedure in which participants highlight areas of concern, examine options for resolving the problems, and seek a mutually acceptable solution to the issues (Abeynayake, 2015).

3.1.3 Mediation

Mediation is a collaborative, cooperative dispute resolution method in which the parties maintain influence over the outcome. Moreover, a systematic settlement of negotiation assisted by a neutral third party with no decision-making power is known as mediation (Kiridana et al., 2024). Mediation is a confidential process in which a neutral third party known as a mediator assists the parties in discussing and attempting to settle their disputes and consequently, the mediator has no authority to make a decision on behalf of the parties.

3.1.4 Conciliation

Conciliation is a procedure in which the parties to a dispute identify the disputed issues, develop options, consider alternatives, and attempt to achieve an agreement with the help of a neutral third party selected by the parties (Soorige & Abeynayake, 2015). Moreover, identified that, conciliation is a method of resolving disputes in which both parties agree to deploy a conciliator to help them resolve their issues and a third person successfully brings opponents together in conciliation.

3.1.5 Adjudication

Adjudication is a means of referring issues to a neutral third party for a decision that is only binding on the parties until the dispute is settled through arbitration or litigation). Abeynayake and Wedikkara (2013) revealed that, parties agree to nominate an adjudicator known as the Dispute Adjudication Board (DAB) or a single adjudicator at the start of the contract and the adjudicator is supposed to perform as an independent expert rather than an arbitrator. As a result, it is critical that the adjudicator be a person who is competent to interpret technical and contractual problems Abeynayake and Wedikkara (2013) revealed that, there is no such statutory recognition for adjudication methods in Sri Lanka, therefore the adjudicator's award has no legal standing. It is carried out in accordance with the CIDA Federation Internationale Des Ingenieurs-Counseils (FIDIC) conditions of contract, and consequently, unless the parties agree to enforce the award, the adjudicator's decision is not legally enforceable (Abeynayake & Weddikkara, 2013).

3.1.6 Arbitration

If a dispute cannot be settled amicably through mediation or adjudication, the case will be referred to an arbitrator for a binding decision (Kiridana et al., 2024). This is generally the forward methodology, and it incorporates the formal recognition of opposing viewpoints and issues. Moreover, according to Cheung et al. (2002), the most popular way for resolving construction disputes is arbitration, and most construction contracts have arbitration clauses that require the parties to refer any disagreements to arbitration. Abeynayake and Weddikkara (2013) identified that, an arbitral tribunal is supposed to act reasonably and impartially, as well as to follow procedures that minimize unnecessary

delays and costs. Moreover, arbitration, according to the American Institute of Architects, has been firmly established as a preferred way of private construction dispute resolution for many years. According to Stephenson (2018), arbitration is a legally binding process in which two or more parties agree that a dispute or potential dispute between them will be resolved by one or more unbiased persons in a judicial manner based on evidence presented before such person or group of people for a decision, and the decision is referred to as the award (Stephenson, 2018).

Analysis of the interview data revealed a consistent theme across all participants: the selection of the most suitable ADR method for a given dispute depends heavily on the dispute's nature, complexity, and characteristics. This conclusion was reached through thematic coding of the qualitative responses, where all 10 respondents independently highlighted that no single ADR method is universally applicable to every situation. For example, six experts emphasised that negotiation or mediation is often more effective for less complex disputes involving relationship-sensitive issues, while four experts stressed that adjudication or arbitration becomes necessary in technically complex disputes or where contractual interpretation is contested. Several respondents further noted that disputes involving high monetary values, multiple stakeholders, or cross-contractual claims often require more formal ADR mechanisms due to evidentiary and enforcement considerations. This recurring observation was coded under themes such as "ADR method selection factors," "complexity-based approach," and "dispute-specific tailoring," all of which appeared in every transcript. The universal occurrence of these themes across the sample provided the basis for the conclusion in Topic 6 that *all respondents agreed* on the situational nature of ADR method selection.

4. IMPORTANCE OF ADR METHODS FOR SETTLEMENT OF CONTRACTOR-RELATED VARIATION DISPUTES IN BUILDING CONSTRUCTION PROJECTS

When planning a construction project, the cost from start to finish seems to be of great importance, but variations have a significant impact on project cost overruns (Ranasinghe, 2014). In a construction project, the need to make changes is a practical reality (Keane et al., 2020). Even the most planned projects may necessitate changes due to various factors (Arain & Pheng, 2006). Variations orders are mostly responsible for cost and time overruns in building projects, with variation orders accounting for 6-17 % of cost overruns in building projects. Assaf et al. (2019) have revealed that the most significant contributors to claims and disputes were variation orders related to new requirements from clients and injustices to the contractor in variation evaluation.

Gillie et al. (1991) revealed that the main objective of alternative dispute resolution (ADR) is to resolve disputes by having the support of a neutral third party. Abeynayake and Wedikkara (2013) stated that there are two ADR groups such as formal – binding and informal – non-binding methods, and also stated that, most predominant requirement to achieve successful ADR is to aspiration for the parties to inspect the possibility for settlement. Different ADR methods consist of different characteristics, and those ADR methods have various times and cost factors, hence, choosing the precious method is important for a better outcome (Illankoon et al., 2019). Gunasena (2010) stated that arbitration, adjudication, mediation, conciliation and negotiation are widely used, basic ADR methods which can be used to the resolution of variations related disputes. As a

result, ADR methods are appropriate for resolving contractor-related variation disputes in the building construction sector, and they can be a component in a successful project (Kumaraswamy, 1997). The potential of maintaining business relationships is high when using the ADR method and this feature is critical to the building construction industry (Jannadia et al., 2000).

Table 1 illustrates the classification of variation disputes based on their underlying causes, as outlined by Keane et al. (2010). This cause-based categorisation is useful in the Sri Lankan construction context because it allows disputes to be traced directly to the responsible party either the client or the consultant thereby enabling a more targeted resolution strategy. Client-related causes typically stem from changes in project scope, inadequate planning during the project definition stage, or financial constraints affecting the owner's ability to proceed with the work. In contrast, consultant-related causes often involve technical aspects such as design changes, errors or omissions in design documentation, or poor coordination between design disciplines. By understanding these specific causal categories, stakeholders can more effectively assess the risk of variations leading to disputes and select appropriate dispute resolution mechanisms tailored to the dispute's origin.

4.1 REVIEW THE USAGE OF ADR IN THE BUILDING CONSTRUCTION INDUSTRY IN SRI LANKA

The conclusion that the appropriate ADR method depends on the nature, complexity, and characteristics of the dispute was based on expert survey results. Respondents rated factors such as dispute complexity, nature, and contractor's financial stability as highly influential in ADR selection. Over 80% identified these as key considerations.

Additionally, open-ended responses emphasized that ADR should be chosen based on the specifics of each case.

4.2 ISSUES TOWARDS MEDIATION

Table 2: Issues towards mediation

Issue	Sources	References
Mediator's lack of technical competence	8	11
Issue regard to the enforceability, because of non-binding	7	10
Mediator is only facilitator and not giving any opinions or decisions	5	6
Mediation provision is not included in SBDs in Sri Lanka	3	3
No guarantee that settlement will be reached	3	3
Reluctance of government stakeholders to take responsibility for the problem	2	2

4.3 ISSUES TOWARDS CONCILIATION

Table 3: Issues towards conciliation

Issue	Sources	References
Issue regard to the enforceability, because of non-binding	8	10
No guarantee that settlement will be reached	5	6
Lack of adequate skills of the conciliator regarding construction issues	4	5
Conciliation provision is not included in SBDs in Sri Lanka	3	3
Strong-willed conciliator can exercise much control	2	2

Although the issues identified in Tables 2 and 3 such as the mediator's or conciliator's lack of technical competence, enforceability concerns, and absence of statutory provisions could indeed arise in other types of construction disputes, their inclusion in this study is specifically linked to variation-related disputes for two main reasons. First, during the interviews, participants were explicitly asked to reflect on their experiences with *contractor-related variation disputes* and to identify mediation- or conciliation-related challenges they had encountered in resolving such disputes. Therefore, while the nature of these issues is not unique to variation disputes, the context in which they were reported was exclusively variation-related cases. Second, variation disputes often involve complex technical evaluations, contract interpretation, and valuation matters; these characteristics make issues such as a mediator's or conciliator's technical competence, enforceability of agreements, and procedural limitations particularly critical. As a result, even though similar challenges could affect other disputes, the frequency and impact of these issues were found to be especially pronounced in the context of variation disputes in this study's dataset.

According to both literature and expert survey findings, several drawbacks of mediation and conciliation in the construction industry of Sri Lanka. Findings of the expert survey also proved that the construction industry in Sri Lanka always attempts to present their disputes to a third party who has a broad understanding of a field. That is the immediate reason why those are not popular in construction industry in Sri Lanka.

4.4 EFFECTIVE ADR METHODS FOR IDENTIFIED CONTRACTOR RELATED VARIATION DISPUTES

According to the literature review findings, ten causes of contractor-related variation disputes are identified. In the expert interview, respondents suggested their views and the most appropriate ADR method for identified disputes. Further, findings of the expert survey proved that many of the above causes are practical issues and common in the construction industry. However, for practical reasons, some of the facts identified in the literature were excluded by the experts. As an example, unavailability of equipment and unavailability of skills were excluded by the experts by citing reasons. Moreover, experts were explained that contractor have responsibility to use technically appropriate equipment to relevant works and contractor should have skilled personnel and all required workers to perform the tasks according to contract. Therefore, the findings of expert interview proved that the contractor is ultimately responsible for the variation disputes caused by unavailability of skills and unavailability of equipment. Therefore, finding

solutions by ADR methods is a waste of time for such issues. Table 4 illustrates the given appropriate ADR methods by respondents.

Table 4: Contractor related variation disputes and ADR solutions

Contractor related variation dispute	ADR solution
Lack of involvement in design	Negotiation
Contractor's financial difficulties	Adjudication
Desired profitability	Adjudication
Differing site conditions	Adjudication
Fast-track construction	Negotiation
Poor procurement process	Adjudication
Lack of communication	Adjudication
Consultant's lack of experience	Adjudication

5. ARTIFICIAL INTELLIGENCE MODELS FOR SELECTION OF ADR METHOD

AI techniques can significantly support the development of intelligent systems for selecting appropriate Alternative Dispute Resolution (ADR) methods in construction-related disputes. While the following algorithms are general-purpose in nature, they can be integrated into comprehensive decision-making models to enhance the accuracy and effectiveness of ADR selection. These techniques analyse factors such as dispute type, financial impact, project complexity, and historical outcomes to support data-driven decisions.

5.1 SUPPORT VECTOR MACHINES (SVM)

SVMs are effective in handling complex and nonlinear data relationships. When incorporated into a broader decision-support system, they can classify disputes based on key features and predict the most suitable ADR method (e.g., mediation, adjudication) by learning from historical dispute data.

5.2 ARTIFICIAL NEURAL NETWORKS (ANNS)

ANNs can process large volumes of structured data to identify patterns and correlations among dispute characteristics. Within an integrated model, ANNs can support ADR recommendation by analyzing inputs such as dispute causes, contract type, and financial scale.

5.3 K-NEAREST NEIGHBOURS (K-NN)

K-NN algorithms are useful for identifying past disputes similar to the current case. As part of a larger ADR recommendation framework, K-NN can suggest methods that were effective in similar historical cases (Goh & Zhang, 2020).

5.4 NATURAL LANGUAGE PROCESSING (NLP)

NLP techniques allow for the processing of unstructured textual data—such as emails, reports, and contracts—to extract relevant dispute indicators. These indicators can then serve as input features for machine learning models used in ADR method prediction

Random Forest Algorithm and Reinforcement Learning (RL). Random Forests enhance prediction reliability by aggregating the output of multiple decision trees. In combination with RL, which optimizes decisions through iterative feedback, these algorithms can form part of adaptive systems that improve ADR recommendations over time.

5.5 FUZZY LOGIC SYSTEMS

Fuzzy Logic systems are particularly suited for handling ambiguity and subjectivity in dispute characteristics. When used within hybrid decision models, they offer flexibility by applying fuzzy rules to determine the most appropriate ADR pathway (Goh & Zhang, 2020).

In summary, while these algorithms are not standalone ADR selection models, they provide critical computational capabilities that can be combined with domain expertise and structured methodologies to develop robust, intelligent ADR decision-support systems tailored to the construction industry.

6. GUIDELINE TO SETTLEMENT OF CONTRACTOR RELATED VARIATION DISPUTES BY USING ADR METHODS IN BUILDING SRI LANKA

Guideline to settlement of contractor related variation disputes by using ADR methods in building construction industry in Sri Lanka can be mentioned as follows.

Figure 1 presents a structured guideline for resolving contractor-related variation disputes in the Sri Lankan building construction industry. It integrates Alternative Dispute Resolution (ADR) mechanisms with a novel application of Artificial Intelligence (AI) to support informed, efficient decision-making. At the center of this guideline is a pretrained AI model designed to assist in the early assessment of the dispute.

The AI model is trained on historical dispute data, incorporating features such as dispute type, financial impact, project complexity, and behavioral patterns of involved parties. When a new dispute arises, the model analyzes these inputs to determine whether negotiation is likely to be effective as a first-line ADR method. This ensures that the decision to negotiate is not made solely based on subjective judgment but is supported by evidence from past cases with similar profiles.

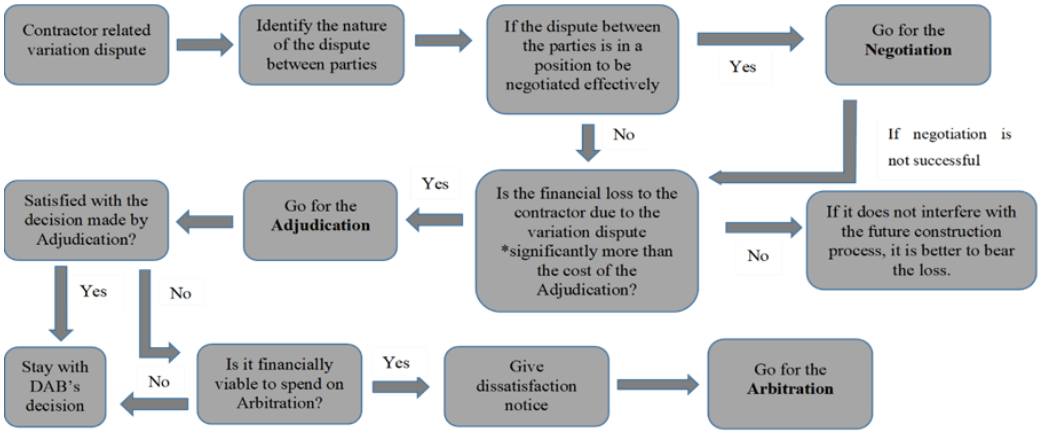


Figure 1: Guideline to settlement of contractor related variation disputes by using ADR in building construction industry in Sri Lanka

If the model predicts a high likelihood of successful negotiation, the process proceeds accordingly. However, if negotiation is deemed inappropriate or fails, the guideline shifts to a cost-benefit analysis stage, where the parties evaluate whether the potential financial loss warrants escalation to adjudication. If the loss justifies it, the dispute progresses to adjudication, and if the outcome remains unsatisfactory, it moves on to arbitration—ensuring that more formal and costly ADR methods are employed only when necessary.

This integration of a pretrained AI model with the ADR pathway ensures consistency, objectivity, and efficiency in the dispute resolution process. By aligning AI predictions with decision points in the guideline, the model functions as a decision-support tool, promoting faster, less adversarial outcomes and reflecting a proactive adoption of intelligent technologies in the construction dispute management framework.

7. CONCLUSION

Due to the industry's complexity, completing the project without making changes and adjustments to the construction process is practically impossible. Therefore, variations are inevitable in construction projects. According to the literature, Variation in construction refers to changes in design, quality, and quantity of work, as well as changes in the standard of materials or goods to be used in the work and the removal from site of any material that does not comply with the contract (Asamaoh & Offei-Nyako, 2013). Moreover, the literature has proven that variations can escalate into disputes, and then it can highly be influenced project cost, delays, conflicts, project quality, and issues in construction cost management in building construction projects. Accordingly, it is important to use a good settlement method to drive a project to successful completion. Consequently, in literature, variation disputes have been grouped into three categories for the contracting parties: client-related variations disputes, consultant-related variations disputes, and contractor-related variations disputes. In addition, a new group called "other variations disputes" has been created to represent non-party-related issues.

According to the classification derived from the literature survey, there are four main types of variation dispute categories. Among them, taking into account the specifics of contractor-related variation disputes as proven in the literature, it was taken to an expert interview. The purpose of these expert interviews was to discuss each of the above contractor-related variation disputes and select the ADR method that would lead to the most effective settlement for each type. However, in order to bring this work to a successful level, firstly got a basic understanding of the ADR methods used in Sri Lanka and their drawbacks from experts. As per the expert interviews, many of the facts mentioned in the literature were discussed, up to the point of proposing an effective ADR method, although some of the facts identified in the literature were excluded by the experts because of practical reasons. As an example, unavailability of equipment and unavailability of skills were excluded by the experts by giving reasons. However, with the exception of the two exclusions mentioned above, all the causes of contractor related variation disputes such as lack of involvement in design, Contractor’s financial difficulties, Desired profitability, differing site conditions, fast-track construction, Poor procurement process, Lack of communication and Consultant’s lack of experience have been accepted by experts and the most suitable ADR methods have been introduced for settle them. In developing this guideline, it was considered the expert reviews and according to that much attention was paid to selecting the ADR method with the most suitable cost range, depending on the financial value of the variation problem. Since

construction is an industry that must always be balanced with money, hence, every decision must be made in a way that does not lead to financial risk. Furthermore, considering the complexity and nature of the problem, attempts have been made to list ADR methods in an easy-to-use sequence, resolving issues that can be resolved through negotiations at an early stage and moving on to further methods only if they fail. Establishment of Negotiation and Mediation methods are suitable for settlement of disputes in the construction industry. Finally, to deviate this research to modern and smart Artificial Intelligence application is checked to select the most appropriate ADR method settlement of Dispute. It shows that the Artificial Intelligence concept can be applied where the AI models are trained using past project experience.

8. RECOMMENDATIONS

To further enhance the effectiveness and efficiency of the ADR methods in resolving contractor-related variation disputes, Artificial Intelligence (AI) can be employed as a highly effective tool. AI can be employed to examine large volumes of project data like contracts, designs, and communication records to identify trends and predict potential areas of dispute at an early stage of the project. AI can also provide real-time recommendations on the most appropriate ADR process with regard to the specifics of the controversy, such as economic considerations, nature of deviation, and parties involved. With the integration of AI into the ADR process, mediators and negotiators can obtain data-driven insights, which enable decision-making, minimize biases, and increase the likelihood of a successful resolution. Further, AI-based systems can automate bureaucratic tasks, such as document management and scheduling, so that the parties can focus on resolving the key issues properly. The adoption of AI into the ADR system can hence make the resolution of disputes more proactive, accurate, and inexpensive, ultimately paving the way to the smoother project completion of Sri Lankan constructions. Finally, as a whole, it can be concluded that the settlement of contractor-related variation disputes by using ADR in the building construction industry is not yet largely prevalent in the context of Sri Lanka. Though most Sri Lankan building contractors and construction sector possess the necessary basic knowledge and capacity to use ADR, an intercession from all related people and the government is necessary to effectively use and have faith and good practice ADR in the Sri Lankan context. The proposed guideline can be helpful to any level of the contractor to a better settlement of variation dispute by choosing the most appropriate ADR method by concerning the nature of the dispute.

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APPLICABILITY OF LEAN MAINTENANCE PRACTICES TO MITIGATE MAINTENANCE MANAGEMENT ISSUES IN SRI LANKAN HIGH-RISE RESIDENTIAL BUILDINGS

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ABSTRACT

Maintenance management (MM) is considered a critical function in residential buildings, ensuring longevity, safety, operational efficiency and cost-effectiveness. Compared to low-rise or mid-rise residential structures, high-rise residential buildings often face more complex and frequent maintenance-related issues due to their scale, building systems, and occupancy density. According to previous studies, implementing lean in maintenance is an effective strategy to improve maintenance efficiency. Thus, this study investigates the applicability of lean maintenance practices to mitigate such issues in Sri Lankan high-rise residential buildings and proposes suitable strategies for improvement. A qualitative case study approach was adopted, involving semi-structured interviews with maintenance personnel from four high-rise residential buildings in Colombo district. Additionally, the findings revealed that seven out of eight lean maintenance wastes prevailed in the selected cases. Further, three expert interviews were carried out to propose strategies to overcome the identified challenges in lean implementation. The findings of expert interviews revealed that the lack of lean knowledge and resistance to change in top management are the main challenges to implement lean maintenance in high-rise residential buildings in Sri Lanka. Further, experts proposed several key strategies for high-rise residential buildings, including encouraging lean certificates for maintenance supervisors, integrating feedback systems using QR codes or CMMS, visual dashboards, conducting lean awareness workshops, etc. The findings of this study are useful to address the existing MM issues and implement lean maintenance practices in high-rise residential buildings in Sri Lanka.

Keywords: *High-Rise Residential Buildings; Lean; Lean Maintenance; Maintenance Management; Strategies.*

1. INTRODUCTION

Maintenance management (MM) is a systematic process of planning, organizing, and evaluating maintenance activities and the associated costs (Khider & Hamza, 2022). Organizations consider maintenance as a critical requirement for providing a better built

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environment to occupants by ensuring assets and equipment are optimally functional (Mong et al., 2019).

MM is crucial in the housing industry to support human daily routines and improve the productivity of the activities in and around the residences (Au-Yong et el., 2019). In prior studies, it is mentioned that the maintenance issues faced by residents of high-rise residential buildings are mainly caused by inefficient maintenance management systems, insufficient regulations in maintenance management, and resident dissatisfaction with the service quality of building management because of the increasing demand (Amani et al., 2018). Through the implementation of lean concepts and procedures, lean thinking can be integrated into maintenance works and it can be applied to address challenges in MM while aligning maintenance with business objectives, thus maximizing revenues (Ghayebloo & Shahanaghi, 2010). According to Jasiulewicz-Kaczmarek and Saniuk (2018), Lean Maintenance (LM) aims to achieve the optimal level of equipment reliability while using a minimum of resources. In addition, maintenance performance can be enhanced by implementing LM tools (Mostafa et al., 2015).

However, there is a lack of empirical research on its application within the context of high-rise residential buildings in developing countries such as Sri Lanka. This gap is particularly critical given the increasing demand for high-rise housing and the complex challenges associated with managing such facilities. Therefore, this paper aims to investigate the potential for applying Lean Maintenance principles in high-rise residential buildings in Sri Lanka. Specifically, the study explores existing MM practices, identifies barriers to LM adoption, and recommends strategies for effective implementation. The paper begins with a literature review, followed by the research methodology, data analysis, key findings, and concludes with practical implications and future research directions.

2. LITERATURE REVIEW

2.1 COMMON MAINTENANCE MANAGEMENT ISSUES IN HIGH-RISE RESIDENTIAL BUILDINGS

MM is critical in high-rise residential buildings as it directly impacts the safety, functionality, and longevity of the building's systems and structures (Horner et al., 1997). Au-Yong et al. (2018) reported that poor MM performance in high-rise residences often arises from systematic inefficiencies, including the absence of maintenance standards, irregular preventive maintenance and poor service quality. According to Au-Yong et al. (2023), common MM issues include lack of awareness or cooperation of the residents, lack of preventive maintenance, unavailability of spare parts, etc. More recent findings by Au-Yong et al. (2023) highlighted specific challenges such as unqualified contractors, inadequate staff training, limited use of maintenance software, unclear job roles, and non-cooperative residents. According to De Silva et al. (2012), the lack of defined maintenance policies and reliance on reactive approaches increases such challenges. Although MM issues are prevalent in high-rise residential buildings in Sri Lanka, they have not been extensively explored; therefore, it is essential to address these issues through structured and proactive strategies (De Silva et al., 2012).

2.2 LEAN MAINTENANCE IN HIGH-RISE RESIDENTIAL BUILDINGS

The LM concept is based on lean manufacturing, which emphasizes reducing waste and increasing production efficiency (Bruun & Mefford, 2004). LM aims to increase overall equipment efficiency (OEE), decrease unnecessary downtimes and streamline operations by eliminating non-value-added activities (Womack & Jones, 1997). There are eight types of lean waste identified during maintenance which can negatively impact operational efficiency (Bhamu & Sangwan, 2016). While lean principles have been widely adopted in the manufacturing and industrial sectors to improve process efficiency and eliminate non-value-added activities, their application in residential building maintenance, especially in high-rise environments, is still underexplored (Womack & Jones, 1997).

Residential buildings show unique challenges that are not present in industrial operations, such as unpredictable tenant behaviour, varied building system usage patterns, shared responsibilities, and lack of centralized operational management (Au-Yong et al., 2018). These variations in context limit the direct transferability of traditional lean tools, which were initially intended for structured, repetitive industrial processes (Ghayebloo & Shahanaghi, 2010). Furthermore, the research indicates a lack of prior studies focusing on the integration of lean practices within the high-rise residential maintenance context in developing countries like Sri Lanka (De Silva et al., 2012). The majority of research focuses on Lean applications in manufacturing or on general maintenance strategies in commercial and public facilities, with little emphasis on adapting lean thinking to address the unique maintenance inefficiencies in high-rise residences (Au-Yong et al., 2023). However, Mostafa et al. (2015), stated that, in high-rise residential buildings with high complexity and maintenance demands, lean tools like as 5S, visual management, standardised work, and root cause analysis can assist in simplifying operations and decreasing delays caused by poor planning, unqualified employees, or a lack of preventive maintenance. Further, lean can be considered as the most flexible, easiest and low-cost solution for any buildings (Ahiakwo et al., 2012).

2.3 CHALLENGES IN IMPLEMENTING LEAN MAINTENANCE IN HIGH-RISE RESIDENTIAL BUILDINGS

De Silva et al. (2012), have established eight challenges of lean maintenance out of fifty-one maintainability causes associated with building maintenance in a study conducted in thirty high rise buildings in the Colombo district namely, 1) Architecture and design, 2) Service integration, 3) Materials and spare parts, 4) Construction quality, 5) Accessibility, 6) Structural and detailing, 7) Maintenance requirements, and 8) Maintenance management. Except for maintenance management, every other issue starts during a building's design and construction phases, making it difficult to deal with them during the operational stage (De Silva et al., 2012). According to Wood (2005), long-term and cost-effective strategies are not used in building maintenance, which makes it more challenging to apply lean principles and effective use resources. People are resistant to change because they feel more comfortable and safer being in the immediate environment and fear the consequences of change, which makes it challenging to implement lean maintenance in high-rise buildings (Asnan et al., 2015).

3. RESEARCH METHODOLOGY

This study aims to investigate the applicability of lean maintenance practices as a solution to mitigate the maintenance management issues in Sri Lankan high-rise residential buildings. As proven in the background and literature review, it is evident that MM in high-rise residential buildings has not been paid enough attention and can be improved by applying lean maintenance principles and tools. Therefore, MM practices in high-rise residential buildings in Sri Lanka were selected as the unit of analysis for this study. A comprehensive literature review was conducted to perceive theory-based knowledge regarding the concept of lean maintenance and identify the applications of lean maintenance in building maintenance.

Data collection for this study was carried out in two phases. Phase I involved a case study analysis, focusing on four high-rise residential buildings located in the Colombo District. These buildings, each exceeding 50 meters in height, were purposefully selected to generate comparable results relevant to the study. Further selection was narrowed down to four cases with a time limitation. From these buildings, eight participants were chosen for semi-structured interviews, representing a range of roles from managerial to technician level. All respondents had over five years of direct experience in maintenance operations.

The selection of four high-rise residential buildings was based on purposeful sampling to ensure relevance and data richness. These buildings were chosen as they represent typical residential high-rises in Sri Lanka facing common maintenance issues. Criteria included building height, residential function, being operational for over five years, and accessibility to maintenance data. In qualitative case study research, depth of insight is prioritized over quantity. A multiple-case design with as few as four well-documented cases can offer robust analytical generalization when each case is carefully selected based on theoretical and practical relevance. The four selected buildings provided a comprehensive dataset through interviews, observations, and document analysis, which allowed for meaningful cross-case comparisons.

The primary aim of the case studies was to identify common maintenance management (MM) issues, examine existing lean maintenance waste, and explore challenges in implementing lean maintenance practices in high-rise residential buildings. Given the exploratory nature of the study, a qualitative approach was deemed appropriate. Data collected from the interviews were analyzed using manual content analysis and cross-case analysis techniques to uncover key themes.

The profile of the selected high-rise residential buildings and the case study participants in this research are provided in Table 1 and Table 2 respectively.

Table 1: Profile of the selected cases

Case name	Description
Case A	A residential building which is 182 meters in height in Colombo
Case B	A residential building which is 240 meters in height in Colombo
Case C	A residential building which is 50 meters in height in Colombo
Case D	A residential building which is 126 meters in height in Colombo

Table 2:Profile of the respondents with experiences

Building	Code of respondents	Description	Years of experience
A	A1	Property Manager	10 years
	A2	Technician	More than 5 years
B	B1	Property Manager	10 years
	B2	Technician	5 years
C	C1	Property Manager	More than 5 years
	C2	Technician	More than 5 years
D	D1	Property Manager	10 years
	D2	Technician	More than 5 years

Expert interviews were conducted under Phase II of the data collection to suggest strategies to eliminate identified lean maintenance waste which then contributes to mitigating maintenance issues. Another purpose of the expert interviews is to suggest strategies to overcome challenges in implementing lean maintenance in high-rise residential buildings in Sri Lanka. Three specialists with experience in both lean and maintenance fields were chosen for the expert interviews. The experts were questioned through semi-structured interviews and revealing the gathered data from case studies securing confidentiality. The data gathered from expert interviews were analysed using a qualitative data analysis technique called template analysis. Table 3 presents a summary of the experts selected.

Table 3: Profile of the selected experts

Expert Respondents	Year of Experiences	Description
E1	10+ years	Senior Lecturer, Lean Consultant
E2	15 years	Certified Total Production System & Total Management System Practitioner (Grade IV) by a leading automobile manufacturer in Japan
E3	27+ years	Systems Consultant (KAIZEN, TQM, Japanese 5S, TPM, Japanese Management Practice)

4. FINDINGS AND DATA ANALYSIS

4.1 FINDINGS OF THE CASE STUDY

Data collection from case studies was executed based on a semi-structured interview guideline which mainly covered areas such as existence of MM issues, existence of lean maintenance wastes and challenges to implement lean maintenance. Existence of the following common MM issues were identified through the case studies.

Table 4:Responses on existing maintenance issues in selected cases

Common MM Issues	Case A		Case B		Case C		Case D		Total
	A1	A2	B1	B2	C1	C2	D1	D2	
Lack of Awareness or Cooperation of the residents	✓	✓	✓	✓	✓	✓	✓	✓	8/8
Unqualified Maintenance Contractors	✓		✓		✓		✓	✓	5/8
Lack of Maintenance Personnel Training and Motivation	✓				✓		✓		3/8
Budget Constraints					✓	✓	✓	✓	4/8
Lack of knowledge and Skills	✓		✓		✓		✓		4/8
Lack of staff and Specialists	✓		✓		✓	✓	✓		5/8
Lack of Maintenance Software Tools	✓		✓		✓		✓		4/8
Unclear Job Description or Department Structure	✓		✓		✓		✓		4/8
Failure of preventive maintenance	✓	✓	✓		✓		✓		5/8
Unavailability of Spare parts	✓		✓		✓		✓		4/8

Table 4 presents the summary of the respondents in selected cases regarding the existence of common maintenance issues in high-rise residential buildings. According to responses, each case has more than five maintenance issues.

4.1.1 Lack of Awareness or Cooperation of the Residents

As noticed in the interviews, residents' cooperation plays a crucial role in maintenance efficiency. All the respondents highlighted that lack of awareness or cooperation of residents is an issue in all four cases. Respondents C1 and D1 highlighted that delays often occur due to residents failing to report issues promptly. A1 further noted that ineffective communication between residents and maintenance staff leads to repeated visits for the same issue. Similarly, B1 explained that when residents are unaware of their responsibilities, such as reporting minor leaks or faults, small issues escalate into major repairs. Moreover, D2 stated that, by the time they get to a reported issue, it has already worsened because residents waited too long to inform them.

4.1.2 Unqualified Maintenance Contractors

In all four cases, respondents A1, B1, C1 and D1 mentioned that maintenance contractors are often hired based on cost rather than expertise. Respondent C1 observed that some contractors perform unnecessary repairs due to a lack of specialized training, which

increases operational costs. Respondent B1 highlighted that sometimes unqualified contractors often fail to diagnose the root causes of issues, leading to repetitive repairs.

4.1.3 Lack of Maintenance Personnel Training and Motivation

Training and motivation gaps were commonly mentioned by most of the respondents. Respondent D1 emphasized that some junior technicians lack formal training, making them inefficient in troubleshooting complex building systems. Respondent C1 added that due to poor career development opportunities, maintenance staff often feel demotivated, leading to suboptimal performance.

4.1.4 Budget Constraints

Financial limitations are commonly in all four cases. Respondent C1 mentioned that maintenance budgets are frequently cut due to financial constraints from building management committees, which delays crucial repairs. In addition, respondents C2 and D1 both agreed that budgetary restrictions also hinder the adoption of advanced maintenance technologies, reducing efficiency in the long run.

4.1.5 Lack of Knowledge and Skills

Respondents D1 and B1 both pointed out that maintenance personnel often lack updated technical knowledge, particularly in specialized systems such as HVAC, elevator maintenance, and fire safety. Further, respondent A1 also agreed with the above statements and suggested that regular technical training sessions could solve more problems in-house instead of relying on expensive external contractors.

4.1.6 Lack of Staff and Specialists

Both respondents A1 and B1 noted that many high-rise residential buildings face a shortage of skilled maintenance personnel, leading to increased workload for existing staff. Moreover, respondent C1 highlighted that specialist services, such as major electrical and plumbing repairs, frequently require outsourcing due to the unavailability of in-house experts, increasing overall maintenance costs and response times.

4.1.7 Lack of Maintenance Software Tools

Respondents A1, B1, and C1 noted that their buildings still rely on paper documents for tracking and recording maintenance tasks and information, which is leading to inefficiencies and data loss. Furthermore, A1 pointed out that they planned to include maintenance record process into a software in near future which needs high investment and staff training.

4.1.8 Unclear Job Description or Department Structure

All four respondents in four cases, A1, B1, C1 and D1, agreed that unclear job responsibilities cause inefficiencies in maintenance operations. However, all respondents stated that in their buildings, the occurrence of unclear job descriptions and department structure is limited.

4.1.9 Failure of Preventive Maintenance

As observed in the case studies, preventive maintenance strategies are implemented in all four buildings but often result in inefficiencies. Respondents A1 and B1 stated that excessive preventive maintenance is sometimes unproductive, as certain tasks are

performed without evaluating necessity. Further, respondent A2 argued that even preventive maintenance takes time it is essential to perform which cannot be skipped.

4.1.10 Unavailability of Spare parts

The unavailability of spare parts is a common issue identified among all four cases. Respondent A1 explained that they only keep spare parts which needed in their daily minor maintenance activities and all other major activities are outsourced, and the required spare parts will be provided by them.

4.2 The Relationship between Common Maintenance Issues and Existing Lean Maintenance Wastes

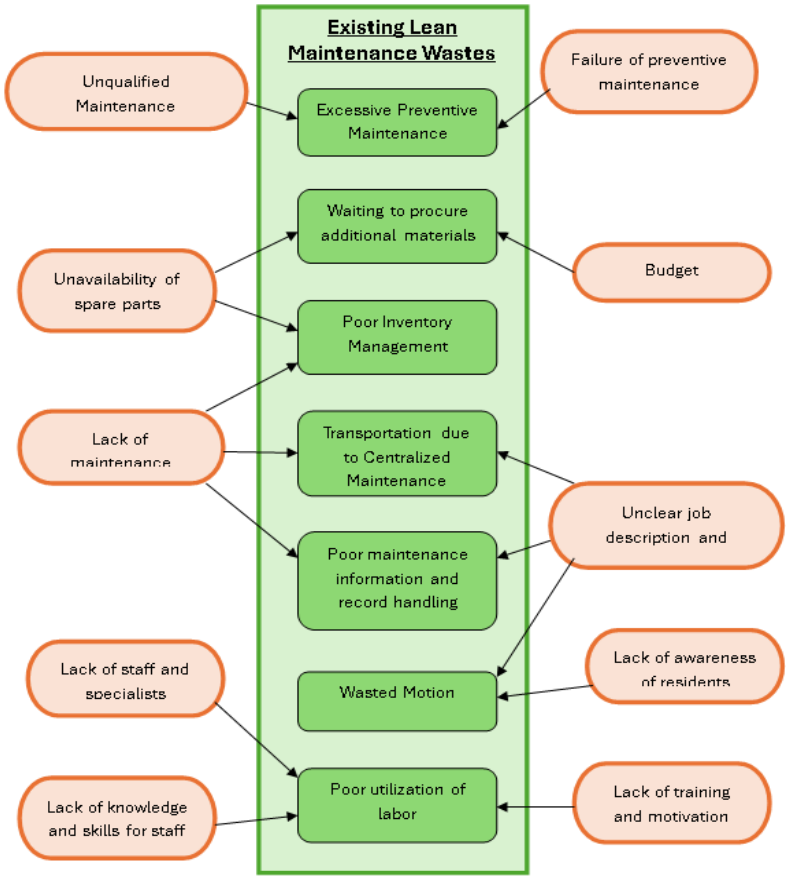


Figure1: Relationship between common maintenance issues and existing lean maintenance wastes

Figure 1 presents the relationship between the identified maintenance issues in the selected cases which are caused for the occurrence of identified existing lean maintenance waste. The indicated LM wastes in Figure 1 identified and confirmed through the conducted four case studies. Further, the relationship between these MM issues and LM wastes were identified with the discussion of experts who were involved in expert interviews.

4.3 Identification of Challenges in Implementing Lean Maintenance in High-Rise Residential Buildings in Sri Lanka

Challenges identified in the literature in implementing lean maintenance in high-rise buildings were discussed with the interviewees in four case studies to verify their

availability in the selected cases. The presented challenges were modified based on the interview findings and the list of challenges are shown in Table 5.

Table 5:Responses on challenges in implementing lean maintenance

Challenges	Case A		Case B		Case C		Case D		Total
	A1	A2	B1	B2	C1	C2	D1	D2	
Ineffective maintenance strategies	✓	✓	✓	✓	✓	✓	✓	✓	8/8
Lack of standards and regulations	✓	✓	✓	✓	✓	✓	✓	✓	8/8
Lack of policies	✓	✓	✓	✓	✓	✓	✓	✓	8/8
Lack of lean knowledge	✓	✓	✓	✓	✓	✓	✓	✓	8/8
Poor involvement of top management and resistant to change	✓		✓		✓	✓	✓	✓	6/8
Lack of technology usage	✓	✓	✓		✓		✓		5/8
Infirm feedback collecting mechanisms	✓		✓		✓		✓	✓	5/8

As Table 5 shows, all the respondents agreed that they face ineffective strategies, lack of standards, regulations, policies and knowledge of lean. Furthermore, poor involvement of top management, infirm feedback collecting mechanisms and lack of technology usage also prevail in all the selected cases. The following subsections present the explanation of the challenges shown in Table 5.

4.3.1 Ineffective Maintenance Strategies

All the respondents agreed that they follow preventive maintenance as their main maintenance strategy in their buildings. It was shown that only cases A, B and C have adopted to condition based maintenance up to a certain extend which is a preventive maintenance strategy that relies on the monitoring of assets or equipment to determine when maintenance work is necessary. But in case D they mentioned that, sometimes they follow corrective maintenance strategies with the preventive maintenance as well. It is evident that currently none of the cases has been fully adopted for any cost-effective maintenance strategy like condition-based maintenance. Therefore, it will be challenging to adopt lean with the traditional maintenance methods.

4.3.2 Lack of Standards and Regulations

All the respondents confirmed that currently, they do not follow any specific standard or regulation relating to maintenance. However, some of the respondents mentioned that in the Apartment Ownership Law there are certain rules regarding the maintenance. Further, respondent B1 stated that for the condominiums the governed law is Apartment Ownership Law, and, in that law, there are certain requirements regarding apartment maintenance like management council is only responsible for managing common areas and residents should manage and maintain the inside of their apartment units, etc. In addition to that, respondents in cases C and D also stated that they are not following any

standard or regulations related to maintenance. Therefore, it is evident that none of the cases are following or complying with standards or regulations relating to maintenance except the Apartment Ownership Law.

4.3.3 Lack of Lean Knowledge

All the respondents in four cases stated that they do not have knowledge regarding the lean concept and its applications. However, respondent A1 mentioned that even though she has learnt about lean in higher studies, she has not specifically come across lean maintenance before. Therefore, it is revealed that all the respondents do not know about lean. Thus, for the successful implementation of lean, it will be required to educate maintenance staff about lean concept, its principles and tools.

4.3.4 Lack of Policies

It was discovered that none of the cases has an explicit maintenance policy. All the respondents affirmed this. Respondent A1 stated that their plan is to shift from preventive maintenance to conditioned based maintenance. Respondent B1 also confirmed that they always aim to reduce maintenance costs and reduce breakdowns as much as possible, even though they do not have a policy. Respondents from cases C & D also stated that there is no maintenance policy. Therefore, it can be concluded that none of the cases have identified need for a maintenance policy.

4.3.5 Poor Involvement of Top Management and Resistant to Change

Six out of eight respondents identified top management's involvement in maintenance as a key obstacle to implementing lean maintenance strategies. Respondents from cases A, B and C mentioned that it is difficult to get the approval from top management for the new maintenance systems since they are resistant to change from the traditional maintenance methods due to high costs and unclear returns. For getting approval from top management, they require the estimated cost savings, but the maintenance staff does not track the cost of replacements or improvements, making it hard to prove financial benefits. Similarly, respondents D2 mentioned that top management does not fully understand the need for maintenance upgrades and remains hesitant due to uncertainty about potential benefits. Therefore, it is identified that resistant to change among the top management is the main challenge of lean implementation.

4.3.6 Lack of Technology Usage

The respondents from all cases confirmed that no advanced technology is currently used for maintenance, only use MS Excel and no dedicated software. Respondent A1 stated that they plan to incorporate maintenance activities into resident complaint management software and respondent B1 emphasized that they plan to implement a helpdesk system to track maintenance activities. Moreover, all the respondents mentioned that having a centralized system for tracking maintenance tasks and spare parts availability would be much easier to reduce delays and ensure preventive maintenance.

4.3.7 Infirm Feedback Collecting Mechanism

Five out of eight respondents mentioned that there is no formal mechanism for collecting and recording feedback on attended maintenance complaints. Respondent B1 also stated that they do not have proper feedback collection process, but they plan to include that feedback mechanism also in the proposed helpdesk system. The responses from respondents A1, B1, C1, D1, and D2 indicate that the feedback collection process in these

buildings is entirely informal and lacks consistency, which makes it difficult to assess customer value and service quality. Therefore, it is important to implement such a computerized mechanism to collect and review feedback from end-users for improving maintenance operations and enhancing customer satisfaction.

4.4 STRATEGIES TO OVERCOME CHALLENGES IN IMPLEMENTING LEAN MAINTENANCE IN HIGH-RISE RESIDENTIAL BUILDINGS IN SRI LANKA

4.4.1 Strategies to Overcome Poor Involvement of Top Management and Resistance to Change

All the experts suggested conducting awareness programmes for the management regarding lean as the main strategy to overcome poor involvement of top management as most of the organizations do not practices lean tools and have no proper knowledge about lean. Further, they emphasized the importance of providing financial information such as, implementing costs and expected ROI, to help top management make informed decisions. Additionally, they suggested introducing low-cost or no-cost lean suggestions as pilot projects to encourage top management's involvement in capital intensive maintenance projects.

4.4.2 Strategies to Overcome Ineffective Strategies

According to respondent E1, it is important to have brainstorming sessions in between the maintenance staff and stakeholders which help to fine-tune the existing strategies and practices. Moreover, conducting brainstorming sessions with people in the work floor give effective results because they have the best experience in every perspective. In addition to that, setting KPIs are essential to make strategies effective.

4.4.3 Strategies to Overcome Infirm Feedback Collecting Mechanism

All the respondents agreed that it is essential to implement computerized feedback collecting software to collect feedback from residents. Further, respondent E2 added that feedback is very important to improve the current state of the maintenance works. Therefore, it would be easy for them to have a computerized system to collect feedback. Similarly, respondent E3 also stated that the best option is to streamline feedback collection system, in that way it is easy to trace the jobs requested, actions taken and to give feedback on the job performed. Therefore, it is confirmed that implementing computerized feedback collection system is essential.

4.4.4 Strategies to Overcome Lack of Lean Knowledge

All the experts unanimously agreed that to increase awareness of lean among maintenance staff is important and for that conducting awareness programs are crucial. Furthermore, Respondent E3 added that practical knowledge in implementing lean can be gained by engaging in lean professional qualifications for instance lean six sigma professional qualifications. Similarly, E1 also mentioned that it would be beneficial to engage with lean experts.

4.4.5 Strategies to Overcome Lack of Policies

Lack of proper policies will impact the proper implementation of lean maintenance. To overcome this challenge, both E2 and E3 experts mentioned that it is essential to establish proper maintenance policies, and those policies need to be drafted integrating SMART such as, specific, measurable, achievable, relevant, and timely objectives. Furthermore,

link the established policies with incentives, which means rewarding teams for reducing downtime or energy waste in the building systems

4.4.6 Strategies to Overcome Lack of Standards and Regulations

Lack of proper standards and regulations also will impact negatively when implementing lean maintenance in any organization. When addressing this challenge experts suggested that align with industry benchmarks such as, adopt ISO 41001 standard for facility management or NFPA codes for fire safety compliance are important. Similarly, E3 added that if there are no local standards and regulations relating to maintenance it is essential to comply with other global standards available with appropriate modification. Furthermore, developing customized SOPs can also be identified as a strategy.

4.4.7 Strategies to Overcome Lack of Technology Usage

In present, technology is a key aspect in any organization, which improves the operational efficiency and saves time. To overcome this challenge, experts suggested that application of Industry 4.0 and the adaptation of information technology advancements in maintenance sector is essential.

5. DISCUSSION

This study investigates the suitability of LM approaches for addressing MM challenges in Sri Lankan high-rise residential buildings. The findings demonstrated a clear relationship between LM wastes and common MM issues in the local residential context, confirming the importance of applying lean strategies to this sector. Across all four case studies, recurring issues such as excessive preventative maintenance, high wait times, poor inventory management, and personnel underutilisation were directly associated with recognised Lean maintenance wastes. These inefficiencies restrict building performance and highlight the necessity for structured, proactive approaches. For example, excessive PM was prevalent within all four cases, typically due to rigid OEM schedules and unprepared application of standard checklists. This supports Mostafa et al. (2015), who emphasized that over-maintenance could result in waste if not tailored to actual asset conditions. Similarly, transportation waste due to centralised maintenance hubs and waiting for spare parts was evident in the cases investigated, echoing Lean theory which emphasis on reducing unnecessary movements and delays (Womack & Jones, 1997). These issues were worsened by a limited use of digital tools, poor inventory control, and fragmented job responsibilities, which decrease system reliability and increase costs.

All cases indicated a lack of Lean awareness, the absence of maintenance policies, and limited involvement from top management, demonstrating structural barriers to implementing Lean. The consistency of these findings across multiple buildings suggested systemic weaknesses rather than isolated operational failures. The lack of computerised systems or digital tracking methods limited real-time monitoring, resulting in inadequately documented procedures and reactive maintenance behaviour. This finding supports Jasiulewicz-Kaczmarek and Saniuk (2018), who identified digitalization as critical to Lean integration. Notably, unqualified contractors and lack of skilled labour resulted in more rework, longer downtimes, and high costs, which is consistent with prior findings by Au-Yong et al. (2023), on MM inefficiencies in high-rise residential contexts. The reported absence of formal standards, such as ISO 41001, emphasises the need for regulatory support to enable Lean adoption in residential settings.

Expert interviews validated these findings and suggested practical Lean strategies. For example, to address excessive PM, experts proposed switching to condition-based maintenance and autonomous maintenance. These approaches, while frequently used in industry, are novel in the residential sector and show potential for increasing system uptime and decreasing resource waste. Similarly, the idea of using mobile carts and decentralised hubs to reduce technician travel time aligns with Lean's philosophy of minimising motion waste. Additionally, experts emphasised the importance of computerised feedback systems, visual dashboards, and Industry 4.0 technologies to enhance decision-making and transparency. These solutions could help minimise feedback gaps and increase maintenance teams' responsiveness, which were previously restricted by paper-based processes.

Overall, the study shows that Lean Maintenance can be successfully applied to the residential high-rise context when supported by simple technologies, adequate training, and leadership commitment. These findings contribute to developing both theory and practice by providing a context-specific approach for improving maintenance performance in the built environment.

6. CONCLUSION

This study examined the applicability of LM practices in mitigating MM issues in Sri Lankan high-rise residential buildings. Through case studies, the research identified seven out of eight lean wastes prevalent in the selected buildings. Common MM issues were found to correspond with known lean inefficiencies. Further, key challenges are lack of lean knowledge and limited support from top management factors that hinder the lean adoption. Expert interviews validated these findings and proposed suitable strategies including, lean awareness programs, feedback systems using digital tools and aligning maintenance policies with SMART objectives. This study provides practical insights for facility managers and decision makers, highlighting feasible strategies to improve building maintenance efficiency. Thus, this study emphasizes the applicability of lean maintenance practices in mitigating maintenance issues in Sri Lankan high-rise residential buildings.

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ARTIFICIAL INTELLIGENCE DRIVEN SYSTEMS FOR ENHANCING WORKER SAFETY MONITORING IN CONSTRUCTION ENVIRONMENTS: A COMPREHENSIVE REVIEW

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ABSTRACT

The construction industry remains one of the most hazardous sectors globally, largely due to inefficiencies, high operational costs, and delayed risk detection associated with traditional safety procedures. This comprehensive review synthesizes findings from 88 peer-reviewed studies published between 2017 and 2025 to evaluate the potential of Artificial Intelligence (AI)-driven systems in enhancing worker safety. The review addresses three primary objectives: (1) evaluating the effectiveness of AI technologies in improving safety monitoring, (2) examining regional variations in AI adoption and their influence on safety outcomes, and (3) identifying key challenges related to implementation, scalability, and ethical considerations. The analysis reveals that AI technologies significantly contribute to improved safety outcomes. For instance, drone-based inspections reduce assessment times from several days to approximately 1.5 hours with high accuracy; computer vision systems detect personal protective equipment (PPE) violations with over 91% precision; and predictive analytics forecast accident risks among migrant workers with 89% accuracy. Regional case studies highlight disparities, such as a 60% reduction in fall incidents in the United Arab Emirates through convolutional neural network (CNN) based surveillance, contrasted with barriers in Ghana, including high implementation costs and cultural resistance. Despite these advancements, challenges persist, including privacy concerns, technological limitations, and inadequate infrastructure in low-resource settings. The review underscores the need for explainable AI models, adaptable frameworks for diverse environments, and harmonized international regulations to ensure equitable and effective deployment of AI-driven safety systems.

Keywords: *Artificial Intelligence; Construction Safety; Ethical Governance; Predictive Analytics; Real-time Monitoring.*

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1. INTRODUCTION

Occupational fatalities in the construction industry represent approximately 20% of global work-related deaths, primarily resulting from electrocution, falls, and equipment misuse. These incidents are often exacerbated by dynamic work environments and human error (Jaafar et al., 2018; Saleh & Othman, 2022). Traditional safety practices, including manual inspections and reactive hazard assessments, have proven inefficient, with reported accuracy rates between 50% and 60% and delays of up to three days in risk identification (Jaafar et al., 2018; Tamoor et al., 2023). The economic impact of workplace injuries, exceeding $170 billion annually, underscores the urgent need for more effective safety interventions (Vitharana et al., 2015). Recent advances in Artificial Intelligence (AI) offer promising alternatives to conventional safety protocols. AI-driven systems enable automation in compliance monitoring, structural analysis, and real-time data integration from wearables, drones, and Internet of Things (IoT) devices. For example, IoT-based structural health monitoring can identify material degradation earlier than manual methods (Plevris & Papazafeiropoulos, 2024), while AI-powered simulations can model structural resilience under environmental stress (Sargiotis, 2024).

This study aims to evaluate the potential of AI-based technologies in enhancing worker safety within construction environments. Specifically, it examines the efficacy of systems such as wearables, drones, and computer vision in reducing risks related to falls, environmental exposure, and equipment hazards. Notable findings include a 40% reduction in heatstroke incidence with wearable use (Tamoor et al., 2023) and the ability of drones to perform structural inspections in under two hours with high precision (Häikiö et al., 2020). Additionally, the study investigates regional disparities in AI adoption, (Shanti et al., 2021) as well as barriers in countries like Ghana, where adoption is hindered by financial constraints and cultural resistance (Acheampong et al., 2025; Mustapha et al., 2024). By addressing issues of scalability, ethical concerns, and regulatory fragmentation, this review contributes to a more comprehensive understanding of the transformative role AI can play in construction safety management.

2. METHODOLOGY

This study employs a structured Systematic Literature Review (SLR) guided by established frameworks such as PRISMA and Kitchenham (Kitchenham et al., 2009; Ogunmakinde et al., 2024). The process is organized into four phases: planning, selection, execution, and analysis. Each tailored to the study's objectives and summarized in Figure 1 to ensure rigor, transparency, and reproducibility.

The primary objective was to assess how AI-driven systems contribute to improving safety monitoring in construction environments. To guide the review, a structured protocol was developed that included the definition of inclusion and exclusion criteria, database selection, Boolean search strategy, and a multi-stage screening process.

Studies were included in this review if they met the following criteria: (1) publication in peer-reviewed journals between 2017 and 2025; (2) a primary focus on the real-world application of AI technologies in construction worker safety; (3) publication in the English language; and (4) provision of empirical results, either quantitative or qualitative.

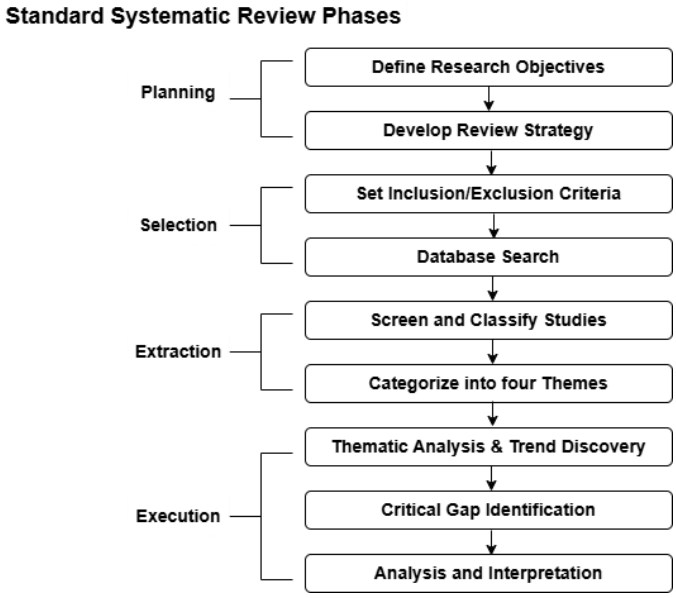


Figure 1: Method and steps of systematic literature review (SLR)

Conversely, studies were excluded if they were conceptual or theoretical without practical validation, if they addressed general industrial safety outside the construction context, if they were published in languages other than English, or if they focused on unrelated safety domains such as environmental protection. To identify relevant literature, a comprehensive search strategy was employed using Google Scholar as a supplementary tool to broaden access across disciplines. Boolean queries were applied, and although Google Scholar does not support database filtering, each article's publication venue and indexing status were manually verified via DOI metadata and publisher records. The final dataset comprised 88 peer-reviewed studies published between 2017 and 2025, sourced from the following databases: Scopus (n = 46), Google Scholer (n = 40), Research Gate (n = 36), ScienceDirect (n = 17), and other reputable academic sources (n = 25). This hybrid approach ensured both methodological rigor and broad disciplinary coverage, in alignment with systematic review standards.

The Boolean queries used included:

- ("artificial intelligence" OR "AI") AND ("worker safety monitoring" OR "worker safety") AND ("construction environment" OR "construction sites")
- ("AI-driven systems" OR "AI-powered systems") AND ("worker safety" OR "worker safety monitoring") AND ("construction industry" OR "construction environments")
- ("artificial intelligence") AND ("safety monitoring systems") AND ("construction worker safety")
- ("AI applications" OR "AI technologies") AND ("worker safety monitoring") AND ("construction sites" OR "construction environments")
- ("real-time safety monitoring" OR "real-time hazard detection") AND ("AI-driven") AND ("construction worker safety")

These initial records were subjected to a multi-stage screening process as described below.

1. Duplicate Removal.
    - 17 duplicate records were identified and removed across databases.
2. Title and Abstract Screening.
    - Of the remaining 147 articles, 12 were excluded for irrelevance to AI-driven worker safety monitoring in construction (e.g., studies focused on non-construction sectors or unrelated AI applications).
3. Full-Text Review.
    - 135 articles underwent full-text assessment against predefined inclusion and exclusion criteria.
    - Exclusions at this stage were as follows.
        - 14 studies excluded for lacking empirical data or real-world validation.
        - 11 studies excluded due to being conceptual or theoretical without actionable insights.
        - 8 studies excluded for language other than English.
        - 14 studies excluded for focusing on unrelated safety topics outside worker monitoring (e.g., environmental safety).
4. Final Inclusion.
    - A total of 88 peer-reviewed studies met all criteria, providing empirical evidence on AI applications for worker safety monitoring in construction environments.

The selected 88 studies were then classified into four thematic areas to structure the analysis and synthesis effectively.

Table 1: Thematic categories of the literature review

No.	Category	Description
1	AI Technologies in Construction Safety	Identifying AI technologies that are increasingly applied to multiple facets of construction safety, primarily focusing on fall detection and prevention, unsafe act identification, behaviour monitoring, and predictive safety modelling.
2	Performance Evaluation of AI Safety Systems	Assessing the effectiveness of AI safety systems in construction requires comprehensive evaluation metrics, including accuracy, precision, recall, other performance indicators and model comparison
3	AI's Role in Labour Displacement	Explores ethical and workforce-related implications, including resistance, retraining needs, and job shifts.
4	Research Gaps and Future Directions	Identifies unresolved challenges including implementation barriers, privacy issues, and scalability.

3. LITERATURE REVIEW

The motivation for conducting this review stems from the urgent need to enhance safety standards in the construction industry, one of the most hazardous sectors globally, responsible for approximately 20% of occupational fatalities (Jaafar et al., 2018).

Traditional safety measures, including manual inspections and reactive hazard checklists, often suffer from inefficiency, high costs, and delayed risk detection, with accuracy levels ranging from 50% to 60% and inspection times extending over several days (Jaafar et al., 2018; Wu et al., 2020). Artificial Intelligence driven systems present promising alternatives by automating hazard detection, enabling real-time monitoring, and facilitating predictive risk management (Kim et al., 2025; Shanti et al., 2021; Tamoor et al., 2023). This review was undertaken to achieve three primary objectives. First, it aims to evaluate the effectiveness of various AI technologies such as drones, wearable devices, and computer vision systems in enhancing worker safety monitoring within construction environments. Second, it seeks to examine regional disparities in the adoption of AI-based safety systems and their corresponding impact on safety outcomes across different socioeconomic contexts. Third, the review identifies critical research gaps associated with global implementation, including challenges related to scalability and ethical concerns such as data privacy and algorithmic bias (Falco et al., 2021; Jaafar et al., 2018; Mustapha et al., 2024).

3.1 AI TECHNOLOGIES IN CONSTRUCTION SAFETY

Falls are a leading cause of injuries and fatalities on construction sites, with many studies using AI models like CNNs and deep learning to detect falls in real-time by analyzing video feeds and issuing alerts (Aslam & Badi, 2025; Kim et al., 2025; Shanti et al., 2021; Tunji-Olayeni et al., 2018). Wearable AI-enabled sensors monitor posture and movement to proactively predict fall risks (Tamoor et al., 2023), while behaviour recognition algorithms trained on annotated datasets accurately classify risky actions and notify site managers instantly (Abioye et al., 2021; Mohan & Varghese, 2019; Tang, 2024; Vitharana et al., 2015). Advanced systems employ multimodal data fusion combining video, audio, and sensor inputs for comprehensive behaviour tracking (Manuel et al., 2024). Predictive analytics using historical and real-time data forecast potential accidents based on site conditions and environmental factors, often integrated with BIM for spatial hazard mapping and dynamic risk assessments (Bajwa, 2025.; Gnoni et al., 2020; Okpala et al., 2020; Tamoor et al., 2023). IoT sensors enable continuous risk data collection to support preventive interventions (Abbas & Duijster, 2025; Barrera-Animas & Davila Delgado, 2023). Despite barriers in low-resource settings, AI's transformative potential in construction safety is clear, as seen with AI-powered drones reducing inspection times from days to hours with high accuracy in flaw detection (Tamoor et al., 2023). Table 2 compares AI adoption and impact between high- and low-income regions.

Table 2: Contrasting AI applications in high-income vs. low-income regions

AI Application	High-Income Regions (e.g., UAE, EU, USA, South Korea)		Low-Income Regions (e.g., Ghana, Nigeria, Malaysia)	
	Benefits	**Challenges**	**Benefits**	**Challenges**
AI-Powered Drones	100% accuracy in hazard detection Reduced inspection time from days to hours. (Tamoor et al., 2023) Real-time risk mapping	High setup costs Worker resistance Weather dependency	Potential for remote site monitoring Reduced manual labor	Limited infrastructure for data transmission Lack of skilled operators High import costs for advanced drones (Tamoor et al., 2023)
Computer Vision (PPE Detection)	91%+ accuracy in detecting safety gear. (Shanti et al., 2021) Real-time alerts for violations	Dataset diversity issues Integration with legacy systems	Basic surveillance for compliance	Lack of labeled training data. Poor lighting conditions on sites. Limited computational resources (Shanti et al., 2021)
Wearable IoT Sensors	Real-time health monitoring. Fatigue and hazard alerts.	Privacy concerns Battery life limitations (Häikiö et al., 2020), (Awolusi et al., 2019)	Low-cost solutions for migrant workers	Cultural resistance Lack of reliable power sources Minimal awareness of IoT benefits (Häikiö et al., 2020), (Awolusi et al., 2019)
Predictive Analytics	Reduced accident rates via risk prediction Customized safety training	Data integration complexity - Ethical concerns over worker surveillance (Kim et al., 2025), (Tamoor et al., 2023)	Potential to address high-risk scenarios (e.g., falls)	Scarce historical accident data - Limited AI expertise - Poor internet connectivity (Kim et al., 2025), (Tamoor et al., 2023)
AI-BIM Integration	Proactive hazard simulation Automated safety planning	High software costs Technical complexity (Mohan &	Long-term potential for compliance	Minimal BIM adoption Lack of standardized protocols

AI Application	High-Income Regions (e.g., UAE, EU, USA, South Korea)		Low-Income Regions (e.g., Ghana, Nigeria, Malaysia)	
	Benefits	**Challenges**	**Benefits**	**Challenges**
		Varghese, 2019)		Insufficient training (Mohan & Varghese, 2019)
Generative AI (e.g., ChatGPT)	Enhanced design and risk management Automated reporting	Ethical governance gaps Workforce scepticism (Rane, 2023)	Low-code tools for safety training	Language barriers Limited access to AI platforms Regulatory inertia (Rane, 2023)
AI for Regulatory Compliance	Automated audits (Falco et al., 2021) GDPR/OSHA alignment	Algorithmic bias risks Legal ambiguity	Potential to enforce safety laws	Weak enforcement institutions Corruption (e.g., bribery in Ghana, (Boadu et al., 2021)) Lack of localized AI frameworks
Key Regional Disparities	Advanced infrastructure Regulatory frameworks Funding for R&D	Workforce resistance Over-reliance on technology	Growing tech interest Low labor costs	Poor internet/electricity Fragmented policies Limited investment in AI

3.2 PERFORMANCE EVALUATION OF SAFETY SYSTEMS

Some specific studies report accuracy rates exceeding 90% for AI-based safety detection systems used in construction site monitoring. For example, Shanti et al. (2021) detail a CNN based model for PPE detection that achieved 91.26% accuracy and nearly 99% precision. Several studies employ confusion matrices to evaluate classification outcomes by comparing true positives, false positives, and false negatives. Notable works by Gao and Sultan (2023), Tamoor et al. (2023), and Kim et al. (2025) apply this technique to assess the performance of computer vision models used for onsite safety monitoring. In addition to classical metrics, advanced indicators such as the F1-score, Area Under the Curve (AUC), and Receiver Operating Characteristic (ROC) curves are increasingly adopted, particularly in cases involving imbalanced class distributions a common scenario in safety incident datasets (Manuel et al., 2024; Mohammed et al., 2024; Rane et al., 2023). As evidenced by, Gao & Sultan (2023), they have compared Faster R-CNN and YOLO models, concluding that YOLO is better suited for real-time applications due to its faster inference speed, albeit with slightly lower accuracy. Similarly, Abioye et al. (2021) advocated for ensemble learning approaches, which improve detection robustness by aggregating predictions from multiple models. A common theme across these studies

is the trade-off between model accuracy and computational complexity. To address this, some researchers, such as Manuel et al. (2024), recommend lightweight models that can be deployed on edge devices in resource-constrained environments without significantly compromising detection performance. These metrics provide a more nuanced evaluation by balancing sensitivity and specificity, offering insights into the robustness of AI systems under varied site conditions.

3.3 AI'S ROLE IN LABOUR DISPLACEMENT

The integration of AI technologies into the construction industry is increasingly automating tasks traditionally performed by manual labourers, raising significant concerns regarding labour displacement particularly for low-skilled workers (Hajirasouli et al., 2025) . Innovations such as robotic exoskeletons, drones, and collaborative robots (cobots) are now capable of executing physically demanding or repetitive activities, including lifting heavy materials and performing routine safety inspections, thereby reducing the demand for human intervention in these roles (Licardo et al., 2024). Positions involving manual, routine labour are especially vulnerable, whereas roles requiring advanced technical competencies such as AI programming, robotics maintenance, and data analysis are experiencing growth (Alcover et al., 2021; Morandini et al., 2023). In the construction sector, upskilling initiatives will be critical in enabling workers to manage, operate, and collaborate effectively with AI-driven systems, thus supporting a more resilient and technologically adaptive workforce (Grant Nwaogbe et al., 2025).

3.4 RESEARCH GAPS AND FUTURE DIRECTIONS

According to Shanti et al. (2021), Gao and Sultan (2023), Okpala et al. (2020), and Gnoni et al. (2020), current AI safety frameworks in construction lack scalability, fail to integrate heterogeneous data sources effectively, and do not support advanced analytics or real-time decision-making. Existing systems tend to be narrowly focused, addressing discrete safety components such as PPE compliance or fall detection, without offering a comprehensive or integrative perspective. For example Bajwa, (2025) explicitly emphasizes the need for robust, end-to-end frameworks capable of managing diverse safety risks and operational variables across multiple construction phases. AI tools often function as standalone applications without interoperability with widely adopted systems such as Building Information Modelling (BIM) and project management software, resulting in fragmented safety monitoring solutions that limit efficiency and scalability, to overcome this, Okpala et al. (2020) and Manuel et al. (2024) emphasize the development of standardized interoperability protocols and middleware architectures to enable seamless data exchange and coordinated safety workflows across platforms.

Existing research on AI-driven construction safety predominantly focuses on a limited set of hazards and tends to be conducted under controlled or narrowly defined site conditions (Aslam & Badi, 2025; Kim et al., 2025; Vitharana et al., 2015). Recent studies have emphasized the importance of extending AI-based monitoring systems to diverse environmental contexts, such as underground construction, remote or inaccessible job sites, and developing regions, areas where data availability is often limited and infrastructure constraints pose significant implementation barriers (Barrera-Animas & Davila Delgado, 2023), (Abbas & Duijster, 2025).

4. DISCUSSION

This systematic review aimed to evaluate the effectiveness of AI technologies in enhancing worker safety monitoring, examine regional disparities in AI adoption, and identify key gaps in global implementation, scalability, and ethical considerations. In relation to Objective 1, the findings indicate that AI technologies significantly improve safety outcomes. For instance, AI-powered drones have reduced inspection times from 2–3 days to approximately 1.5 hours while maintaining near-perfect accuracy (Tamoor et al., 2023). Similarly, computer vision systems have achieved 91.26% precision in detecting PPE violations (Shanti et al., 2021), and predictive analytics models have forecasted migrant worker accidents with an accuracy rate of up to 89% (Kim et al., 2025).

Regarding Objective 2, the review reveals clear regional disparities in AI adoption and effectiveness. High-income countries, such as the United Arab Emirates and South Korea, have implemented AI technologies with measurable success—for example, a 60% reduction in fall-related incidents in the UAE through CNN-based surveillance (Shanti et al., 2021), and enhanced safety outcomes for migrant workers in South Korea using predictive models (Kim et al., 2025). Conversely, in low-income contexts such as Ghana, implementation is hindered by financial barriers (52%) and cultural resistance (30%) (Acheampong et al., 2025; Mustapha et al., 2024), limiting the scalability and utility of AI systems in such environments.

In addressing Objective 3, this review identifies several persistent challenges that hinder the global applicability and effectiveness of AI-driven safety monitoring systems. Chief among these are the opacity of black-box AI models, which limit explainability and hinder user trust (Gao & Sultan, 2023; Yang et al., 2024), and the risks of privacy violations stemming from surveillance-based tools such as computer vision and wearables (Aloisi & Gramano, 2019). Furthermore, algorithmic bias remains a critical concern, particularly when AI systems are trained on non-representative datasets, leading to unequal safety outcomes across worker groups (Falco et al., 2021). These technological and systemic issues are further compounded in low-resource settings by inadequate digital infrastructure and limited access to reliable connectivity (Acheampong et al., 2025; Boadu et al., 2021), restricting the scalability and adaptability of AI technologies.

Ethical considerations are central to AI's responsible deployment. Key issues include data privacy, algorithmic bias, and the lack of transparency in AI decision-making processes. These concerns are particularly acute in safety-critical sectors like construction. The literature highlights the necessity for transparent, explainable AI systems and the adoption of enforceable regulatory frameworks (Falco et al., 2021; Villegas-Ch et al., 2024). Mechanisms such as the AAA framework and international policy alignment (Cha, 2024) may help address these challenges by enhancing accountability and fostering public trust in AI systems.

A critical finding of this review is the lack of longitudinal research. Approximately 88% of the studies reviewed did not include long-term performance evaluations. This gap limits our understanding of how AI systems perform over time, particularly in relation to maintenance demands, risk adaptability, and performance degradation. For example, while AI-powered inspection drones offer short-term efficiency, there is limited evidence on their long-term effectiveness across varying construction phases and environmental conditions (Tamoor et al., 2023). Similarly, workforce adaptation and reskilling remain

underexplored, especially concerning the impact of AI on productivity and safety behaviour (Li et al., 2022; Trivedi & Alqahtani, 2024). In order to create focused AI literacy programs for site workers and safety officials, industry leaders should collaborate with vocational schools. Legislators must provide tax breaks or subsidies to building companies that spend money on worker training connected to AI.

Another significant concern is the geographic imbalance in the literature, with a strong concentration of studies originating from high-income countries. Expanding AI field studies to low and middle-income countries (LMICs) is critical, given the unique contextual challenges they face, such as informal construction practices and exposure to extreme climatic conditions (Mustapha et al., 2024; Shanti et al., 2021; Tunji-Olayeni et al., 2018). Solutions such as IoT-enabled monitoring systems must be tailored for low-resource settings to overcome infrastructural and socio-cultural barriers (Awolusi et al., 2019; Hinze et al., 2022).

To fully leverage AI's transformative potential while mitigating its risks, policy and industry efforts must focus on two fronts: (1) developing ethical AI governance structures, and (2) investing in workforce reskilling initiatives. Regulatory mechanisms should target critical issues such as algorithmic fairness, data protection, and model transparency. Furthermore, policy initiatives must support tools like explainable AI, algorithm audits, and the standardization of safety metrics across jurisdictions (Cha, 2024; Falco et al., 2021).

Emerging AI paradigms also present promising directions for future research. Federated learning, which allows decentralized model training across multiple construction sites without sharing raw data, enhances both privacy and generalizability (Berkani et al., 2025; Li et al., 2022). Integrating federated learning into hazard prediction models (e.g., fall risks) may significantly improve scalability across diverse site conditions. Edge AI, which enables on-device processing in drones and wearables, can enhance real-time decision-making, especially in regions with limited cloud connectivity (Bajwa, 2025; Rane et al., 2023; Tunji-Olayeni et al., 2018). Finally, the integration of AI-driven digital twins, combining BIM, IoT, and AI for proactive risk forecasting, remains underexplored in construction safety and warrants further investigation (Gnoni et al., 2020; Pan & Zhang, 2023).

5. CONCLUSION

This review confirms that AI technologies such as drones, computer vision, and predictive analytics significantly enhance construction safety by automating hazard detection, improving monitoring precision, and enabling proactive risk management. However, their adoption remains uneven due to infrastructure limitations, high costs, and ethical concerns, particularly in low-resource settings. Key challenges include algorithmic bias, privacy risks, and the lack of long-term evaluations. Addressing these issues through explainable, scalable, and context-sensitive AI frameworks is essential for ensuring the responsible and equitable integration of AI into global construction practices.

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ASSESSING FACTORS INFLUENCING WORKER RETENTION IN THE INDIAN CONSTRUCTION INDUSTRY

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ABSTRACT

India's real estate and construction sector has grown substantially over the years. Although many technological advancements have occurred to aid construction, a high demand for construction labourers remains. The construction industry faces issues concerning high labour turnover, which threatens project continuity and efficiency. This study assesses the key factors influencing worker retention in the Indian construction industry. The study adopted a mixed methods approach by identifying the factors from the existing literature, a structured survey tool was developed, and field data were collected through a questionnaire with 159 construction workers. The responses were evaluated using a 5-point Likert scale. The results reveal that wage delays, lack of safety measures, poor living conditions, limited social security, and insufficient skill development opportunities are primary deterrents to worker retention. Findings emphasize that improving financial stability, enhancing workplace safety, fostering supervisor support, and providing growth opportunities are essential for workforce stability. The study proposes actionable strategies for construction companies and policymakers to mitigate turnover and improve long-term labour retention. It offers a holistic insight into the socio-economic and organizational challenges construction workers face in India.

Keywords: *Construction worker; Socio-economic factors; Worker retention.*

1. INTRODUCTION

The construction industry is one of the leading indicators of India's economic development, contributing nearly 9% to the national GDP (Construction Skill Development Council of India, 2022). The sector continues to expand rapidly, underscoring its crucial role in infrastructure growth and job creation. Despite such significant importance, the industry faces persistent challenges in retaining its workforce. The construction industry stands vulnerable to this persisting issue, with several studies (Ayodele et al., 2022; De Winne et al., 2018) underscoring the numerous challenges the construction industry faces.

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In recent years, many researchers have focused on why employees voluntarily leave their jobs, exploring the main reasons behind labour turnover (Carmeli & Weisberg, 2007; Hausknecht & Trevor, 2010). Labour turnover is important in human resource management, affecting how companies plan and manage their workforce (Arokiasamy et al., 2013). This is especially crucial in the construction industry, where many workers are involved. High labour turnover can also increase costs and reduce organizational productivity (De Winne et al., 2018).

Studies by Ayodele et al. (2022) and De Winne et al. (2018) have identified core deterrents to retention, including wage delays, unsafe working conditions, inadequate living arrangements, and social security. Workers not within the purview of their primary employers have often faced difficulties accessing protections and benefits. Furthermore, a significant gap exists between the intent of labour welfare policies, such as the Building and Other Construction Workers' (BOCW) Act, and their actual implementation on the ground level.

Effective workforce planning is essential for improving organisational efficiency. Inconsistent planning can lead to employee turnover, which disrupts overall workforce performance and reduces competitiveness (Duda & Zurkova, 2013). Employees often leave voluntarily due to low job satisfaction, lack of job security, alternative job opportunities, and poor work–life balance (Ayodele et al., 2022). These factors are linked to poor performance and low productivity in the construction sector.

The sector heavily depends on migrant and informal workers, who lack job security, social protection, and career growth opportunities (Bora, 2014). This leads to frequent job switching, particularly between project phases, creating difficulties in workforce planning and increasing recruitment and training costs (ILO, 2020). Regional disparities, inconsistent labour policies, and the lack of long-term employment contracts further complicate the situation.

Although existing studies have examined turnover drivers such as pay dissatisfaction, insufficient safety, or weak supervisory support, limited research integrates these diverse factors holistically, especially from the perspective of the most affected workers. Most past studies focus on organizational policies or macroeconomic analysis, creating a significant gap in understanding the nuanced, ground-level realities of labour retention in the Indian construction sector.

This study explores the key factors influencing worker retention in India's construction industry, focusing on workers' perspectives. It adopts a comprehensive, multi-dimensional framework that integrates financial, health-related, work-related, and state-related factors to reflect construction labourers' complex realities, particularly those from informal and migrant backgrounds. The study provides a grounded understanding of retention's most critical issues by analysing these dimensions through structured field data. The findings are intended to support construction firms and policymakers in designing more targeted and effective retention strategies that enhance workforce stability, reduce project disruptions, and promote long-term sectoral growth.

2. LITERATURE REVIEW

Financial stability has consistently emerged as a fundamental driver of worker retention in the construction industry. Studies such as Palaniappan et al. (2023) highlight that pay satisfaction is closely linked to worker well-being and long-term commitment to

employers. Consistent and adequate earnings are often cited as primary motivators, with the widespread preference for overtime opportunities reinforcing the value workers place on supplemental income. Furthermore, research by Ayodele et al. (2022) and Duda and Zurkova (2013) suggests that the loss of skilled and experienced workers due to poor financial incentives can lead to significant productivity losses and increased costs for construction firms.

Worker retention remains a persistent challenge in the global construction industry, driven by complex, interrelated factors such as job satisfaction, wage stability, working conditions, and career growth opportunities. Arokiasamy et al. (2013) highlighted that voluntary turnover in the private sector often stems from dissatisfaction with pay, lack of career advancement, and poor organizational culture, equally relevant issues in the construction industry. Similarly, Lambert and Hogan (2008) established that job satisfaction and organizational commitment significantly shape turnover intentions, while Carmeli and Weisberg (2007) emphasized the role of emotional and psychological attachment in predicting retention.

In the construction context, Ayodele et al. (2022) developed a framework identifying project-specific dynamics, work-life imbalance, and lack of supervisor support as key contributors to labour turnover. These findings are reinforced by Kissi et al. (2024), who found that supervisor support significantly reduces turnover intentions when mediated by worker engagement.

Duda and Zurkova (2013) demonstrated that high turnover disrupts productivity, inflates operational costs, and leads to the loss of institutional knowledge. Ohueri et al. (2018) further noted that motivation strategies, including fair compensation and skill recognition, are essential to improve retention and productivity. These insights are echoed in India's context, where the Construction Skill Development Council of India (2022) emphasized the urgent need to align skilling programs with retention objectives, especially given the sector's heavy reliance on informal, often migrant, labour.

Transformational leadership has also been recognized as critical in improving organizational retention. Bass and Avolio (1994) argued that leaders who inspire, mentor, and provide individualized support can reduce turnover by fostering loyalty and motivation. Furthermore, macro-level studies such as ILO (2020) and OECD (2019) advocate for policy interventions to support fair wages, safe working conditions, and long-term employment contracts to mitigate workforce instability. Samanta and Gochhayat (2023) also identified poor safety practices as a significant deterrent to retention in India's construction sector.

To fill this gap, the study aims to identify and consolidate the key factors affecting the retention of construction workers through a comprehensive literature review, analysing the data through a survey to know actual worker perceptions. This approach highlights the most influential retention drivers and explores potential reasons for any observed discrepancies. The ultimate objective is to provide actionable recommendations for construction firms and policymakers to improve retention rates by developing targeted interventions.

3. RESEARCH METHOD

This study employed a structured questionnaire survey as the primary method for data collection. This approach was selected due to its ability to systematically measure

multiple dimensions influencing worker retention and efficiently capture responses from a relatively large number of participants. The questionnaire was developed based on key themes identified in the literature review and was simplified to suit the literacy levels of many construction workers, ensuring inclusiveness and clarity. Similar methodologies have been adopted in workforce studies by Ayodele et al. (2022) and Ohueri et al. (2018), demonstrating the validity of structured surveys for field-based research in developing countries. As illustrated in Figure 1, the research process consisted of three key phases: identifying influencing factors through literature synthesis, developing and administering the questionnaire, and statistical analysis of collected data.

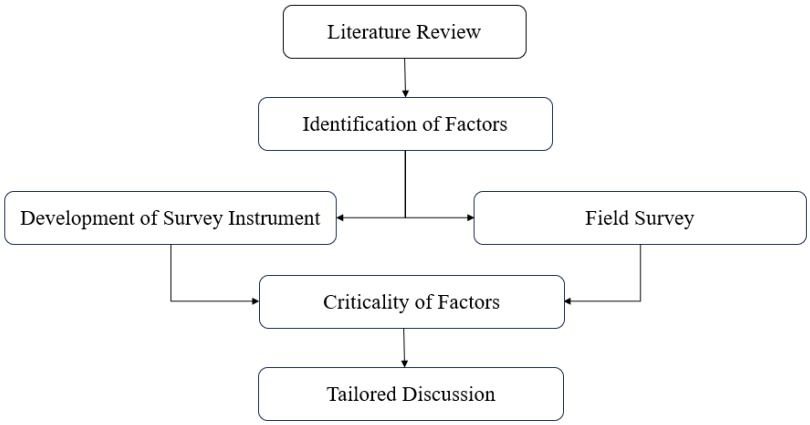


Figure 1: Research methodology

3.1 IDENTIFICATION OF WORKER RETENTION FACTORS

This initial stage consisted of a comprehensive review of scientific literature, industry reports, and policy documents to recognize the key determinants of construction worker retention in India. This process synthesized thirteen retention-related factors, representing the most frequently cited drivers influencing workers' decisions to remain in or leave their jobs. As shown in Table 1, these factors were classified into four thematic dimensions: financial, workplace, state-related, and health-related. This categorization ensures a holistic understanding of the multi-dimensional aspects that affect worker retention in the Indian construction industry.

Table 1: Factors influencing worker retention

Category	Code	Factors	Source
Finance-Related Factors	F1	Wage Satisfaction	Ayodele et al. (2022); Palaniappan et al. (2023)
	F2	Timeliness of Pay	ILO (2020)
	F3	Overtime Opportunities	Ayodele et al. (2022)
	F4	Incentives/Rewards	Duda and Zurkova (2013)
Health-Related Factors	F5	Healthcare Access	ILO (2020); WHO (2016)
Work-Related Factors	F6	Work Relocation Frequency	Zhao et al. (2005)
	F7	Supervisor Behaviour	Kissi et al. (2024); Bass and Avolio (1994)

Category	Code	Factors	Source
	F8	Personal Protective Equipment Kit	Samanta and Gochhayat (2023); ILO (2020)
State-Related Factors	F9	Accommodation Quality	Bora (2014); ILO (2020)
	F10	Welfare Measures	OECD (2019); ILO (2020)
	F11	Skill Development Opportunities	CSDCI (2022); OECD (2019)
	F12	Social Security Benefits	ILO (2020)
	F13	Grievance Redressal Mechanisms	Arokiasamy (2013); ILO (2020)

3.2 DATA COLLECTION

The data for this study were gathered through a structured questionnaire administered to workers engaged in a construction project in Guwahati, India. A total of 159 responses were collected through in-person interactions on a 5-point Likert scale, as shown in Table 2. Due to the low literacy levels among respondents and the absence of prior exposure to formal surveys, each question was explained individually in the simplest and most relatable way.

The ethical principles of voluntary participation, anonymity, and informed consent were maintained throughout the data collection process.

Table 2: Likert scale adapted for criticality rating

Scale	Description
1	Very low criticality
2	Low criticality
3	Moderate criticality
4	High criticality
5	Very high criticality

3.3 DATA ANALYSIS

The collected data were analysed using descriptive statistical methods suitable for exploratory research involving ordinal Likert-scale responses. This approach effectively summarizes participant perceptions and identifies key factors influencing worker retention. Using SPSS, the mean, standard deviation, skewness, and kurtosis for each of the thirteen factors have been calculated. These metrics helped rank the factors based on their perceived criticality among workers.

Descriptive analysis was chosen due to the study's exploratory nature and moderate sample size (n = 159). Similar approaches have been adopted in related construction workforce studies, such as those of Ayodele et al. (2022) and Ohueri et al. (2018), validating their relevance and applicability in similar contexts.

4. RESULTS AND DISCUSSION

This section presents the findings from the field survey and the subsequent statistical analysis of factors influencing worker retention. The data collected through the structured questionnaire were analysed using descriptive statistical techniques widely used in exploratory studies to interpret perception-based data.

This method was selected because it effectively summarizes and ranks multiple variables based on participant responses, particularly when dealing with a moderate sample size and ordinal-scale data such as Likert ratings. Similar approaches have been adopted in construction workforce studies, including Ayodele et al. (2022) and Ohueri et al. (2018), where descriptive statistics were used to evaluate labour-related factors in developing countries.

In this study, each of the thirteen retention factors has been rated on a 5-point Likert scale, and their mean scores, standard deviations, and distribution characteristics (including skewness and kurtosis) were calculated using SPSS software. These statistical measures helped identify which factors were most critical to the respondents and how consistent their responses were across the sample.

Descriptive analysis was considered appropriate given the study's objective of gaining foundational insight into worker retention from a field-based perspective. More advanced statistical techniques were not applied, as the study was exploratory and the available sample size (n = 159) did not support robust inferential modelling. Nevertheless, the chosen approach effectively captured meaningful patterns in worker perceptions and laid the groundwork for future, more detailed analyses.

4.1 DEMOGRAPHIC PROFILE OF THE RESPONDENTS

The surveyed population consisted of all male construction workers, 159 workers in total, reflecting the gender imbalance traditionally seen in India's construction industry. No female workers were present at the selected construction site during data collection. The workforce was primarily concentrated in the 21–40 years bracket, with the highest proportion falling within the 21–30 age group, as shown in Figure 2. This suggests that construction work continues to draw from the labour force's younger, physically active segment. The presence of workers above 40 years, though lower in number, indicates a continued dependence on long-serving labourers who may not have transitioned to more stable or skilled occupations.

Professionally, the survey captured respondents engaged in key trades such as masonry, carpentry, bar bending, tiling, and scaffolding, as shown in Figure 3. Among these, the most common occupation was listed as 'Other', which often includes general helpers and support labourers not tied to a specific skill. This highlights the high prevalence of multi-purpose unskilled workers, whose retention is critical to daily site operations.

Age distribution analysis indicates a relatively young to middle-aged workforce with 34% of respondents falling in the 25-34 age bracket, followed by 29% in the 35-44 category. The 18-24 age group constituted 20%, while workers above 45 represented 17% of the sample. This age distribution aligns with industry patterns where physical labour intensity favours younger and middle-aged workers.

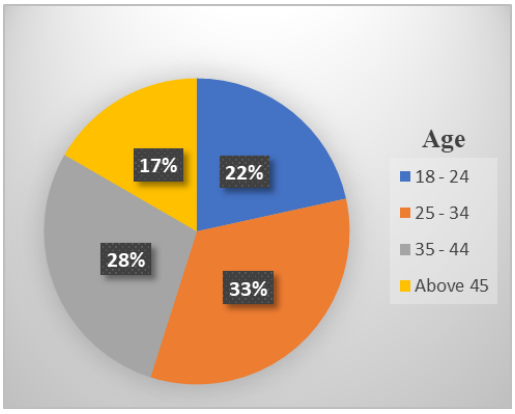


Figure 2: Age distribution of respondents

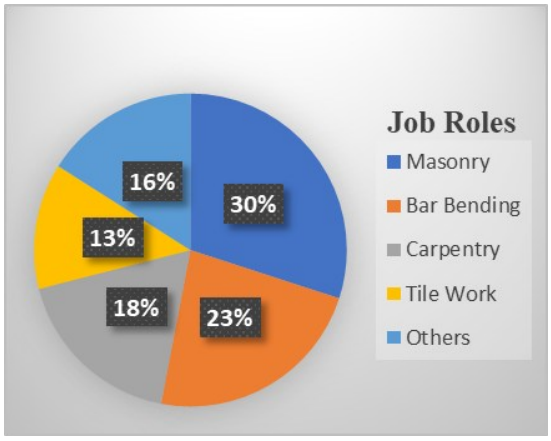


Figure 3: Job role distribution

Regarding job specialization, the respondents represented diverse construction trades, such as 30% of the respondents belong to masonry, 23% bar bending, 18% carpentry, 13% tile work, and 16% other specialized roles, as shown in Figure 3. Work experience distribution indicated that 8% had less than 1 year, 37% had 1-5 years, 42% had 5-10 years of experience, and 13% had over 10 years of construction experience, as shown in Figure 4.

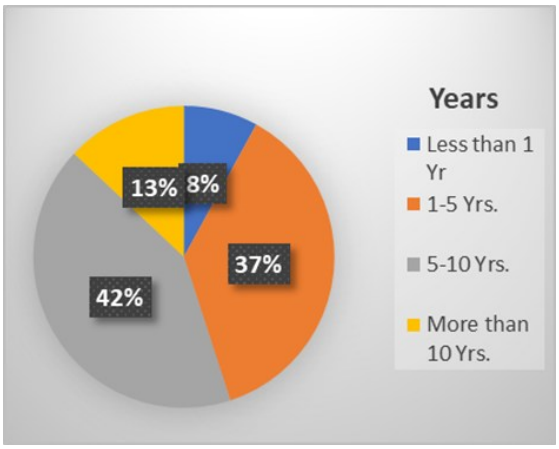


Figure 4: Work experience distribution

4.2 RELIABILITY ANALYSIS

The study, 159 workers were surveyed out of 300 contacted workers, meaning about 53% came forward for the exercise. The reliability analysis was conducted using Cronbach's alpha to assess the internal consistency of the survey instrument. Cronbach's alpha is a prerequisite for ensuring that subsequent analyses, such as criticality assessment, are based on dependable and valid data. The analysis yielded a Cronbach's alpha coefficient of 0.730, exceeding the commonly accepted threshold of 0.7, which indicates satisfactory reliability (Chammout et al., 2024).

4.3 CRITICALITY OF FACTORS

The statistical analysis provides critical insights into the various retention factors. Wage satisfaction and accommodation quality emerged as the most critical factors for worker retention. Workers rated wage satisfaction at an average of 4.38, with responses tightly clustered around this high value, as indicated by the slight variation in responses. Similarly, accommodation quality received an average rating of 4.35, with somewhat more varied responses across participants. The strong negative skewing of responses for both factors confirms that worker opinions were heavily concentrated at the higher end of the scale.

Further analysis revealed that nearly 72% of respondents considered wage satisfaction the most significant, while 70% considered accommodation quality significant. Notably, no workers rated wage satisfaction below a three on the scale, and accommodation quality was rarely rated below a 2, underscoring the universal significance of these factors across the entire construction workforce.

Overtime opportunities also demonstrated relatively high importance, with an average rating of 3.94 and more than half (55%) of workers considering it significant. Though responses tended toward the higher end of the scale, they showed greater variability than the wage and accommodation factors, suggesting somewhat less consensus among workers regarding the importance of overtime availability.

Most factors fell into the moderate importance range (between 2.97 and 3.26), including safety kit provision, healthcare access, skill development, social security, supervisor behaviour, grievance redressal, welfare measures, and work relocation concerns. These factors exhibited relatively normal distributions with skewness values close to zero, ranging from -0.34 to 0.27, and standard deviations between 0.73 and 0.91.

Cross-tabulation analysis revealed interesting patterns within these moderately rated factors. Workers with more than five years of experience assigned slightly higher importance to skill development opportunities, rating it at an average of 3.21, compared to less experienced workers who gave it a lower average rating of 2.87. This difference suggests that career progression becomes more salient as workers gain experience and tenure in the construction industry. Similarly, workers above 35 placed greater emphasis on social security benefits, with an average rating of 3.18, while younger workers rated this factor lower at approximately 2.86. This age-based variation likely reflects life-stage concerns, with older workers increasingly focusing on long-term financial security and benefits as they progress through their careers and take on greater family responsibilities.

Timeliness of pay received the lowest average rating among all factors at 2.81, though this still falls within the moderate importance range. Workers' opinions about this factor

showed considerable variability, as evidenced by the wider spread of responses compared to other factors. This suggests diverse perspectives on the importance of payment timing within the workforce. The mean importance ratings of these factors were ranked on the 5-point Likert scale and are shown in Table 3.

Table 3: Criticality of factors influencing worker retention

Factor	Mean	Standard Deviation	Rank by Mean	Distribution Characteristics	
				Skewness	Kurtosis
Wage Satisfaction	4.38	0.50	1	-1.50	0.38
Accommodation Quality	4.35	1.06	2	-1.35	0.32
Overtime Opportunities	3.94	1.11	3	-0.82	-0.06
Incentives/Rewards	3.26	0.91	4	0.27	-0.02
Healthcare Access	3.05	0.77	5	-0.34	0.79
Safety Kit Provision	3.02	0.73	6	-0.23	0.09
Supervisor Behaviour	3.02	0.74	7	0.06	0.12
Skill Development Opportunities	3.02	0.78	8	0.05	-0.25
Social Security Benefits	3.00	0.79	9	0.00	0.26
Grievance Redressal Mechanism	3.00	0.74	10	-0.10	0.18
Welfare Measures	2.99	0.75	11	-0.08	0.03
Work Relocation Frequency	2.97	0.74	12	0.05	-0.12
Timeliness of Pay	2.81	1.14	13	-0.71	-0.71

5. DISCUSSION

This section examines the key factors considered in the study, how important they were rated, and what they mean for worker retention. It also helps identify which issues need the most attention to improve workforce stability.

5.1 FINANCE-RELATED FACTORS

The finance-related factors adopted in the study are connected to the economic benefits of workers, such as wage satisfaction, timeliness of pay, overtime opportunities, and incentives/rewards. Among all the factors considered in the study, wage satisfaction is the most critical, as indicated by the survey results, underscoring its importance for labour retention. The variation in ratings among the respondents was also drastically less than the other factors, implying that most individuals deem it important. The findings correlate perfectly with financial remuneration directly linked to worker motivation, job satisfaction, and organizational loyalty (Ayodele et al., 2022; Palaniappan et al., 2023).

On the other hand, overtime opportunities are slightly less rated, but individuals differ in their responses. Incentives and rewards are found to be less critical, with variations in responses being on the higher side since their renumeration is subject to various factors within or beyond one's control. Past studies (Duda & Zurkova, 2013) indicate that non-

wage financial rewards can significantly influence employee morale and productivity. However, there might be certain other factors beyond this study's scope.

Interestingly, Timeliness of Pay ranked lowest among all factors, suggesting that while essential, it may be less of a distinguishing factor in environments where workers are habituated to payments getting delayed under subcontracting or working under an arrangement where regular pay is institutionalized. Nonetheless, delayed payments negatively affect worker trust and emotional well-being (ILO, 2020), indicating that this factor's influence may vary by industry or geographic context.

5.2 HEALTH-RELATED FACTORS

Although considered important in various domains, especially construction, where occupational hazards are a primary concern, health-related factors have been rated less critical for sustaining worker retention. In this study, healthcare access reflects a moderate level of importance as perceived by workers. Though not among the top, it has scored above the neutral midpoint, indicating its acknowledged relevance.

Occupational health literature consistently emphasizes the importance of accessible healthcare in mitigating work-related illnesses and ensuring long-term workforce sustainability (ILO, 2020). In this study, healthcare access was rated lower than financial factors, suggesting it may not be a top reason workers stay. However, many construction projects are in remote areas and may offer higher pay, which can influence worker decisions.

5.3 WORK-RELATED FACTORS

In this category, Supervisor behaviour, Work relocation frequency, and PPE kit provision reflect moderate concerns among workers, suggesting that the immediate work environment holds particular value in satisfaction and continuity.

Supervisor behaviour and supportive leadership have been closely associated with fostering trust, enhancing communication, mitigating job stress, and promoting a healthy work environment (Bass & Avolio, 1994). The mean score suggests that while supervisor conduct is valued, it may not be a deciding factor for many, though its latent impact on morale and conflict resolution is substantial.

In this context, Work Relocation Frequency scored lower, implying moderate discontent. However, high mobility often disrupts personal life, impairs community ties, and contributes to job dissatisfaction, especially among older or family-bound workers (Zhao et al., 2007). Organizations that frequently relocate workers without appropriate compensation or support often see higher attrition.

Including safety kit provision under work-related categories also reflects its dual role, as a safety resource and an operational expectation. Its moderate score highlights its continued relevance across domains, though the willingness to comply with safety regulations also rests considerably with the workers. Work-related factors are denoted as moderate to high criticality in this study. Improving supervisory practices and stabilizing work assignments can significantly enhance retention outcomes, particularly when aligned with professional development and well-being strategies.

5.4 STATE-RELATED FACTORS

While external to the employer, state-related factors significantly influence workers' long-term attachment to the labour force. None featured among the top critical factors, but they stand out as relevant given their scores near or just above the midpoint.

Grievance redressal and social security benefits received identical moderate critical scores, indicating a shared perception among workers about their trust in institutional arrangements. Workers are likelier to remain with employers or sectors where their concerns are heard and resolved fairly, strengthening their trust in the state and the judiciary (Arokiasamy et al., 2013). Social Security Benefits, such as pensions, insurance, and retirement plans, form a safety net that enhances workers' social well-being and long-term planning. The ILO (2020) underscores the role of social protection in reducing turnover and sustaining workforce resilience, especially in sectors vulnerable to economic volatility or occupational hazards.

Skill development opportunities scored slightly higher criticality, revealing workers' interest in career progression and a better life. Access to training not only improves retention but also boosts productivity and adaptability (OECD, 2019). Welfare measures, encompassing services like housing, canteens, and childcare, were ranked lowest among state-related factors. This may reflect either a lack of availability or low expectations from the state/employer regarding these provisions.

6. CONCLUSION

This study sought to examine and categorize the determinants of worker retention through a multi-dimensional lens encompassing finance, health, work, and state-related factors. The findings underscore that financial variables, particularly wage satisfaction and opportunities for overtime, are the most critical in retaining workers. Health and safety considerations, including access to healthcare and the provision of personal protective equipment, were moderately rated, highlighting their conditional importance, especially in sectors characterized by physical risk.

Work-related aspects, particularly supervisor behaviour and job relocation frequency, emerged as critical in shaping employees' day-to-day experience. These elements influence job satisfaction and emotional engagement, often as tipping points in retention decisions. Though often external to the organization, state-related factors support institutional trust and future security through grievance redressal, social security, and skill development programs.

Given the moderate to high criticality of many identified variables, this study recommends a prioritized, integrated approach to workforce management that combines fair compensation, safe working conditions, supportive supervision, and robust state support mechanisms. Future research may expand upon this model by investigating sector-specific retention drivers or exploring longitudinal impacts of policy interventions on workforce stability. While this study provides a broad overview of multiple retention factors, future research should focus more deeply on individual categories, such as financial incentives or organizational practices, to uncover more targeted strategies for improving worker retention.

7. LIMITATIONS

While the study provides valuable insights, several limitations should be acknowledged. The data were collected from only Northeastern India, which may not fully capture the diversity of labour dynamics across the country. As the study was done at one point, it cannot show how retention priorities change over time. The moderate sample size and focus on only workers' perspectives may also limit the findings' generalizability to other construction workforce segments.

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ASSESSING KEY RISK FACTORS FOR WORKERS DURING NIGHTTIME IN THE INDIAN CONSTRUCTION INDUSTRY

Naman Srivastava[1], Rohit Sahu[2] and Sparsh Johari[3]

ABSTRACT

Construction activities are crucial for global infrastructure development, but are often accompanied by significant risks, particularly at night. The transition from day to night amplifies hazards due to inadequate lighting, disrupted routine work, fatigue, and heightened stress levels. This study uses a field-based approach, incorporating expert interviews, to identify and prioritize 17 critical safety attributes construction workers face during nighttime. The study conducted 15 expert interviews, and the Analytic Hierarchy Process (AHP) was employed to quantify and prioritize these risks in the Indian context. The attributes identified were categorised into five factors, i.e., environmental, human, work-related, equipment, and organizational. By prioritizing through AHP, work-related risks, such as construction height, emergency preparedness, and falling objects, emerge as the most critical. While equipment hazards like poor lighting and faulty electrical grounding also rank high. However, organizational issues, including lack of training and weak supervision, significantly affect safety but are often normalized in the informal sector. Notably, human factors like fatigue, sleep deprivation, and stress rank lowest, despite their known long-term impact on alertness and safety, revealing a significant gap in current safety approaches. The study highlights the need to increase awareness of often-overlooked risks, particularly human and organizational factors. The findings support policymakers and practitioners in prioritizing safety concerns, planning, supervision, and training efforts for nighttime construction. This study contributes to developing more targeted, evidence-informed safety strategies in nighttime construction in the Indian construction sector.

Keywords: *Construction Worker; Nighttime Construction; Occupational Safety.*

1. INTRODUCTION

Occupational accidents are the cause of more than 3,00,000 mortalities and 300 million injuries around the world each year (International Labour Organization, 2014). The construction industry is one of the most hazardous occupational sectors globally. In particular, these risks are magnified during nighttime operations due to reduced visibility,

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disrupted circadian rhythms, and increased fatigue, making night work particularly dangerous for construction workers (Amiri et al., 2015).

One of the earliest studies to examine the differences between daytime and nighttime highway construction was conducted in Colorado in 1986 (Price, 1986), marking a foundational effort to understand the unique challenges associated with night work in the construction sector. Research on shift work's health and safety effects indicates that shift workers experience adverse health symptoms more frequently and severely than day workers (Folkard & Lombardi, 2006). There is a large body of evidence indicating that night workers, in particular, suffer from chronically impaired health and well-being, including sleep problems, headaches, anxiety, poor concentration, nervousness, mild depression, mood disturbances, cardiovascular and musculoskeletal problems (Loudoun & Allan, 2008).

During nighttime construction, the hazard level to construction workers is manifold when working with heavy machinery, operating at elevated heights (Arditi et al., 2005). These risks endanger the lives and health of construction workers, affect economic costs, and cause delays. The transition from day to night creates a complex and challenging work environment, which is very difficult for the workers. The tasks that are straightforward during the day may be hazardous at night.

Despite advancements in safety practices in the construction industry, nighttime construction remains under-researched, especially in low and middle-income countries where most infrastructure development is labour-intensive and informal. India has one of the largest construction industries in the world, employing over 70 million workers (Chellappa et al., 2021; Statista, 2024). However, research on the safety health of Indian construction workers is limited, despite the high prevalence of safety problems among construction workers. In India, the construction sector accounts for one of the highest occupational fatality rates, with estimates ranging between 11,614 and 22,080 fatalities annually between 2008 and 2012 (Patel & Jha, 2016).

In India's rapid urbanization and growing infrastructure demands, nighttime construction has become increasingly common, particularly in metropolitan cities. The Indian construction industry, predominantly informal and labour-intensive, often lacks standardized protocols for nighttime operations (Chellappa et al., 2021). As a result, to complete the tasks, the construction workers have to work more, so the construction safety is lower. The hazards become even more dangerous during nighttime construction, where reduced visibility, extreme weather, and disrupted sleep cycle contribute to an increased threat to occupational health and safety (Arditi et al., 2005).

Challenges such as inadequate lighting, absence of proper signage, insufficient protective gear, and limited health and safety monitoring contribute to increased workers' vulnerability during night shifts (Hinze & Carlisle, 1990). Despite the increasing reliance on nighttime construction, there is a notable absence of empirical research that systematically assesses the risk factors unique to these settings in the Indian context. Addressing this gap is essential for informing evidence-based safety policies and improving working conditions in India's construction sector.

Although several studies have explored construction site safety and occupational risks, most focus on daytime conditions or aggregate safety data without distinguishing between shift timings. Research addressing the specific challenges of nighttime construction, such as reduced visibility, worker fatigue, psychological stress, and lack of supervision,

remains limited, especially in low and middle-income countries like India. Furthermore, existing literature seldom applies multi-criteria decision-making methods like the Analytic Hierarchy Process (AHP) to prioritize these risks based on expert judgment. This lack of focused, empirical research on night-specific risks in the Indian construction context represents a critical gap that this study aims to address.

2. LITERATURE REVIEW

Nighttime work presents unique challenges and risks due to visibility issues, worker fatigue, and environmental factors. This review synthesizes findings from multiple studies to highlight the factors affecting nighttime operations. Nighttime work increases hazards for workers due to poor visibility and human factors such as sleep deprivation.

2.1 FATIGUE AND SLEEP DEPRIVATION IN NIGHTTIME OPERATIONS

Fatigue is a leading risk factor in nighttime construction, often resulting from disrupted circadian rhythms and insufficient rest. Sleep deprivation has been shown to impair attention and cognitive function, increasing the likelihood of accidents (Powell & Copping, 2010). In a study conducted in Vancouver, construction workers monitored with actigraphs exhibited sleep patterns far below the recommended 8 hours, correlating with a 9% increase in accident risk.

2.2 IMPACT OF SHIFT WORK AND SUBSTANCE USE

Night shifts are also a source of stress, a situation that can induce "escapist" consumption of addictive substances such as tobacco, coffee, alcohol, etc. To this must be added the problem of having to work during periods of rest that are usual for the rest of the population, such as holidays, weekends, and nights (Elrahman & Perry, 1994). All these circumstances, acting together, reduce the efficiency of the workers at the time of concentration. Night shifts are stressful, and to counteract it, workers use tobacco or alcohol to feel better and stay attentive during nighttime construction. This may be effective during the time of work, but when it becomes an addiction, then the absence of it may lead to ineffectiveness, and workers become inattentive. Working at a time when most people take rest, like nights, weekends, or holidays, makes it more challenging. This disrupts personal and social connections, which are needed to help in recovering from addiction.

2.3 LIGHTING, VISIBILITY, AND ENVIRONMENTAL HAZARDS

Similarly, lighting is an essential element of any nighttime project since it affects quality, productivity, and safety. Adequate lighting makes constructing at night as easy as constructing during the day, as it positively affects visibility. In a study by Hinze and Carlisle (1990), state highway agencies and contractors stated that adequate lighting is an important safety aspect in nighttime construction projects. Based on the study's suggestions, Hyari and El-Rayes (2006) developed illumination guidelines for nighttime highway construction and maintenance.

In addition to lighting, weather has contributed significantly to construction safety factors, especially during night shifts. Many studies show that adverse weather can influence the frequency of accidents and the seriousness of their consequences. The data also reveal that wet conditions, particularly night shifts, pose significant safety risks (Kim & Xiong, 2025). This pattern underlines the riskiness of construction work on and off-

site, especially considering that weather conditions are exacerbated by "lighting conditions"- day versus night. Low light and visibility increase the chances of falls at night, especially at height. In addition to physical injuries, falls from heights can also cause mental trauma (Zaini et al., 2020; Hyari & El-Rayes, 2006).

In addition, slippery surfaces, reduced visibility, and structural instability due to severe weather contribute to heightened accident risks. During nighttime, the temperature drops, and due to this, the moisture in the air condenses. This condensation makes the surfaces, such as walls and ground, slippery. Due to this, accidents occur, and workers slip on these surfaces and fall. If they carry a heavy object, they cause harm to themselves (Amiri et al., 2015).

2.4 EQUIPMENT, MACHINERY AND HUMAN FACTORS

Scaffolding failures, lack of personal fall protection systems, and inadequate safety barriers are primary factors leading to fall-related accidents. Unsafe working conditions at elevated platforms, combined with insufficient training on height safety protocols, significantly increase the risk of severe injuries or fatalities (Amiri et al., 2015).

Many construction accidents occur due to a lack of proper training, with workers often failing to recognize or respond appropriately to hazards in their work environment. New and inexperienced workers are at a higher risk of injury, making structured safety education and on-site training essential components of accident prevention strategies (Amiri et al., 2015; Brolin et al., 2021).

Many accidents occur due to inadequate hazard identification and risk assessment before the commencement of construction activities. Effective risk assessment strategies, such as predictive analytics and data-driven decision-making, can significantly reduce workplace hazards. Though safety awareness in the construction industry is increasing, a significant research gap remains, as most trainings focus on general or daytime risks, with minimal attention to nighttime hazards (Yang et al., 2024). There is a lack of structured studies using statistical methods to prioritize these risks for decision-making. The current study addresses this gap by identifying and evaluating the factors that impact workers' safety in nighttime construction through applying the Analytic Hierarchy Process (AHP), particularly from an Indian perspective.

3. RESEARCH METHOD

The research adopts a structured approach consisting of the following steps: identification of the factors, data collection, data analysis, computations, and results. Each step is defined in the following subsections as shown in Figure 1.

3.1 IDENTIFICATION OF RISK FACTORS

A thorough analysis was conducted from literature reviews of research articles, news articles, and government reports. This study identifies key risk factors that affect construction worker safety, specifically during nighttime operations. These factors and attributes are shown in Table 1.

3.2 AHP – BASED RISK PRIORITIZATION

The safety climate refers to the overall attitude of workers towards safety precautions and practices during construction. Thus, the information should be handled qualitatively.

Therefore, in this study, an AHP questionnaire was administered to a group of safety experts who have performed safety management tasks for an extended period to maintain the consistency of the results. To do so, a questionnaire was first formed based on the AHP technique. In AHP analysis, the evaluation criteria and alternatives are organized in a hierarchical structure, and then, the priority is determined by deriving relative importance. A flowchart of the AHP process is shown in Figure 2.

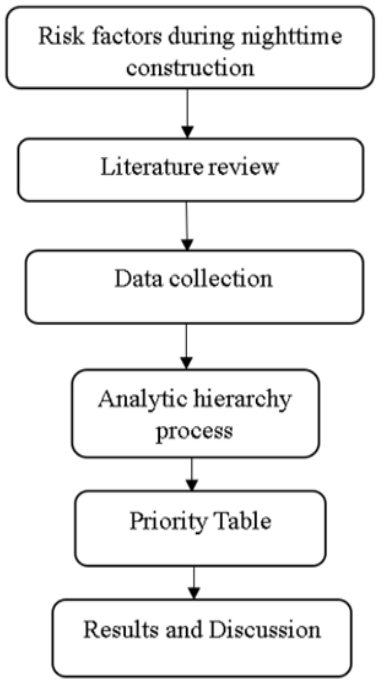


Figure 1: Research methodology flowchart

Table 1: Categorization of risk factors and attributes identified from literature

Factors	Attributes
Environmental	A1. Glare from Roadways
	A2. Extreme temperature
	A3. Slippery surface due to moisture during the night
Human	B1. Hypertension
	B2. Fatigue
	B3. Sleep Deprivation
	B4. Addictive intake
	B5. Psychological Impact
Work-related	C1. Height of construction sites
	C2. Lack of emergency readiness
	C3. Falling and Falling Objects
Equipment and Machinery Hazards	D1. Reflective PPE Kits (if not used properly)
	D2. Inadequate lighting at the construction site.
	D3. Heavy machinery operation (crane, hoists) is riskier in low visibility
	D4. Grounded electrical wiring
Organizational and Supervision	E1. Inadequate training for nighttime hazards
	E2. Improper supervision during construction

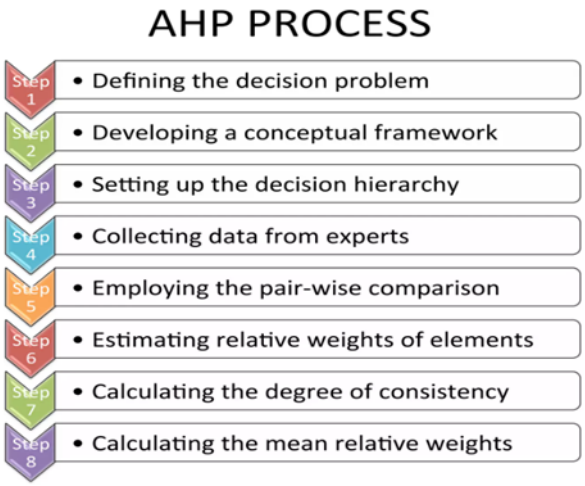


Figure 2: Flowchart of AHP process

After developing a questionnaire, industrial experts were interviewed to acquire the data to conduct AHP. The experts have given weight to the combination of two risks. This structured approach ensures that the identified risks are prioritized systematically and aligned with expert judgment.

3.3 STUDY EXPERTS

This study surveyed safety experts working at construction sites in India. The survey period was for 2 months from March to April in 2025. Out of the 20 questionnaires collected, only 15 with a consistency of 0.1 or less were selected.

As shown in Table 2, most of the surveyed experts (53.33%) had between 5 and 10 years of experience in construction safety, indicating a well-informed sample with mid-level professional insights. Among all the interviewees, all 15 were male and had graduate degrees in allied construction engineering.

Although the sample size of 15 experts is relatively limited, it aligns with established practices in AHP studies, where smaller expert panels (typically between 10–20 participants) are considered sufficient when participants have high domain expertise and consistency ratios are within acceptable thresholds (Saaty, 2008; Tsyganok et al., 2012; Nguyen et al., 2022). In this study, all selected responses had a consistency ratio ≤ 0.1, indicating reliable judgment. Moreover, the selected experts had a minimum of graduate-level education and significant field experience in construction safety, further supporting the adequacy and credibility of the sample.

Table 2: Demographic profile of safety experts participating in AHP survey

Experience (in years)	Number of experts	Percentage
less than 5 years	4	26.6
5-10 years	8	53.3
10-15 years	2	13.3
15+ years	1	6.6

3.4 ANALYSIS

In AHP analysis, the evaluation criteria and alternatives are organized in a hierarchical structure, and the priority is determined by deriving relative importance (Lim et al., 2021). For conducting AHP, the evaluation factors and attributes should be stratified to analyse the relative importance of the risk severity evaluation. The decision-making issues of this study were developed with the help of the experts in the form of a stratified pattern as shown in Figure 3. Therefore, the goal of AHP analysis in this study is to derive the importance of the safety climate evaluation factors. This comprises five dimensions (factors) and 17 items (attributes). Refer to Table 1 for details on the evaluation items for each level in Figure 3. The items of each dimension are analyzed after determining the relative importance of the dimensions of the first level. Subsequently, the relative priorities of the evaluation factors are derived.

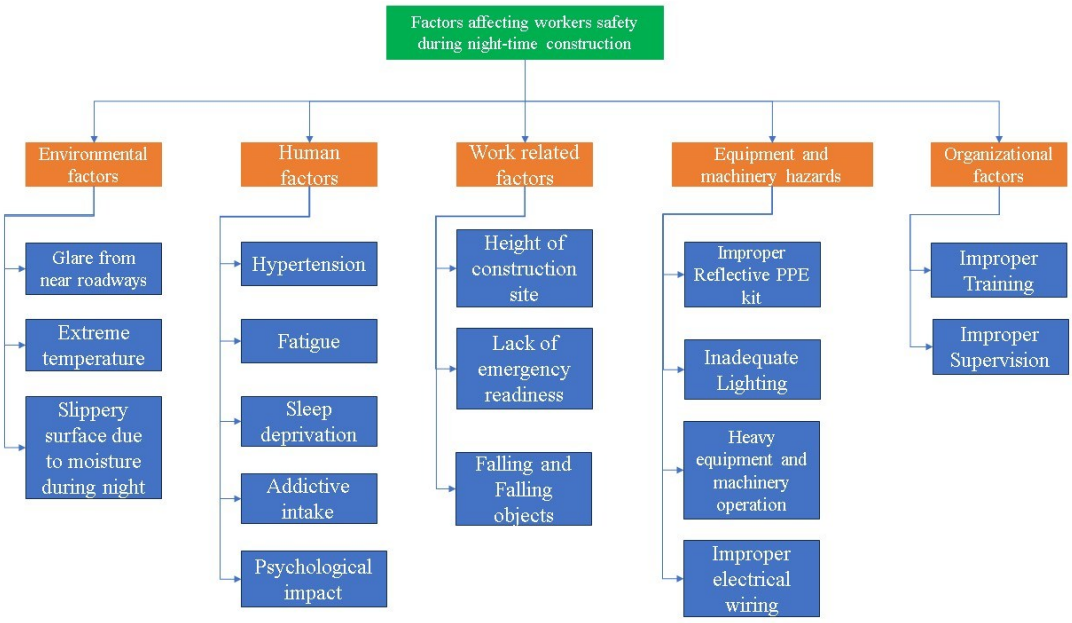


Figure 3: Hierarchical structure of AHP factors

After developing the hierarchical structure, the weights to each of the 17 items were computed with the help of the 9-point Likert scale developed by Saaty (2008). This scale is widely used in the Analytic Hierarchy Process (AHP) for pairwise comparisons. The experts related the importance of each item through a consistent framework ranging from 1 (equal importance) to 9 (extreme importance). The comparison matrix of this study takes the form of an inverse centred around the diagonal. When the values of the two factors in the matrix are 1, they have equal relative importance. In addition, the size of the comparison matrix may depend on the number of factors in the hierarchy. The AHP scale used in this study is shown in Table 3.

Table 3: Saaty's 9-point AHP scale for pairwise comparison

Scale	Definition	Explanation
1	Equally important	Both factors have the same criteria.
3	Moderately important	One criterion is slightly more important than the other.
5	Strongly important	One criterion is more important than the other.
7	Very strongly important	One criterion is far more important than the other.
9	Extremely important	One criterion is hugely more important than the other.
2,4,6,8	The median of the two scales	The median of the two scales.

4. RESULTS AND DISCUSSION

The results of the AHP analysis revealed the ranking of the five primary risk dimensions based on their overall impact on worker safety during nighttime construction. As shown in Table 4, work-related factors received the highest priority (weight = 0.353), followed by equipment and machinery hazards (0.286), organizational factors (0.242), environmental factors (0.070), and human factors (0.049).

Table 4: Relative importance and priority of risk dimensions identified through AHP analysis

Code	Dimension	Weight	Priorities
C	Work-related	0.353	1
D	Equipment and machinery hazards	0.286	2
E	Organisational	0.242	3
A	Environmental	0.070	4
B	Human	0.049	5

The criticality of the factor is justified by the fact that there is a much higher chance of slips. It falls during nighttime construction when there is inadequate lighting, particularly in areas with uneven surfaces or elevation changes (Chan et al., 2008). The significance of hazards related to equipment, like poor lighting and improper electrical grounding, shows the technical issues that are often overlooked during nighttime construction, especially since nighttime work and bad weather can negatively impact how well the equipment works (Arditi et al., 2005).

Furthermore, the local and global relative importance and priority measurements on items in risk factors during nighttime construction are shown in Table 5. Local weight measures a sub-criterion's relative importance within its main criterion in multi-criteria decision-making techniques such as AHP. It is obtained by comparing sub-criteria under the same category pairwise. Conversely, global weight indicates a sub-criterion's overall significance concerning the ultimate objective. It is determined by multiplying the sub-criterion's local weight by the weight of the main criterion. This aids in determining each sub-criterion's overall influence on the choice and ranking them all on a standard scale.

Table 5: Local and global priority rankings of risk attributes in nighttime construction

Dimension	Risks	Local weight	Local priorities	Global weight	Global priorities
Environmental (0.070)	A1. Impact of glare from near roadways on construction worker safety.	0.099	3	0.007	14
	A2. Influence of extreme temperatures on worker performance and risk levels.	0.537	1	0.037	7
	A3. Influence of slippery surface due to nighttime moisture.	0.364	2	0.025	9
Human (0.049)	B1. Effect of hypertension on construction worker safety.	0.102	4	0.005	15
	B2. Influence of fatigue on accident risks.	0.008	5	0.0002	17
	B3. Impact of sleep deprivation on worker efficiency and safety.	0.324	1	0.016	10
	B4. Risks associated with addictive intake during night shifts.	0.293	2	0.014	11
	B5. Psychological effects of night shift work on construction safety.	0.199	3	0.009	13
Work-related (0.353)	C1. Safety concerns are due to the height of construction sites.	0.195	2	0.069	5
	C2. Readiness and effectiveness of emergency response at night.	0.717	1	0.253	1
	C3. Risks associated with falling and falling objects in nighttime construction.	0.088	3	0.003	16
Equipment and Machinery hazards (0.286)	D1. Proper usage and potential risks of reflective PPE kits.	0.042	4	0.012	12
	D2. Impact of inadequate lighting on construction site safety.	0.235	2	0.067	6
	D3. Safety risks are associated with operating heavy machinery (cranes, hoists) in low visibility.	0.104	3	0.029	8
	D4. Hazards are due to the improper grounding of electrical wiring at construction sites.	0.619	1	0.177	2
Organisational (0.242)	E1. Adequacy of training programs for nighttime construction hazards.	0.500	1	0.121	3
	E2. Effectiveness of supervision during night shifts to ensure safety compliance.	0.500	1	0.121	3

Table 5 provides a more granular breakdown, showing the local and global weights of the individual attributes. Among the highest-ranked sub-criteria are the readiness and effectiveness of emergency response at night, hazards due to improper electrical grounding, and training adequacy for nighttime safety. These attributes indicate a clear need for improving operational readiness and supervision for nighttime operations.

Interestingly, organizational risks, specifically inadequate training and poor supervision, ranked third, suggesting that while these factors are acknowledged as influential, they

may not be as immediately threatening as physical or environmental risks. However, this could also reflect a deeper issue within India's predominantly informal construction sector, where regulatory enforcement and structured safety programs are limited. The lower weight may indicate that such systemic challenges are normalized and therefore underestimated by practitioners.

Human factors, including hypertension, sleep deprivation, and psychological stress, were ranked lowest. This may be because their impacts are often long-term and not as directly observable as other risks. Nonetheless, chronic fatigue and mental stress have been shown to reduce alertness and decision-making ability, contributing to accidents over time (Powell & Copping, 2010). Their low ranking highlights a critical oversight in workplace safety strategies, which often focuses more on immediate risks than long-term worker health.

The high priority assigned to equipment and lighting issues, such as poor visibility and risks from machinery operation, reinforces the urgent need for infrastructure investment in lighting systems and updated equipment standards for nighttime work. For example, the significance of electrical grounding issues points to a systemic lack of technical inspections and quality control during off-peak operations.

5. CONCLUSIONS

This study presents a thorough literature review to find the risks to construction workers during nighttime construction. Twenty safety experts were interviewed to analyse the priority of each risk by conducting an AHP analysis. The study concluded that the most significant factors are work-related, equipment, safety hazards, and organisational aspects. Emergency response readiness and effectiveness at night are the most critical subfactors, highlighting the importance of a rapid response mechanism and robust emergency planning. The study advocates enhanced planning in construction sites, specialized training for workers during nighttime operations, and improved site management to ensure safety during nighttime operations. These measures will lead to safer work environments and more efficient, resilient construction practices.

The study also has some limitations, such as expert interviews were conducted on a limited sample size, which may not fully represent the insights of the global construction industry. Additionally, the Analytic Hierarchy Process (AHP) relies on subjective judgments, which may introduce bias. Real-time data observations from active night construction sites could further enhance the results.

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ASSESSING ORGANISATIONAL READINESS FOR DIGITAL TRANSFORMATION: KEY ATTRIBUTES FOR INDIGENOUS SOUTH AFRICAN CONSTRUCTION FIRMS

Mayowa Adedapo Ogungbe[1], Matthew Ikuabe[2] and Clinton Ohis Aigbavboa[3]

ABSTRACT

Digital transformation is a critical driver of efficiency, competitiveness, and sustainability in the construction industry. However, the readiness of indigenous South African construction firms for digital transformation remains underexplored. This study evaluates key attributes influencing organisational readiness for digital transformation within these firms. A structured questionnaire, developed from existing literature, was distributed to construction professionals engaged in digital technologies within Gauteng Province, South Africa. Using a purposive sampling approach, 68 valid responses were obtained from a sample of 100, resulting in a response rate of 68%. Data analysis was conducted using descriptive statistical techniques to rank critical attributes for digital transformation readiness. Findings indicate that an innovation mindset is the most crucial attribute, emphasising the importance of fostering a culture of technological advancement. Leadership commitment ranked second, highlighting the necessity of strong strategic leadership. Other key enablers include sustainability focus, data-driven decision-making, and technical skills development. This study contributes empirical insights into the organisational factors shaping digital transformation in indigenous South African construction firms. It underscores the need for fostering an innovation-driven culture, reinforcing leadership commitment, and integrating sustainability into digital strategies. These results lay the groundwork for policymakers, industry participants, and researchers to create focused strategies aimed at enhancing digital transformation preparedness in the South African construction industry.

Keywords: *Digital Transformation; Indigenous Construction Firms; Organisational Readiness; South Africa; Technology Adoption.*

1. INTRODUCTION

The construction sector is experiencing a fundamental shift driven by digital technologies that improve efficiency, productivity, and sustainability (Leong et al., 2024). Digital

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transformation (DT) involves the incorporation of advanced technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), the Internet of Things (IoT), and cloud computing into construction processes (Lanzolla et al., 2020). These innovations streamline project management, improve collaboration, and optimise resource allocation, making digitalisation a key factor in achieving competitiveness and operational resilience. The COVID-19 pandemic significantly hastened DT in the construction sector (Olanipekun & Sutrisna, 2021), forcing companies to adopt digital tools to enhance operational efficiency and ensure business continuity. (Kim et al., 2022). However, the successful implementation of digital transformation depends largely on a firm's organisational readiness, which is influenced by several key attributes.

Indigenous construction firms are critical to any country's infrastructure development, contributing significantly to economic growth, job creation, and urban expansion (Ofori, 2015). However, these firms face significant challenges and opportunities in their digital transformation journey. Many operate in a volatile business environment, characterised by fluctuating economic conditions, evolving regulatory frameworks, and limited access to digital infrastructure (Oko-Odion & Angela, 2025). While some firms have successfully integrated digital technologies such as BIM, automation, and cloud computing, a significant portion lags behind due to financial constraints, a shortage of skilled professionals, and resistance to change (Bandara et al., 2024; Windapo & Cattell, 2013).

According to Gillani et al. (2024), organisational readiness for digital transformation is shaped by key attributes such as technological infrastructure, workforce digital skills, financial investment, leadership commitment, and organisational culture. These attributes determine how well a firm can transition from traditional construction methods to digitalised operations. However, comprehensive studies assessing these readiness factors in indigenous South African construction firms remain scarce. Therefore, this study aims to evaluate the essential attributes required for digital transformation within indigenous South African construction firms. The specific objective is to:

- Evaluates key attributes influencing organisational readiness for digital transformation within the South African construction firms.

By filling this research gap, the study aims to equip industry stakeholders, policymakers, and business leaders with actionable strategies for improving digital readiness and fostering a competitive, digitally advanced construction industry.

2. ORGANISATIONAL READINESS FOR DIGITAL TRANSFORMATION IN THE CONSTRUCTION INDUSTRY

Digital transformation (DT) revolves around how organisations evolve through the integration of digital technologies, reshaping their operations and enhancing the value they deliver to customers (Hanelt et al., 2021). According to Konopik et al. (2022), the literature surrounding DT encompasses a wide range of knowledge areas. This diversity has resulted in the absence of a unified definition for the concept. Furthermore, according to Vararean-Cochisa and Crisan (2025), construction organisations are still adjusting to the transformations driven by digitalisation, leading to the absence of standardised protocols or clearly established frameworks for the structured and efficient adoption of new technologies.

Digital advancements are essential for the smooth progress of the construction industry. However, organisational readiness for digital transformation in the construction industry is a multifaceted concept that involves technological, strategic, cultural, and human resource dimensions (Trenerry et al., 2021). Research over the past thirty years indicates that nearly 70% of large system implementations fail to deliver their expected benefits within the planned timeline and budget. Importantly, more than 85% of these failures are not due to technological flaws but rather due to challenges in integrating human factors, gaining acceptance, and building commitment to effective utilisation (Erdogan et al., 2005). This underscores the significance of organisational readiness in digitalisation adoption. Therefore, understanding the concept of organisational readiness is crucial for ensuring successful implementation. Organisational readiness for change is inherently context-dependent and lacks a universally accepted definition. It is shaped by a combination of factors, including the organizational environment, the nature of the stakeholders involved, and the specific circumstances under which change is initiated (Tran et al., 2011). In general terms, readiness refers to an organisation's proactive initiatives to prepare for and implement change, particularly digitalisation advancements. Moreover, readiness is dynamic, fluctuating based on the organisation's initiatives and capacity to adapt (Li et al., 2022). Given its variability, it is essential to examine how organisational readiness manifests in construction firms.

An organisation’s technological readiness serves as a foundational pillar in determining an organization’s ability to initiate and sustain digital transformation (Nguyen et al., 2019). This encompasses not only the availability but also the maturity and integration of digital tools and infrastructures, such as Building Information Modeling (BIM) and Immersive Technologies (ImT), which are increasingly recognized as essential for enhancing construction management practices (Wong & Abbasnejad, 2025). However, technological capability alone is insufficient without strategic leadership to drive its implementation. Leadership readiness, characterized by visionary thinking and strategic orientation, also plays a crucial role in fostering digital transformation. Similarly, effective leaders cultivate leadership schemas including strategic, future-oriented, capability-based, and experimental thinking, which collectively guide digital initiatives and promote organizational adaptability (Galli et al., 2017).

In addition to technological and leadership readiness, cultural readiness emerges as a critical enabler of digital transformation. A culture that supports innovation, embraces change, and promotes digital adoption is vital for the successful integration of emerging technologies. Organisations that exhibit cultural orientations centered on production efficiency, task achievement, and openness to innovative construction processes demonstrate a higher propensity for digital integration (Zakariyyah et al., 2021). Human resource readiness centres on the capabilities, adaptability, and preparedness of an organization’s workforce to engage with digital transformation. Among the most frequently cited challenges in this domain is the technical skills gap, which poses a significant barrier to the successful implementation of digital initiatives. The ability of personnel to comprehend, adopt, and effectively utilize digital technologies is a critical determinant of transformation success (Cetindamar et al., 2021). Addressing this challenge requires a proactive approach, including sustained investment in employee training and development programs. Additionally, organizations must build strong data management competencies to support the integration and use of digital tools, thereby enhancing overall workforce digital literacy and operational efficiency. Collectively,

these attributes technological infrastructure, strategic leadership, and organizational culture, innovative mindset, sustainability focus, and skill development, form the core attributes that influence an organization's readiness for digital transformation.

Within the construction industry, firms encounter distinct challenges that impact their digital transformation readiness. Construction companies encounter distinct challenges stemming from the intense competition within the industry, the reliance on project-based frameworks, and the ongoing demand to efficiently control both time and costs. (Ibrahim, 2018). Readiness for digitalisation in construction firms involves an organisation's ability to plan and prepare for the adoption of digital tools, ensuring seamless integration into existing workflows (Tran et al., 2011). When firms fail to adequately prepare, they often experience resistance to change, implementation delays, and inefficient utilisation of new systems (Kamm, 2017). Hence, the need to assess the needed attributes of Indigenous South African construction organisations for effective and efficient digital transformation.

Table 1 shows a summary of reviews of the key attributes that shape organisational readiness, drawing on established theoretical and empirical studies across the domains of management, information systems, and innovation.

Table 1: Attributes for digital transformation

Attribute	Definition	Readiness Category	Academic Domain	Key Citations
Leadership Commitment	Top management's dedication to driving digital transformation initiatives.	Strategic Orientation	Management	Westerman et al. (2014); Kane et al. (2015)
Cultural Adaptability	Ability to evolve organisational values and behaviours.	Cultural and Operational Readiness	Management / Organisational Behaviour	Schein (2010); Tabrizi et al. (2019)
Data-Driven Decision Making	Making decisions based on data and analytics.	Technical Readiness	Information Systems	Wamba et al. (2017); McAfee et al. (2012)
Technical Skills Development	Building digital capabilities across workforce.	Technical Readiness	Information Systems / HRM	Erol et al. (2016); Khin & Ho (2019)
Collaboration and Communication	Internal knowledge sharing and teamwork.	Cultural and Operational Readiness	Management / Organisational Behaviour	Sambamurty et al. (2003)
Risk Management	Identifying and mitigating digital transformation risks.	Cultural and Operational Readiness	Management / Information Systems	
Client-Centric Approach	Aligning transformation efforts with customer needs.	Cultural and Operational Readiness	Innovation / Marketing	Verhoef et al. (2021)
Sustainability Focus	Integrating environmental and	Strategic Orientation	Sustainability / Innovation	Geissdoerfer et al. (2018)

Attribute	Definition	Readiness Category	Academic Domain	Key Citations
	social goals into transformation.			
Change Management Expertise	Managing transition and employee adaptation.	Technical Readiness	Management	Al-Mashari & Zairi (1999)
Innovation Mindset	Openness to experimentation and creative problem-solving.	Strategic Orientation	Innovation Management	Chesbrough (2003); Teece (2018)

3. RESEARCH METHODOLOGY

This research utilized a meticulous design to gather dependable and pertinent data while addressing the specific contextual limitations of the study. The target group consisted of construction professionals in Gauteng Province, South Africa, who are actively involved in the adoption of emerging technologies in construction processes. Gauteng was chosen as the case study area due to its significant number of construction projects undertaken by both government and private entities, making it an appropriate setting for examining digitalisation within the construction (Ogunbayo & Aigbavboa, 2024). However, this geographical focus presents a limitation to the study's generalizability. The findings reflect the perceptions and readiness of firms operating within Gauteng and may not fully capture regional disparities or challenges experienced by indigenous construction firms in other South African provinces, such as Limpopo, Eastern Cape, or KwaZulu-Natal. These regions may differ in terms of technological infrastructure, access to skilled professionals, and the maturity of digital adoption. Therefore, caution should be exercised in applying the results to the broader South African construction industry without further comparative studies.

Data was collected using a structured questionnaire distributed via Google Forms. This questionnaire was crafted based on existing literature concerning digital transformation in the construction field. To ensure alignment between the collected data and the study's aims, a purposive sampling method was employed. A total of 100 questionnaires were sent to professionals with proven expertise in digital transformation in the construction industry. Of these, 68 completed questionnaires were returned, yielding a response rate of 68%, indicating strong interest from the target demographic and highlighting the significance of the research topic. The questionnaire utilized a five-point Likert scale, from "strongly disagree" (1) to "strongly agree" (5), to effectively capture a detailed range of perceptions regarding organisational readiness for digital transformation. The internal consistency of the survey instrument was evaluated using Cronbach's alpha, resulting in a value of 0.834. This high reliability score, surpassing the recommended threshold of 0.7 (Tavakol & Dennick, 2011), confirms the robustness and internal consistency of the measurement tool, ensuring the reliability of the data for subsequent analysis. Data analysis was conducted using the Statistical Package for Social Sciences (SPSS), version 20. Descriptive statistical techniques, including Mean and Standard Deviation, were employed to facilitate the ranking and assessment of variables while maintaining analytical rigor without imposing excessive statistical assumptions. The combination of

a robust sampling strategy, a well-structured questionnaire, and reliable analytical techniques enhances the credibility of this study's findings.

4. FINDINGS

According to the respondents' background information, 44.12% (30) of the respondents holds BSc degree, 23.53% (16) holds honours degree, 11.76% (8) holds MSc degree, 17.65% (12) hold a post-matric certificate or diploma, and 2.94% (2) hold a PhD degree. The largest group of respondents consisted of Quantity Surveyors 58.82% (40), followed by Information Technologists 14.71% (10), Construction Project Managers 20.59% (14), and Construction Managers 5.88% (4). The data also reflects the years of experience of the respondents in using digital technologies in construction processes: 55.88% (38) have 0–5 years of experience, 29.42% (20) have 5–10 years, 8.82% (6) have 10–15 years, and only 5.88% (4) have more than 15 years of experience. The results of this investigation indicate that the participants in the survey possess a substantial level of professional expertise and academic qualifications, thereby enabling them to provide valuable insights to achieve the objectives of the research effectively.

Following a comprehensive review of existing literature, this study identified a set of attributes for digital transformation. These identified attributes were then presented to the study's target respondents for evaluation based on their perceived level of agreement. Respondents rated each indicator using a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree". Table 2 displays the ranking of attributes essential for digital transformation by indigenous South African construction firms, as assessed by the respondents. The table shows that the Innovation mindset ranked highest with a mean item score (MIS) of 4.45 and a standard deviation (SD) of 0.738. Leadership commitment came in second with an MIS of 4.04 and an SD of 0.953. Sustainability focus was third, with an MIS of 3.98 and an SD of 0.829. Data-driven decision-making ranked fourth with an MIS of 3.94 and an SD of 0.929. Technical skills development was fifth with an MIS of 3.93 and an SD of 1.012. Change management expertise followed in sixth with an MIS of 3.92 and an SD of 0.862. Cultural adaptability ranked seventh with an MIS of 3.87 and an SD of 0.913. Collaboration and communication placed eighth with an MIS of 3.85 and an SD of 0.919. Risk management was ninth with an MIS of 3.82 and an SD of 0.863, while the client-centric approach was tenth with an MIS of 3.76 and an SD of 0.902.

Table 2: Attributes for digital transformation for Indigenous South African construction firms

Attributes	MIS	Std.D	R
Innovation Mindset	4.45	0.738	1
Leadership Commitment	4.04	0.953	2
Sustainability Focus	3.98	0.829	3
Data-Driven Decision Making	3.94	0.929	4
Technical Skills Development	3.93	1.012	5
Change Management Expertise	3.92	0.862	6
Cultural Adaptability	3.87	0.913	7
Collaboration and Communication	3.85	0.919	8
Risk Management	3.82	0.863	9

Attributes	MIS	Std.D	R
Client-Centric Approach	3.76	0.902	10

MIS = Mean Item Score; Std.D = Standard Deviation; R = Rank

Further analysis of the respondents' rankings for key attributes necessary for digital transformation is visualised in the radar chart presented in Figure 1. This chart illustrates the mean ratings of various organisational readiness attributes, grouped into three major categories: Strategic Orientation (Blue), Technical Readiness (Green), and Cultural and Operational Readiness (Orange). The findings reveal that South African construction firms exhibit a higher degree of readiness in terms of strategic orientation, with the highest-rated attributes being Innovation Mindset (4.45), Leadership Commitment (4.04), and Sustainability Focus (3.98). These results suggest that many organisations are conceptually aligned with the vision of digital transformation and are led by leadership that supports innovation and long-term value creation. In contrast, the level of technical readiness was found to be moderate, as indicated by the ratings for Data-Driven Decision Making (3.94), Technical Skills Development (3.93), and Change Management Expertise (3.92). This suggests that while firms are beginning to adopt data-informed approaches and are investing in skill development, there are still noticeable gaps in technical infrastructure, capacity, and the processes required to fully support digital transformation. However, the most critical observation is the relatively low ratings in Cultural and Operational Readiness, with Cultural Adaptability (3.87), Collaboration and Communication (3.85), Risk Management (3.82), and Client-Centric Approach (3.76) receiving the lowest scores. These findings underscore a significant weakness in the internal culture, collaborative practices, and stakeholder alignment within South African construction firms. Such limitations may hinder the successful adoption and integration of digital tools and platforms across project teams and organisational functions.

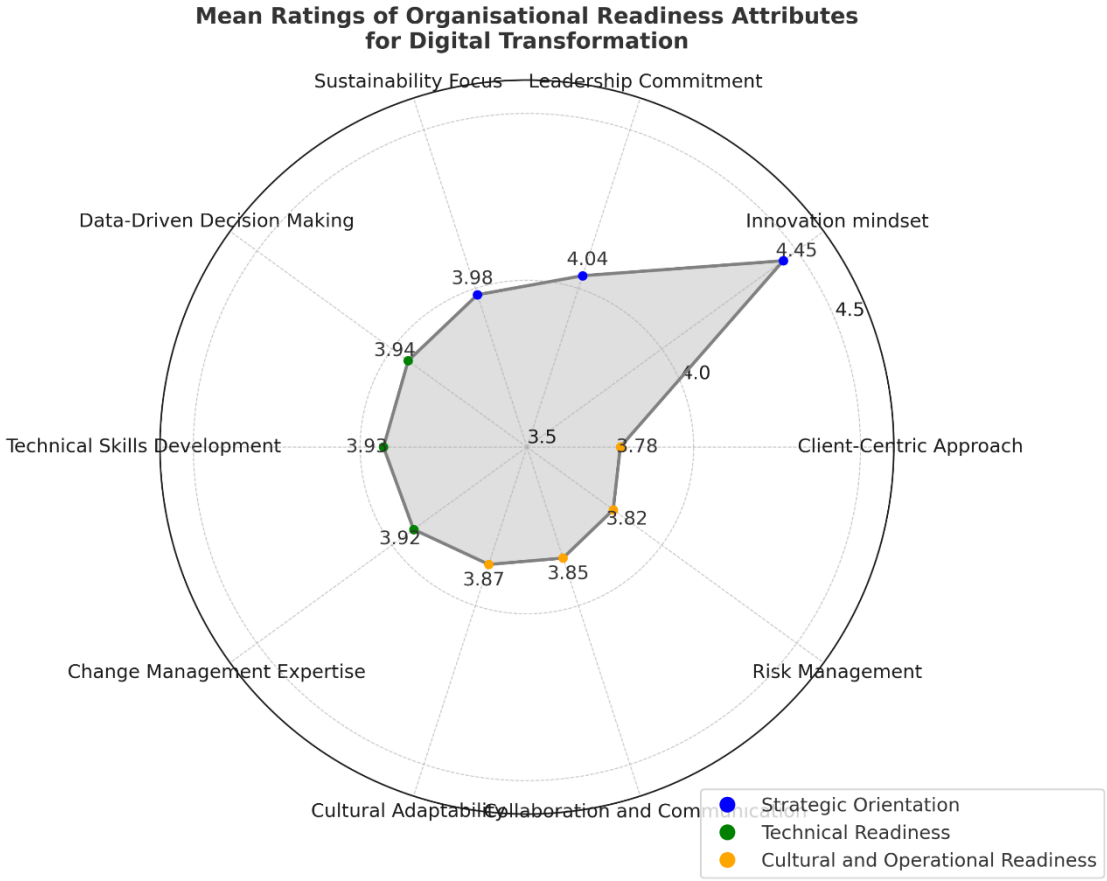


Figure 1: Attributes for digital transformation for Indigenous South African construction firms

5. DISCUSSION OF FINDINGS

The study assessed the key attributes necessary for digital transformation within indigenous South African construction firms. The results revealed that innovation mindset was ranked first, the most critical factor by the respondents, surpassing all other attributes. This finding aligns with (Demirel, 2024), who argues that an innovation mindset is an indispensable yet often invisible strategic component of digital transformation, requiring a collective commitment from leaders, employees, and organisational culture. Similarly, Joukhadar et al. (2023) demonstrated through their qualitative study that the absence of an innovation mindset amplifies the perception of complexity and uncertainty surrounding digital technologies, leading to increased technostress. Organizations that foster an innovative mindset are more capable of managing the challenges posed by digital transformation, improving their adaptability, and sustaining strategic agility in a world that is becoming increasingly digital. (Pratiwi & Justi, 2022).

The importance of leadership commitment was rated second, with MIS of 4.04 and SD of 0.953. This positions leadership commitment as the second most significant factor in driving digital transformation within indigenous South African construction firms. Leadership commitment is widely recognised as a fundamental enabler of digital transformation, as leaders set the strategic direction, allocate resources, and foster a culture that embraces technological advancements (Kane, 2019). The high MIS (4.04)

suggests that respondents view leadership as a key driver of successful digital adoption, reinforcing the argument by Hess et al. (2016) that without strong leadership, digital transformation initiatives often lack direction and fail to achieve their intended impact. According to Schiuma et al. (2022), transformational leadership is particularly crucial in guiding organisations through technological change. Leaders who are proactive, visionary, and committed to digitalisation can motivate employees, reduce resistance to change, and make sure that digital initiatives are in line with the organisation's long-term strategic objectives.

Sustainability focus, ranked third, reflects a growing trend among construction firms globally to integrate sustainability with digital transformation efforts (Kudryavtseva & Vasileva, 2021). The prioritisation of this attribute suggests that South African construction firms are becoming more conscious of the long-term advantages of adopting sustainable practices. not only for environmental outcomes but also for cost savings and regulatory compliance. This finding aligns with existing literature, which emphasises that sustainability and digital transformation are interlinked, particularly in industries like construction that have significant environmental and social impacts (Yilmaz, 2023). Furthermore, attributes like data-driven decision-making and technical skills development indicate a shift toward more strategic, informed decision-making processes as firms implement digital technologies. As suggested by Aghimien et al. (2018), data analytics and technical skills are core competencies that enhance operational efficiencies, reduce risks, and support informed project management. The implication of this result is that digital transformation in the South African construction industry is currently being driven more by strategic ambition than by operational or cultural capacity. Although there is leadership interest and a willingness to embrace innovation, the lack of cultural adaptability, weak interdepartmental communication, and underdeveloped client engagement practices may act as barriers to realising the full benefits of digital transformation.

6. CONCLUSION AND RECOMMENDATIONS

This study has provided valuable insights into the key attributes influencing digital transformation readiness within indigenous South African construction firms. The result shows that digital transformation in the South African construction industry is currently being driven more by strategic ambition than by operational or cultural capacity. Although there is leadership interest and a willingness to embrace innovation, the lack of cultural adaptability, weak interdepartmental communication, and underdeveloped client engagement practices may act as barriers to realising the full benefits of digital transformation. To address these shortcomings, stakeholders including policymakers, construction leaders, and industry training institutions should prioritise capacity-building interventions focused on organisational culture change, collaborative leadership, and human capital development. Targeted programmes such as leadership development, innovation bootcamps, cross-functional collaboration training, and digital literacy initiatives will be critical for translating strategic intentions into effective operational outcomes. By focusing on strengthening technical and especially cultural and operational readiness, the South African construction industry can position itself for a more resilient and integrated digital future. Future research should explore industry-specific challenges and opportunities related to digital transformation, ensuring a more holistic approach to technology adoption in the construction sector.

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ASSESSING SDG 7 PERFORMANCE: IDENTIFYING RELEVANT KPIS FOR THE SRI LANKAN CONSTRUCTION INDUSTRY

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ABSTRACT

The construction industry is the primary driver in achieving Sustainable Development Goals (SDGs), especially SDG 7 – affordable and clean energy. However, the progress towards SDG 7 in Sri Lanka is unclear, and there is not enough consideration given to the construction industry. This highlights the need for measurable indicators related to the Sri Lankan Construction Industry. Therefore, this study aims to assess the relevance of six United Nations (UN) established key performance indicators (KPIs) in achieving SDG 7 in the Sri Lankan construction industry and to examine perception among three different professional groups such as Architect, Engineer and Quantity Surveyor (QS). A quantitative research approach was adopted, and a questionnaire was administered to collect the information from industry professionals. In data analysis, the analyse of differences in perception across professional groups was done by Kruskal-Wallis and post-hoc tests based on the normality of the data. Significant differences in perception were identified regarding Access to Electricity (K1) and Renewable Capacity per Capita (K6), suggested the diverse priorities in promoting sustainable energy practices. Furthermore, Relative Importance Index (RII) was utilized to rank the KPIs. The results revealed that Renewable Capacity per Capita (K6), Renewable Energy (K3), and International Financial Flows (K5) are the most relevant KPIs, whereas Access to Clean Cooking (K2) and Access to Electricity (K1) are ranked as least important. The study highlights the KPIs that can effectively measure and accelerate SDG 7 achievements in Sri Lanka's construction industry. These findings provide a path to policymaker to guide the sustainable energy integration within the construction industry.

Keywords: *Construction Industry; Key Performance Indicators (KPIs); Sri Lanka; Sustainable Development Goals (SDGs).*

1. INTRODUCTION

According to the United Nations (1987), Sustainable Development (SD) meets current needs without compromising the ability of the future to meet its own. To promote sustainable development in a global context, the Sustainable Development Goals (SDGs) were introduced by the United Nations (UN) in 2015 (United Nations, 2015). 17 Sustainable Development Goals (SDGs) have been established with 169 targets to be achieved by 2030 (Patuelli & Saracco, 2022).

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Among them, SDG 7 focuses on promoting sustainable practices related to affordable and clean energy to all (Ogunmakinde et al., 2022). Affordable and clean energy resources are essential to achieve a consolidated and stable world economy (Wijayarathne, 2023). In line with this goal, Sri Lanka has made notable progress in expanding electricity access across the country (International Energy Agency et al., 2024). Even though Sri Lanka has renewable energy options such as solar, wind, hydropower, coal and others, the country's energy sector remains heavily reliant on fossil fuels (Nijam & Nazar, 2017). This dependency has led to both economic challenges (Ministry of Energy, 2022) and environmental concerns (Velayutham, 2023). To address these issues, it is crucial to develop the government policy, increase investment (Wijayarathne, 2023), enhance the indicator system (Nhamo et al., 2020), technological advancement (Zia & Aslam, 2024) and follow other relevant sustainable practices.

Several studies have explored the relationship between SDG 7 and Sri Lanka. For instance, Nhamo et al. (2020) analysed the progress and challenges of achieving SDG 7 in South Asia, including Sri Lanka. Similarly, Zia & Aslam (2024) examined strategies to accelerate SDG 7 implementation in South and Southwest Asia, while Wijayarathne (2023) proposed policy recommendations to achieve SDG 7 in Sri Lanka by 2030. However, those studies failed to give priority to the specific sectors in Sri Lanka.

The progress towards SDG 7 has been identified globally and locally, comprising the contribution of all the sectors such as construction, manufacturing and energy production (Ogunmakinde et al., 2022). Similar to different nations, different sectors also have their own level of priority to attain SDG 7 (Patuelli & Saracco, 2022). Since the construction industry is a significant energy consumer and a key driver of national energy demand (United Nations, 2015), it is crucial to assess the achievement of SDG 7 in Sri Lanka through the lens of the construction sector.

To effectively monitor and evaluate the achievement of SDG 7, the UN has established six Key Performance Indicators (KPIs): access to electricity, access to clean cooking, renewable energy, energy efficiency and financing and investment needs (Ministry of Energy (2022). However, these general indicators do not fully reflect the energy challenges and opportunities in the construction sector. Identifying KPIs tailored to the Sri Lankan construction sector can provide a more accurate measurement framework and accelerate progress toward SDG 7.

Studies done by Watts (2024), Júnior et al. (2024), Wieser et al. (2019) and Blay Jnr et al. (2023), assess the performance of SDG 7 in the construction industry in United Kingdom (UK), Brazil, Australia and Ghana, respectively. However, there is a lack of studies that assess the performance of SDG 7 in the Sri Lankan construction industry. Therefore, this study aims to identify the KPIs related to SDG 7 in the Sri Lankan construction industry through below mention objectives.

1. Examine the variations in perception among the different professional groups regarding the KPIs related to SDG 7 in the Sri Lankan construction industry.
2. Extract the relevance of KPIs in achieving SDG 7 in Sri Lankan construction industry.

2. LITERATURE REVIEW

The United Nations (1987) defined the concept of Sustainable Development (SD) as "meeting the needs of the present without compromising the ability of future generations

to meet their own needs" (p.41). The report further provides a general direction to the public to work towards balancing social, environmental and economic factors (Júnior et al., 2024). Building on this foundation, Sustainable Development Goals (SDGs) were established with the ability to address a wide range of issues through 17 goals and 169 targets (Watts, 2024).

Among these, SDG 7 focuses on affordable and clean energy. Affordable energy refers to energy that is accessible at an affordable cost for all (Kamal et al., 2021), while clean energy refers to the energy that is produced and consumed in ways that minimize environmental impact (Elavarasan et al., 2024). Moreover, affordable and clean energy enhances living standards (Júnior et al., 2024), improves health outcomes and promote educational opportunities (Watts, 2024). Therefore, this goal is crucial in promote economic growth and reduce environmental impact while maintaining the broader sustainability objectives.

2.1 IMPORTANCE OF AFFORDABLE AND CLEAN ENERGY IN SRI LANKA

Sri Lanka relies heavily on fossil fuels to meet its energy demand, despite having limited domestic reserves of coal and natural gas (Nijam & Nazar, 2017). Therefore, the country is highly dependent on fuel imports (Caldera et al., 2023). However, Sri Lanka has several renewable energy options including solar power, wind energy, hydropower, biomass, natural gas and coal ((International Energy Agency et al., 2024)). Expanding the use of renewable energy could reduce reliance on fossil fuels.

According to the Ministry of Energy (2022), nearly half of Sri Lanka's export income is spent on importing fuel, leading to a severe economic crisis. When comparing the cost of the energy system, using renewable energy is estimated to cost about 206 billion euros by 2050, whereas relying on fossil fuels would cost much more than 290 billion euros in Sri Lanka (Caldera et al., 2023).

Beyond economic benefits, the shift to affordable and clean energy significantly reduces carbon dioxide emissions. It is expected to reduce carbon emissions by 14.5 % by 2030 in Sri Lanka (Zia & Aslam, 2024). According to research, 1% increase in clean energy usage results in 0.21% carbon dioxide emission reduction in Sri Lanka (Velayutham, 2023). Further, the author emphasized that affordable and clean energy helps mitigate climate change, improve the economy of the country through new job opportunities and enable more efficient use of land compared to fossil fuels.

Despite progress, the Sri Lankan energy sector continues to face persistent issues such as limited government incentives, supply interruptions, low private investment, and the ongoing economic crisis (Rajapaksha et al., 2024; Yahanpath et al., 2024). Nevertheless, the construction industry offers a significant opportunity to advance SDG 7 by addressing energy sustainability within its operations.

2.2 SDG 7 IN THE SRI LANKAN CONSTRUCTION INDUSTRY

The construction industry is one of the major contributors to Sri Lanka's national economy, accounting for 28% of the industrial sector's GDP (Central Bank of Sri Lanka, 2022). Therefore, it can be identified as one of the major energy consuming sectors in the country, which is approximately 40% of total energy use in global context (Chhabra & Grover, 2024).

However, the construction industry negatively impacts the environment through high energy and resource consumption (Opoku et al., 2022), land development, waste generation, biodiversity and climate change during the development (Wieser et al., 2019). With the rapid urbanization and infrastructure development, Sri Lanka is experiencing a rising demand for energy (Wijayarathne, 2023).

Given the significant sustainability impact of the construction industry, the adoption of sustainable practices is strongly recommended to reduce its high carbon footprint (Opoku et al., 2022), high energy usage and greenhouse gas emissions (Wieser et al., 2019). These influences are mitigatable through the usage of renewable energy systems and energy efficiency practices (Júnior et al., 2024; Opoku, 2022).

As a result, currently in Sri Lanka, the integration of renewable energy systems and energy efficiency practices is increasingly recognized as essential to achieve SDG 7 (Júnior et al., 2024; Opoku, 2022). Despite this recognition, the Sri Lankan construction industry faces challenges in implementing these practices, creating doubt about achieving SDG 7 successfully in Sri Lanka due to high initial capital costs, the economic crisis, and technological and regulatory barriers, among others (Rajapaksha et al., 2024; Yahanpath et al., 2024).

2.3 KPIs FOR SDG 7

Key Performance Indicators (KPIs) serve as a tool to effectively monitor and evaluate the achievement of SDGs (Kanie, 2020). These KPIs act as measurable metrics that reflect progress towards specific targets within the SDGs framework (Schokker et al., 2022).

The United Nations has established specific KPIs for each target of SDG 7, which are shown in Table 1.

Table 1: KPIs for SDG 7
Source: (International Energy Agency et al., 2024)

No	KPIs	Indicator description	Codes
1	Proportion of population with access to electricity.	Access to electricity	K1
2	Proportion of population with primary reliance on clean fuels and technology.	Access to clean cooking	K2
3	Renewable energy share in the total final energy consumption	Renewable energy	K3
4	Energy intensity measured in terms of primary energy and GDP	Energy efficiency	K4
5	International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems.	International financial flows	K5
6	Installed renewable energy-generating capacity in developing and developed countries (in watts per capita).	Renewable capacity per capita	K6

As shown in Table 1, UN established KPIs for SDG 7 are focusing on access to electricity, access to clean cooking, renewable energy, energy efficiency and financing and investment needs.

2.3.1 Current Progress of SDG 7 in Sri Lanka

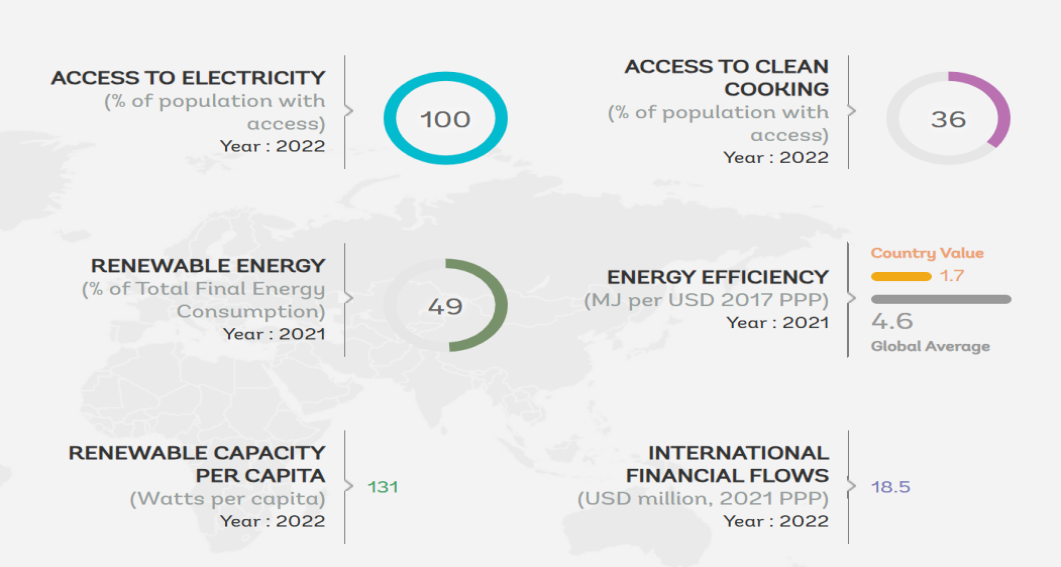


Figure 1: Current progress of SDG 7 in Sri Lanka
Source: Energy Sector Management Assistance Program (ESMAP), 2024

Figure 1 shows the progress towards SDG 7, comprising the contribution of all the sectors such as construction, manufacturing, energy production and others. Further, the progress rate indicated the necessity of accelerating progress towards SDG 7. Since the construction industry is a significant energy consumer and a key driver of national energy demand (United Nations, 2015), identifying the most relevant KPIs for Sri Lanka's construction sector and implementing targeted actions will be crucial for successfully accelerating progress toward SDG 7 in the country.

3. RESEARCH METHODOLOGY

The study adopts a quantitative research approach because it statistically analyses (Nufus et al., 2023) the perceptions of three professional groups on SDG 7's KPIs and then ranks the KPIs based on their relevance to the Sri Lankan construction industry.

The Figure 2 shows the developed research design of this study. Initially, a literature review was conducted to identify the UN established KPIs related to SDG 7. The target population of this study consists of construction professionals such as architects, engineers and quantity surveyors with knowledge on SDG 7. The sample frame is drawn from registered professionals associated with recognized organizations and industry associations such as the Green Building Council of Sri Lanka, the Institute of Engineers Sri Lanka, the Sri Lanka Institute of Architects, and other similar industry associations. Further, purposive sampling was used to get views only from people who have knowledge of research objectives (Huwae et al., 2024).

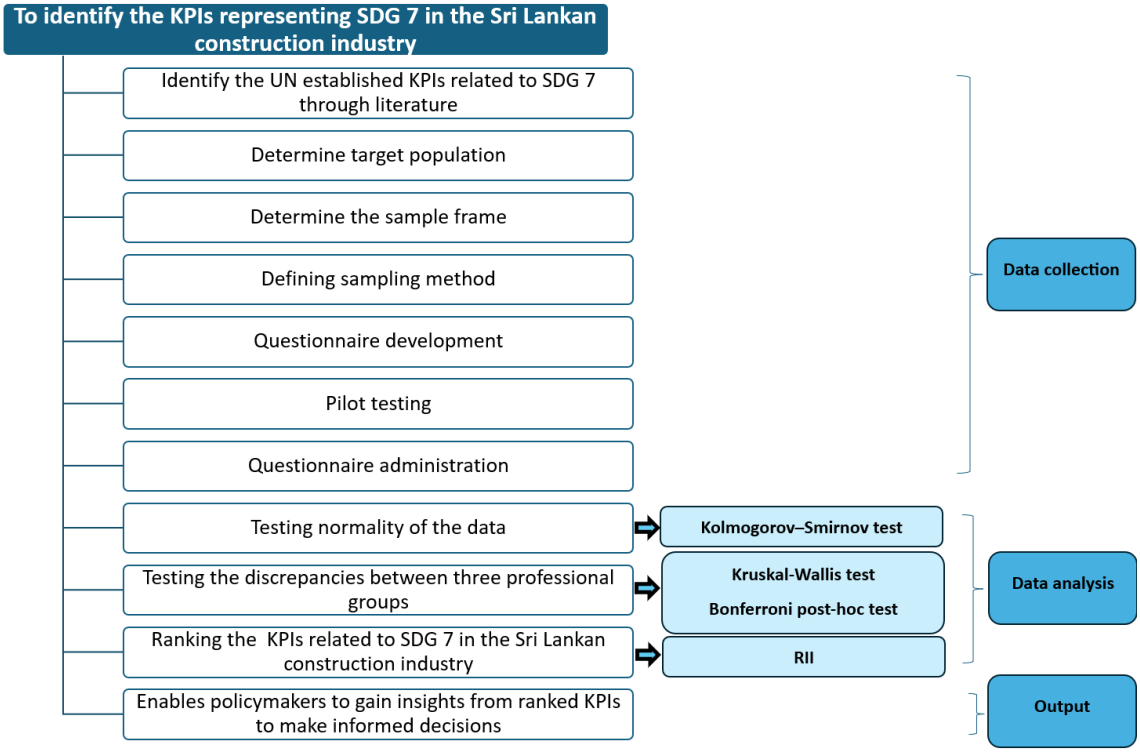


Figure 2: Research design

Since, the questionnaire survey allows data to be collected from a larger set of respondents within a shorter period (Ahmed et al., 2018), a questionnaire was administered as a data collection instrument. Before initiating the main data collection, a pilot survey was carried out among the construction industry professionals who are aligned with the sample frame. According to Ullah et al. (2023), the minimum number required for pilot testing is 20. Thus, 20 construction professionals were selected for the pilot test to check the face value of the instrument.

Following the pilot testing, a questionnaire survey was administered to 100 construction industry professionals to collect data, as it is sufficient to get a moderate response rate of 30-50% (Faleiros et al., 2016). The questionnaire consisted of 2 main sections. 1st section is used to collect the demographic information of the respondents, and 2nd section is used to gather insights into KPIs from the respondents. A 1- 5 Likert scale was utilized in the questionnaire to assess the perceived relevance of each KPI to the construction industry. The questionnaires were administered 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. Kolmogorov–Smirnov test was conducted to check the normality of the data as the sample size (n) > 50 (Mishra et al., 2019). 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 is accepted. Otherwise, the null hypothesis is rejected.

The Kruskal-Wallis test is a nonparametric test that does not require the data to be normally distributed (Cabral & Lucena, 2020). Since the collected data was not normally

distributed, a nonparametric test was conducted to compare the means of three specific groups: quantity surveyors, architects and engineers. Hypotheses of the Kruskal-Wallis test are as follows:

- Null Hypothesis (H_0): There is no statistically significant difference between the ideas of the groups.
- Alternative Hypothesis (H_1): There is a statistically significant difference between the ideas of the groups.

If $p > 0.05$, the null hypothesis is accepted. Otherwise, null hypothesis is rejected.

Kruskal-Wallis test only identifies that there is a different perception of the groups, but it does not specifically identify between which pair of groups the difference lies. Therefore, a post hoc test was conducted to compare pairs of groups and identify where the significant difference lies (Barriocanal et al., 2016).

- Null Hypothesis (H_0): There is no statistically significant difference between the specific pair of groups being compared.
- Alternative Hypothesis (H_1): There is a statistically significant difference between the specific pair of groups being compared.

If $p > 0.05$ the null hypothesis is accepted. Otherwise, the null hypothesis is rejected.

Even after the post hoc test, there is a possibility of having Family Wise Error Rate (FWER) in the results. To eliminate the FWER, the Bonferroni Correction method was applied (Armstrong, 2014).

After the Bonferroni Correction, if still $p < 0.05$, it ensures that the identified differences are truly significant and not due to random chance from multiple comparisons (Armstrong, 2014). Hence, there is a difference between the perceptions of the group of professionals.

3.1 RANKING KPIS

Relative Importance Index (RII) is a technique that is used to rank the factors (Azman et al., 2019). Therefore, RII is employed to rank the KPIs based on their perceived importance in achieving SDG 7 in the Sri Lankan construction industry. The formula for RII is:

$$RII = \frac{\sum W}{A \times N} \qquad \textit{(Equation 1)}$$

Where, W = weight assigned by respondents, A = highest weight on the scale and N = total number of respondents.

The KPI with the highest relative index was ranked first, while the KPI with the lowest relative index was ranked last.

4. RESULTS AND DISCUSSION

4.1 RESPONDENT'S DEMOGRAPHIC INFORMATION

For the pilot questionnaire survey, 20 pilot questionnaires were distributed, and 15 were returned with valid responses, resulting in a response rate of 75%. Subsequently, the main questionnaires were distributed to 100 construction professionals, of which 57 were returned with valid responses, achieving a response rate of 57%. According to Taherdoost & Madanchian (2024), the sufficient average response rate for business and management related studies is 51%. Both survey response rates exceed this threshold.

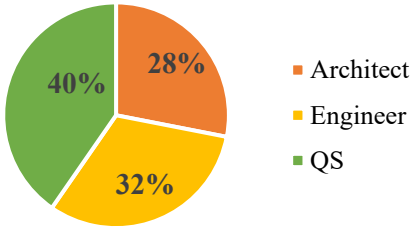


Figure 3: Respondent's profession

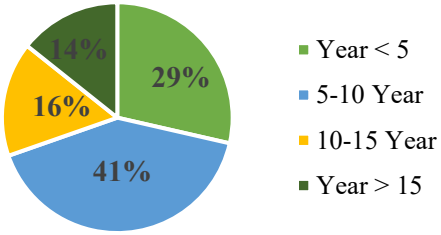


Figure 4: Respondent's experience

As shown in Figure 3, the data was collected from three categories of construction professionals such as architects, engineers, and quantity surveyors. Among the main survey respondents, the majority were Quantity Surveyors.

Further, Figure 4 illustrates the years of experience of the respondents. The average years of experience of the respondents was 11 years. All the respondents had a minimum educational qualification of a degree in a relevant field.

Moreover, as per the demographic analysis of the study, the average years of experience and minimum qualifications suggest a sufficient level of expertise and knowledge, which ensures the ability of respondents to accurately understand and respond to the questionnaire.

4.2 VARIATIONS IN PERCEPTION AMONG THE DIFFERENT PROFESSIONAL GROUPS

UN established 6 KPIs were identified, and their relevance to the Sri Lankan construction industry was evaluated through a questionnaire survey. The identified KPIs encompass access to electricity, access to clean cooking, renewable energy, energy efficiency, international financial flows and renewable capacity per capita (see Table 1).

Initially, a pilot survey was conducted to assess the clarity, relevance, and comprehensiveness of the questionnaire before its distribution for the main data collection. After the pilot survey, only a few minor changes in terminology were made to improve the clarity of the questionnaire.

The main questionnaire was then administered to construction industry professionals, and the data were collected. After data collection, the normality of the data was tested using the Kolmogorov-Smirnov test. The results of the Kolmogorov-Smirnov test are presented in Table 2.

Table 2: Normality test and Kruskal Wallis test

KPIs	Code	Kolmogorov-Smirnova test	Kruskal Wallis Test
		Sig.	Asymp. Sig.
Access to electricity	K1	0.015	0.014
Access to clean cooking	K2	0.020	0.512
Renewable energy	K3	0.000	0.605
Energy efficiency	K4	0.001	0.473
International financial flows	K5	0.001	0.310
Renewable capacity per capita	K6	0.003	0.033

According to Table 2, all significance (Sig.) values from the Kolmogorov-Smirnov 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, Kruskal-Wallis test was applied to determine whether there are differences in perceptions among these groups. Except for Access to electricity (K1) and Renewable capacity per capita (K6), all other KPIs had $p > 0.05$. This indicates that there is no statistically significant difference in perceptions among the groups regarding K2, K3, K4, and K5.

However, the Kruskal-Wallis test results showed a statistically significant difference in perceptions among the groups regarding K1 and K6. Therefore, a post hoc test was conducted to compare pairs of groups and pinpoint where the significant differences occurred. The results of the post hoc test are presented in Table 3.

Table 3: Post hoc test and Bonferroni correction

Code	Pairs of groups	Significance	Adjusted significance*
K1	Architect - Engineer	0.146	0.437
	Architect - QS	0.004	0.011
	Engineer - QS	0.157	0.470
K6	Architect - Engineer	0.010	0.029
	Architect - QS	0.094	0.283
	Engineer - QS	0.271	0.812

**Bonferroni correction*

According to Table 3, the post hoc test shows the following.

- For Access to electricity (K1), the Architect and QS pair have a discrepancy between their ideas ($p < 0.05$).
- For Renewable capacity per capita (K6), the Architect and Engineer pair has a discrepancy between their ideas ($p < 0.05$).

Even after conducting a post hoc test, the possibility of errors due to FWER remains. The Bonferroni adjustment was done to test whether the p-value of K1 and K6 becomes significant due to the FWER.

As shown in Table 3, even after Bonferroni adjustment, the significant values remain below 0.05 for the Architect and QS pair (K1) and the Architect and Engineer pair (K6).

Thus, these differences are genuinely significant and not due to random chance from multiple comparisons. This confirms that there is a difference in the perceptions of the groups of professionals. Interdisciplinary collaboration gaps within the construction industry may contribute to this variation. Construction professionals from different backgrounds often have specialized skills and knowledge unique to their respective disciplines (Faris et al., 2024). As a result, this may create varying levels of exposure towards the sustainable concepts and might influence their attitudes towards access to electricity and renewable energy integration. For instance, according to ESMAP (2024), Sri Lanka had achieved near-universal access to electricity by 2022. Since Quantity Surveyors are often involved in project costing, they may be more aware of national electrification coverage and funding compared to Architects. This may lead to differences in their perceptions regarding K1.

4.3 RELEVANCE OF KPIS IN ACHIEVING SDG 7 IN SRI LANKAN CONSTRUCTION INDUSTRY

To identify the relevance of the identified KPIs in achieving SDG 7 within the Sri Lankan Construction Industry, an assessment was carried out using the Relative Importance Index (RII) method to rank the KPIs based on their perceived significance by industry professionals. The results of the RII method are presented in Table 4.

Table 4: Relative Importance Index (RII) for KPIs

KPIs	Code	Total Weight	Relative Index	Rank
Renewable capacity per capita	K6	232	0.814	1
Renewable energy	K3	231	0.811	2
International financial flows	K5	228	0.800	3
Energy efficiency	K4	209	0.733	4
Access to clean cooking	K2	185	0.649	5
Access to electricity	K1	178	0.625	6

As shown in Table 4, RII results identified that Renewable Capacity per Capita (K6) and Renewable Energy (K3) are the most critical KPIs related to the Sri Lankan construction industry, ranking 1st and 2nd, respectively. It demonstrates the industry's attention to increasing renewable energy sources and their per capita availability. Additionally, the Sri Lankan government has launched several solar projects, such as the Thanamalwila Solar Power Project and the Wishwin Solar Energy Project, as well as wind energy projects like the Westgate Wind Power Project and the Wind Will Wind Power Project, to promote renewable energy adoption in the country (Sri Lanka Sustainable Energy Authority, 2025). These initiatives may have influenced industry professionals to prioritize renewable energy-related KPIs. In contrast, Access to Electricity (K1) was ranked the lowest, illustrating less attention towards this KPI from the Sri Lankan construction industry. According to ESMAP (2024), Sri Lanka has already achieved near universal access to electricity. As electricity access is nearly complete, construction professionals may have ranked this KPI the lowest, shifting their focus toward renewable energy expansion and energy efficiency improvements.

The RII ranking results show alignment with global trends, where countries prioritize energy goals based on their specific needs and development status. For instance, developed nations such as Germany, UK, Iceland, Sweden and others prioritize renewable energy expansion (Climate Council, 2022). In contrast, countries like Nigeria and Kenya focus on increasing electrification rates in their energy policies (International Energy Agency et al., 2024). Sri Lanka, despite being a developing country, is aligning with global sustainable energy practices due to its existing electricity coverage and increasing focus on clean energy solutions. These results highlight the importance of identifying KPIs based on a country's economic context, policy frameworks, and existing energy infrastructure.

5. CONCLUSION

In Sri Lanka, the construction industry significantly contributes to national development while being a major energy consumer. This highlights the importance of integrating SDG 7, which promotes affordable and clean energy, into the sector. To support this effort, the present study identified six key performance indicators (KPIs) in achieving SDG 7 within the Sri Lankan construction industry and explored variations in perception among different professional groups, such as architects, engineers and QSs. Understanding the difference between perceptions is important since professionals play different roles in the design, planning and implementation of construction projects, their influence in the integration of sustainable energy practices may vary. The findings revealed that there is a significant difference in perception among the professionals regarding Access to Electricity (K1) and Renewable Capacity per Capita (K6). The notable differences in perception between Architects and QSs for Access to electricity (K1) and between Architects and Engineers for Renewable capacity per capita (K6) suggest the varying priorities of different professional groups in advancing sustainable energy practices. Furthermore, ranking the KPIs helps prioritize areas of focus for improving SDG 7 performance in the Sri Lankan construction sector. As per RII results, Renewable Capacity per Capita (K6) and Renewable Energy (K3) are identified as the most relevant KPIs for the Sri Lankan construction industry, securing the 1st and 2nd positions, respectively. Conversely, Access to Clean Cooking (K2) and Access to Electricity (K1) were ranked the least important (5th and 6th), suggesting that these aspects receive relatively less attention within the industry. However, the study was limited to 6 KPIs identified by the UN, excluding other locally relevant indicators. Identifying more targeted, construction industry-specific indicators could enhance the precision of progress measurement. This presents a direction for future research to expand the KPI scope and compare findings across other developing countries. Moreover, the study contributes to academic knowledge by filling the gap in research on SDG 7-related KPIs within the Sri Lankan construction industry, and to industry practice by supporting accelerated progress toward SDG 7 through the implementation of these KPIs and by informing policymaking.

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ASSESSING THE IMPACT OF ORGANISATIONAL CULTURE ON DIGITAL TRANSFORMATION IN THE SRI LANKAN FACILITIES MANAGEMENT INDUSTRY

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ABSTRACT

Amid rapid global technological advancements, the Facilities Management (FM) profession has undergone a significant transformation. Digitisation has emerged as a key driver in improving the efficiency, organization, and sustainability of physical infrastructure. Practitioners often perceive digital transformation beyond mere technological adoption, emphasizing the need for organizational change and strategic alignment to fully realize its benefits. This paper aims to analyse the impact of organisational culture on the digitalisation of FM functions in the Sri Lankan FM industry. To achieve the objective, this study employed a quantitative methodology using a survey approach. Data were collected through a questionnaire administered to a sample of 51 respondents[3] from the FM industry. Eight hypotheses were tested using a t-test to examine the impact of cultural dimensions on the digitalisation in FM functions. The findings indicate that organisational culture has a significant impact on the digitalisation of the FM functions. Specifically, factors such as, hierarchical structure, leadership support and advocacy, risk acceptance, cross-department collaboration, employee empowerment, learning and skill development, flexibility and the influence of subcultures were found to positively affect the digitalisation. Conversely, change management practices were not found to have a significant impact. This study makes a novel contribution by addressing an important gap in the existing literature, specifically, underexplored intersection of organizational culture and digitalization within the FM sector, an area that has received limited scholarly attention despite its growing relevance in the digital era.

Keywords: *Digitalisation; Facilities Management; Hypothesis Testing; Organisational Culture; T-Test.*

1. INTRODUCTION

The rapid evolution of digital technologies has significantly transformed the competitive dynamics of industries. While new technologies are driving digitalisation even in sectors traditionally dependent on physical value proposition, they also create new opportunities for businesses' growth (Hartl & Hess, 2017). Digital transformation has made a significant change in how firms operate and interact with their customers, partners, and

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staff, and it entails using digital technologies to develop new business models, increase efficiency, improve consumer experience, and gain a competitive advantage (Karawya, 2024). The introduction of digitalization has resulted in a significant shift in organizational culture, which includes the collective values, beliefs, attitudes, and rituals that determine a company's identity (Deep, 2023). In today's rapidly evolving market, it is critical for businesses to recognise how organisational culture influences the shift toward digitalisation (Deep, 2023). Digital transformation initiatives are prevalent throughout industries yet often experience failure due to inert organizational cultures preventing changes (Hartl & Hess, 2017). A comprehensive strategy that considers factors like flexibility, change management techniques, ongoing evaluation, knowledge acquisition, interdepartmental cooperation, and organisational culture is necessary for effective digital transformation (Deep, 2023; Karawya, 2024). However, the impact of organisational culture on digitalisation has not received sufficient attention in existing literature, in the facilities management industry (Bozkus, 2024; Karawya, 2024; Pradana et al., 2022). Given the limited research specifically addressing the intersection of digitalization and organizational culture in the facilities management sector, this study aims to address this gap by exploring how organisational culture influences the success of digital initiatives. The paper begins with an introduction to the study, followed by a literature review on digitalisation in the FM industry, organisational culture and the impact of organisational culture on digitalisation. It then outlines the research methodology, with the final section presenting the study's conclusion.

2. LITERATURE REVIEW

2.1 DIGITAL TRANSFORMATION IN FACILITIES MANAGEMENT

Digital transformation in FM is an inherent driver in the development of contemporary infrastructural practice. With unprecedented technological advancement occurring in the global context, the profession of FM has also witnessed a radical transformation with the inclusion of digitisation as a key driver for enhancing the organization and sustainability of physical infrastructures (Rane, 2023). The complex field of FM, a profession with numerous dimensions, is situated at the intersection of this paradigm. It is responsible for the flawless operation and optimisation of heterogeneous built environments. FM encompasses a collection of technological interfaces, operational management, and strategic methods that are designed to optimise, maintain, and manage the performance of the physical environment (Lindkvist et al., 2019). In this scenario, the integration of digital technologies emerges as a revolutionary force, redefining established strategies and unleashing unique opportunities for improved efficiency, sustainability, and innovation (Yaqot & Al-Ramadan, 2024).

Key technologies driving this transformation include Building Information Modelling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins (DT), which facilitate real-time data integration and predictive maintenance (Hakimi et al., 2024; Schmitter et al., 2024). According to Opoku & Lee (2022), these technologies enable FM professionals to optimise energy usage, reduce operational costs, enhance occupant comfort, and ensure compliance with safety and sustainability standards. Despite these advantages, the digital transformation of FM poses several challenges. These include a shortage of skilled personnel, high initial investment costs, data privacy concerns, and resistance to change within traditional FM structures (Vimak et al., 2023).

For successful digital adoption, organizations must invest in skill development of the workers, change management strategies, and robust digital infrastructure.

2.2 KEY DIMENSIONS OF AN ORGANISATIONAL CULTURE

Organisational culture is a critical component of operation that influences the efficiency and efficacy of the organisation (Sap, 2021). Organizational culture refers to the shared values, beliefs, norms, and practices that influence the behaviour of individuals within an organisation. It is defined as the set of shared values that a group holds, which shapes how it understands, proposes, and responds to its surroundings (Tadesse & Debela, 2024). Culture of an organisation can be identified through its symbols, rituals, language, and artifacts unique to an organization. According to Cameron & Quinn (2006), there exists four primary types of organizational culture: clan (team-oriented culture), adhocracy (innovative culture where accepts risk), market (competitive and results oriented), and hierarchy (structured and controlled). A strong organizational culture aligns employee behaviours with strategic goals, enhancing performance and productivity (Tadesse & Debela, 2024), while also fostering employee engagement, satisfaction, and retention (Denison & Mishra, 1995).

The culture within organisations is the primary focus of organisational culture dimensions (Tadesse & Debela, 2024). Organisational culture is assessed by researchers using a variety of dimensions. Organisational culture was assessed in certain studies using workplace interactions, norms, and beliefs. Yip et al., (2020) asserted that the fundamental principles of an organisation can be perceived as internal norms and beliefs that influence behaviour. Values and norms are associated with group beliefs and customs regarding the significance of specific behaviours, work methods, and/or how to respond to change, as per Ouellette et al. (2020). Organisational value encompasses innovation, outcome orientation, collaboration, and attention to detail, as stated by Baird et al. (2018). Additionally, Binder (2016) emphasises the importance of environmental sustainability, community service, and innovation in the ethos of non-profit organisations. Furthermore, Belay et al. (2023) investigated cultural dimensions, including innovativeness, adaptability, collaboration, and ethical orientation. Table 1 demonstrates the key cultural dimensions cited by different scholars in their studies.

Table 1: Key cultural dimensions

Dimension	Description	Reference
Norms and beliefs	Group beliefs and customs regarding the significance of specific behaviours	(Yip et al., 2020)
Innovation	Acceptance of innovative ideas and support towards innovations.	(Baird et al., 2018; Binder, 2016; Ouellette et al., 2020)
Responses to change	How openly and quickly an organization and its members adapt to and support organizational transformation efforts	(Alshammari et al., 2024; Azeem et al., 2021; Ouellette et al., 2020)
Cross-Collaboration	Extent to which different departments and teams work cohesively to achieve shared goals	(Baird et al., 2018; Horvey & Moloi, 2024; McNett, 2015; Ouellette et al., 2020)

Dimension	Description	Reference
Adaptability	Organization's ability to respond to internal and external environmental changes through innovation.	(Belay et al., 2023)
Risk acceptance	The degree to which an organization encourages risk-taking and experimentation without fear of failure.	(Bosire & Kinyua, 2022; Fedotova et al., 2024; Horvey & Moloi, 2024)
Hierarchical structure	Clarity and rigidity of authority levels and decision-making processes	(Bencsik, 2024; Bosire & Kinyua, 2022; Fedotova et al., 2024; McNett, 2015)
Learning and skill development	Organization invests in employee education, upskilling, and continuous learning.	(Bencsik, 2024; Rostain, 2021; Suifan, 2021)
Employee empowerment	Autonomy and decision-making power are delegated to employees at various levels.	(Alshammari et al., 2024; Azeem et al., 2021; Bencsik, 2024; Bosire & Kinyua, 2022)
Flexibility	Organization's openness to change in roles, procedures, and strategies.	(Belay et al., 2023; Rostain, 2021)
Leadership support	Leaders actively foster a supportive environment.	(Moreno-Monsalve et al., 2021; Suifan, 2021)

2.3 ORGANIZATIONAL CULTURE AND DIGITAL TRANSFORMATION IN FACILITIES MANAGEMENT

Organizational culture plays a critical role in either enabling or obstructing digital transformation in FM, a field that increasingly relies on smart technologies, data analytics, and automation to enhance efficiency, sustainability, and user experience. Practitioners often perceive digital transformation beyond mere technological adoption, emphasizing the need for organizational change and strategic alignment to fully realize its benefits (Moreno-Monsalve et al., 2021). Organizational culture that comprises a cultural environment of flexibility, ongoing learning, and openness for change allows the incorporation of digital technologies (Alshammari et al., 2024; Fahmi, 2024). Organizational culture is then a success or failure determinant of digitalization as it affects the attitudes, communication, and executions of technological change among employees. An innovative, learning, flexible, and communicative culture provides an environment in which digital transformation is embraced rather than opposed (Fahmi, 2024). In such cultures, workers will be more willing to experiment with new tools, adapt to evolving digital workflows, and collaborate across departments behaviors that are essential to integrating technologies like artificial intelligence, cloud computing, and automation into the core business processes (Hakimi et al., 2024; Vimak et al., 2023). Conversely, rigid, risk-averse, or hierarchical organizations may be plagued by resistance to change, slow uptake, and inability to realize the complete potential of digital tools due to fear, unfamiliarity, or lack of leadership support (Hakimi et al., 2024).

Furthermore, cultural factors including employee empowerment, leadership endorsement, and interdepartmental collaboration significantly influence the rapidity and efficacy with which digital initiatives are implemented (Horvey & Moloi, 2024). When

organizational leaders actively support digital initiatives and designate resources for both training and infrastructure, this behaviour conveys a strong commitment and mitigates uncertainty among personnel (Bencsik, 2024). Further to the author, a culture that emphasizes learning, prioritizing the advancement of skills and innovation, guarantees that employees maintain adaptability and proficiency in response to digital disruptions. Ultimately, digitalization is not just a technical shift but a cultural one its success depends largely on whether the organization's culture aligns with the principles of agility, experimentation, and forward-thinking.

In the Sri Lankan FM industry, organisations exhibit a rigid and resistant culture towards technological adaptation, as revealed by Peiris et al. (2024). According to them, Sri Lankan FM organisations are characterised by several cultural deficiencies, including lack of strategic level involvement, delayed adoption of technology, insufficient knowledge and experience and a lack of skills in implementing technological solutions. As an example of a proactive and innovative culture, FM practitioners in developed regions such as Hong Kong emphasize leadership and technology competencies (Peiris et al., 2024). Sri Lankan FM organisations, by contrast, often operate within hierarchical structures and place greater emphasis on routine service activities and cost control (Rajini & Kaluarachchi, 2019). According to Weerasinghe and Sandanayaka (2013b, 2013a), traditional and relationship-based management styles are often reinforced in Sri Lankan FM integration practices, largely due to organisational factors such as ownership type and closeness of client relationships. FM service consistency is further affected by cultural factors such as poor communication, limited decision-making autonomy, and significant employee turnover (Herath et al., 2019). These characteristics indicate a culture that struggles to adjust to rapid technological changes, highlighting the critical importance of studying digitalisation within the industry. Compared to Sri Lankan FM, the construction and hospitality industries exhibit a higher level of digital maturity, largely due to their more supportive organisational cultures. Driven by innovation-oriented leadership and collaborative work environments, construction firms often adopt technologies such as BIM (Chathuranga et al., 2025). Similarly, the hospitality industry is characterised by customer-centric and adaptive cultures, reflected in its adoption of digital tools such as AI and IoT (Muwandeniya & Eranda, 2022). On the other hand, Sri Lankan FM organisations remain constrained by their lack of digital readiness, limited strategic involvement, and rigid hierarchical structures (Peiris et al., 2024). Insights of these sectors clearly indicate that the FM industry in Sri Lanka must undergo significant cultural transformations to enable successful digitalisation.

3. METHODOLOGY

Aiming to analyse the impact of organisational culture on the digitalisation of the FM functions in the Sri Lankan FM industry, this study adopts a quantitative methodology using a survey-based approach. Using a convenience sampling method, a sample of 51 professionals from the FM industry was selected based on their accessibility and availability to the researcher. The target group comprised individuals/professionals directly involved in or affected by digital transformation within the FM sector, particularly those with relevant insights into organizational culture and change. A questionnaire survey was developed and administered based on insights from existing literature. It comprised two sections: demographic information of the participants and the impact of cultural dimensions on digitalisation. The organisational culture of the

respondents was assessed based on their flexibility in adopting new initiatives and their acceptance of innovations, reflecting their level of digital maturity. Likert style rating questions, using a five-point scale, were used to elicit respondents' opinions of the impact of each nominated variable. The scale intervals are interpreted as follows:

1 = Strongly Disagree
2 = Disagree
3 = Neither Agree nor Disagree
4 = Agree
5 = Strongly Agree

Based on the collected data, hypothesis was developed to assess the study's objective, and hypothesis testing was subsequently conducted. For the data analysis, SPSS v.23 software was used.

3.1 HYPOTHESIS OF THE STUDY

Drawing from the literature, the effects of organisational culture on digitalisation was assessed using 8 hypotheses formulated based on identified cultural dimensions. Although 11 dimensions were initially identified, only 8 hypotheses were developed by consolidating those dimensions that shared similar definitions and suitability to the FM industry. They are:

Hypothesis 1

$H0_1$: The organization's existing hierarchical culture does not significantly influence the adoption of digital technologies.

H1: The organization's existing hierarchical culture significantly influences the adoption of digital technologies.

Hypothesis 2

$H0_2$: The organization's leadership support and advocacy do not play a significant role in facilitating the adoption of digital technologies.

H2: The organization's leadership support and advocacy play a significant role in facilitating the adoption of digital technologies.

Hypothesis 3

$H0_3$: The organization's history of change management does not play a crucial role in the adoption of digital technologies.

H3: The organization's history of change management plays a crucial role in the adoption of digital technologies.

Hypothesis 4

$H0_4$: The organization's cross-department collaboration does not greatly influence the adoption of digital technologies.

H4: The organization's cross-department collaboration greatly influences the adoption of digital technologies.

Hypothesis 5

$H0_5$: The organization's willingness to accept risk does not significantly influence the adoption of digital technologies.

H5: The organization's willingness to accept risk significantly influences the adoption of digital technologies.

Hypothesis 6

$H0_6$: The organization's culture of continuous learning and skills development does not significantly influence the adoption of digital technologies.

H6: The organization's culture of continuous learning and skills development significantly influences the adoption of digital technologies.

Hypothesis 7

$H0_7$: The organization's approach to employee empowerment does not play a significant role in the adoption of digital technologies.

H7: The organization's approach to employee empowerment plays a significant role in the adoption of digital technologies.

Hypothesis 8

$H0_8$: The organization's flexible and adaptive subculture does not greatly impact the adoption of digital technologies.

H8: The organization's flexible and adaptive subculture greatly impact the adoption of digital technologies

3.2 T-TEST

According to Norman (2010), t-tests can be used with Likert scale data irrespective of the normality of the distribution. Since the data are in a Likert scale format, the study adopts one sample t-test with 95% confidence interval to test the hypothesis. A one-sample t-test was applied to statistically assess whether respondents' views substantially deviated from a reference point. This test is suitable for assessing whether a sample mean diverges from a specified theoretical value (Field, 2018), especially in research using perception-based survey data (De Winter & Dodou, 2010). Since the aim was not to compare between groups but to test if the mean level of agreement for each hypothesis was significantly above the reference point, the one-sample t-test provided a suitable inferential tool.

To select a t-test for hypothesis testing, two main requirements need to be fulfilled as per Kim & Park (2019).

The data should preferably conform to a normal distribution since the t-test presumes that the sample means follow a normal distribution.

An appropriate sample size is necessary. While larger sample sizes can help mitigate issues with normality due to the central limit theorem, smaller samples require careful consideration of normality. However, Kwak & Kim (2017) mentioned that if the sample size is closer to 30, the studentized sampling distribution approximates the standard normal distribution.

The t-test equation can be seen in Equation 1.

$$t = \frac{m - \mu}{\sigma/\sqrt{n}} \qquad Equation\ (1)$$

t = *Student's t-test*
m = *mean*
μ = *theoretical value*
σ = *standard deviation*
n = *variable set size*

Decision rule: Reject or accept the hypothesis. If Sig. value < 0.05, then H1 is accepted, and H0 is rejected.

4. RESULTS AND ANALYSIS

The study was conducted with 51 professionals in the Facilities Management industry to examine the impact of various cultural dimensions within organisations on the digital transformation of the FM industry. As shown in Table 2, the majority of the participants (54.9%) are from FM service-providing organisations, while 60.78% of the participants are from organisations with a moderately innovative and adaptable culture. Notably, no participants represented organisations with highly rigid and traditional cultures, and only a small portion (3.92%) were from organisations with moderately rigid and traditional cultural environments.

Table 2: Demographic data of the participants

Demographic	Overall frequency	Percentage
Experience in the FM field		
11-15 Years	4	7.84
6-10 Years	13	25.49
2-5 Years	22	43.14
Less than 2 Years	12	23.53
FM organisation type		
Consultant	5	9.80
FM service provider	28	54.90
In-house FM department	13	25.50
Technology vendor/provider for FM	5	9.80
Organisational culture (Based on Digital Maturity)		
Highly innovative and adaptable	10	19.61
Moderately innovative and adaptable	31	60.78
Neutral	8	15.69
Moderately rigid and traditional	2	3.92
Highly rigid and traditional	0	0

4.1 HYPOTHESIS TESTING

A one-sample t-test analysis was conducted with t-test value of 3.5 and 95% confidence interval to evaluate the acceptance or rejection of the developed hypothesis. The t-test value 3.5 was chosen based on the rationale that it appropriately aligns with the ordinal

nature of the scale used in the study, making it suitable for identifying meaningful differences from a neutral midpoint (Kang et al., 2005; Vieira, 2016). While 3.0 is the mathematical median of a five-point Likert scale, it signifies a purely neutral response. This study used a test value of 3.5 to represent an appropriate midpoint that differentiates neutrality from moderate agreement. This threshold enables the study to identify those who favour a positive view, as opposed to those who remain merely indifferent. Employing 3.5 as the reference point aligns with prior studies (Chyung et al., 2017; Zumrawi & Macfadyen, 2023) indicating that values slightly beyond the numerical midpoint provide a more significant distinction in the interpretation of ordinal Likert-type data.

Table 4: One sample t-test

	Test value= 3.5				
Hypothesis	**T**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**Result of the test**
H1	3.749	103	.000	.308	H01 Rejected
H2	8.361	103	.000	.558	H02 Rejected
H3	1.164	103	.247	.087	H03 Accepted
H4	9.282	103	.000	.577	H04 Rejected
H5	-3.498	103	.001	-.260	H05 Rejected
H6	3.117	103	.002	.212	H06 Rejected
H7	2.218	103	.029	.154	H07 Rejected
H8	9.282	103	.000	.577	H08 Rejected

Confidence interval percentage 95%
α=0.05

Table 4 presents the results of the one-sample t-test, indicating the acceptance and rejection of the null hypothesis based on the test statistics. At the 95% confidence level, a p-value less than or equal to 0.05 indicates the rejection of the null hypothesis, leading to the conclusion that certain dimensions of organizational culture significantly impact the digital transformation of FM functions. The analysis shows that seven out of eight hypotheses led to the rejection of the null hypothesis, suggesting that these specific cultural dimensions significantly influence the digitalisation of FM functions within organisations.

- Pre-existing culture (H1)
- Leadership support and advocacy (H2)
- Cross-departmental collaboration (H4)
- Willingness to take risks (H5)
- Continuous learning and skills development (H6)
- Employee empowerment (H7)
- Flexible and adaptive subcultures (H8)

In contrast, the results indicate that the history of change management (Hypothesis 3) does not have a statistically significant effect on the digitalisation of FM functions within organisations, as the null hypothesis ($H0_3$) for this dimension was not rejected. This suggests that, within the context of this study, the history of change management as a

dimension of organizational culture may not play a significant role in driving digital transformation in the FM industry.

4.2 DISCUSSION

Organisational culture plays a key role in digitalisation by fostering openness to change and building trust, which supports digital transformation processes. The core values and beliefs that constitute various dimensions of organisational culture shape how an organisation adapts to and embraces digital change. The Sri Lankan FM industry is characterised by rigidity, resistance to technological adoption, limited strategic involvement, and low digital readiness. These issues are compounded by traditional, hierarchical structures and relationship-based management styles, which hinder adaptability and innovation (Weerasinghe & Sandanayake, 2013b, 2013a). In contrast, FM sectors in developed regions like Hong Kong prioritise leadership and technological competencies, enabling faster digital progress (Peiris et al., 2024). Similarly, the construction and hospitality industries in Sri Lanka demonstrate higher digital maturity due to more supportive, innovation-oriented cultures (Chathuranga et al., 2025; Muwandeniya & Eranda, 2022). These comparisons highlight the urgent need for cultural transformation within the Sri Lankan FM to enable effective digitalisation. Thus, this study employed a range of organisational culture dimensions to analyse their impact on the digitalisation of the functions within the FM industry.

According to the analysis, H1 (hierarchical culture) was supported based on a t-value of 3.749 at a 95% confidence interval, indicating that organisational hierarchical culture has a significant positive impact on the digitisation of its functions. This finding aligns with the conclusions of Bencsik (2024), an organisation's existing hierarchical culture, leadership role and support, continuous learning and employee empowerment all have a significant impact on the digitalisation of the organisation. Confirming the findings of Bencsik, 2024 and Moreno-Monsalve et al. (2021), H2 indicated that leadership and its supporting role have a significant impact on the digitalization of FM functions within the FM industry. Further, in comparison to Bencsik's study, this research presents a similar perspective on the roles of continuous learning and employee empowerment. H6 and H7 were evaluated with t-values of 3.117 and 2.218, respectively, at a 95% confidence level. This suggests that continuous learning and employee empowerment have a statistically significant effect on the digitalisation of FM functions. However, Alshammari et al., (2024) found that employee empowerment does not significantly impact the success of digital transformation projects, contrary to the findings of the current study, where t-test results of Hypothesis 7 led to the rejection of the Null hypothesis ($H0_7$), indicating a significant effect of employee empowerment on the digitalisation of FM functions. According to the findings of the study, hypothesis 3 demonstrates a p-value (0.247) which is greater than 0.05, accepting the null hypothesis ($H0_3$), suggesting that the organisational history of change management does not have a significant impact on digitalisation. Alshammari et al. (2024) revealed that dimensions such as support of change do not significantly impact the success of digital transformation projects, confirming the results of this study, as the t-test accepts the H0 in hypothesis 3.

Hypothesis 4 yielded t-values of 9.282 (accepting H4), indicating that an organisation's cross-departmental collaboration has a significant effect on the digitalisation of the FM functions. These findings are broadly consistent with the research by Horvey & Moloi (2024), which emphasised that effective digital transformation necessitates cross-

collaboration to manage digital implementation effectively. According to Elena & Johnson (2015) organisations that accept risk and failures have a significant adoption rate of digital tools for their operations. Confirming to that Zhao et al. (2024) explained that openness towards calculated risks, where reacting fast and adapting to challenges in the rapidly changing environment, supported adopting new technologies in the organisation. H5 supported this by rejecting the null hypothesis (H05) and confirming that willingness to take risks significantly influences the adoption of digital technologies. Lastly, Fahmi, (2024) stated that the successful implementation of digital technologies is driven by flexibility and innovativeness, which support more agile responses to market changes and facilitate faster decision-making. In line with this assertion, the results of hypothesis 8 rejected the null hypothesis, confirming that the innovativeness and flexibility of an organisation's culture have a significant impact on the digitalisation of FM functions.

With seven out of eight hypotheses (87.5%) rejecting the null and supporting the alternative hypotheses, the study provides strong evidence that organisational culture significantly influences the digitalisation of FM functions. This study offers a novel, context-specific practical directive regarding the identification of specific organisational cultural dimensions that should be prioritised when integrating digital tools into FM functions. The results, which concentrate on the Sri Lankan FM industry, indicate that successful digitalisation is considerably influenced by dimensions such as leadership support, employee empowerment, cross-departmental collaboration, and organisational flexibility. Conversely, variables such as an organization's history of change management fail to demonstrate substantial influence. These insights assist FM managers and policymakers in culturally constrained environments in identifying the most effective cultural levers to drive digital transformation.

5. CONCLUSION

This study aimed to explore the extent to which organizational culture influences the success of digitalization initiatives within the FM sector. As FM increasingly integrates digital technologies to enhance efficiency, service quality, and sustainability, the role of culture emerges as a critical factor that can either enable or hinder this transformation. To achieve the objective, eight hypotheses were developed based on relevant cultural dimensions. The study employed t-tests to empirically analyse these hypotheses, focusing on key cultural variables affecting the effectiveness of digital transformation efforts. Data were collected from practitioners within the FM industry.

The results revealed that, based on the significance values, the null hypothesis (H0) was rejected for seven of the eight hypotheses, while one hypothesis failed to reject the null hypothesis. In conclusion, the study demonstrates that organisational culture has a significant impact on the digitalisation of FM functions. In particular, factors such as hierarchical structure of the organisation, leadership support and advocacy, risk acceptance, cross-department collaboration, employee empowerment, learning and skill development, as well as the flexibility and adaptability of subcultures, play a key role in enabling digital transformation. These findings underscore the importance of fostering a culture that supports these key dimensions to successfully drive digital transformation within the FM industry.

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BARRIERS AND SOLUTIONS TO ADOPTING DIGITAL TWIN IN SRI LANKAN CONSTRUCTION

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ABSTRACT

In the Industry 4.0 era, Digital Twin (DT) technology has emerged as a key innovation, integrating physical assets with their digital counterparts to enhance coordination, safety, and cost management in construction. Despite its potential, DT adoption in construction remains limited, particularly in developing countries like Sri Lanka, due to high costs, technological barriers, and a lack of standardized integration methods. While DT has significantly improved efficiency in other sectors, the construction industry still lacks practical large-scale applications and a unified framework for implementation. This research aims to explore the applicability of DT in Sri Lankan construction projects. Moreover, semi-structured expert interviews were conducted with 7 experts to gather data. Accordingly, the literature review and insights gathered from interviews highlighted its current usage, benefits, and barriers, and proposed 8 practical solutions to facilitate broader adoption of DT in the Sri Lankan construction industry. The findings of this research are anticipated to contribute significantly to the effective integration of DT technology within the Sri Lankan construction sector. The results underscore the promising role that DT can fulfil in addressing a variety of barriers confronting the construction industry. This study not only emphasizes the critical importance of adopting Digital Twin technology but also seeks to raise awareness of its potential, thereby encouraging its utilization and ushering in a new era of innovation in the Sri Lankan construction industry.

Keywords: *Barriers; Construction Technology; Digital Twin; Sri Lanka.*

1. INTRODUCTION

In the Industry 4.0 era with the advent of digitization, Digital Twin (DT) technology is gradually becoming one of the core technologies (Li et al., 2025). DT technology, which integrates physical assets with their digital counterparts, offers high potential to address critical construction challenges by improving coordination, safety, and lifecycle cost management (Madubuike et al., 2022). The challenges faced by the construction include issues with planning, coordination, and communication, as well as safety hazards, high maintenance costs, and inefficiencies in construction processes (Shahzad et al., 2022;

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Ullah et al., 2019). Recent studies suggest that these persistent issues could be mitigated through the application of DT technologies, which have shown promise in enhancing project efficiency and real-time decision-making (Gunatilaka et al., 2021; Shahzad et al., 2022).

DT technology is an evolving concept that integrates the physical world with the digital world (Madubuike et al., 2022). A DT is an emerging technology that is seen as crucial for an organization's digital transformation. (Qamsane et al., 2021). This method allows for the creation of a virtual model of a physical asset or process that can be monitored and analysed in real-time (Madubuike et al., 2022) . Michael Grieves, formerly of the University of Michigan, is often credited with coining the term "Digital Twin" during his 2002 presentation on Product Lifecycle Management (PLM) (Qamsane et al., 2021).

'Cost' is identified as a major barrier when it comes to developing countries to the applicability of DT (Amirthavarshan et al., 2023; Geekiyanage et al., 2025). DT application in the construction industry is low compared to other industries, despite the rise of smart buildings with automated systems (Jiao et al., 2025; Madubuike et al., 2022). According to the Amirthavarshan et al., (2023) in other sectors, DT technology has been responsible for saving product development time and costs by up to 50%. Liu et al., (2024) stated the market value of DT is expected to increase from $6.9 billion in 2022 to $73.5 billion in 2027, with an average annual growth rate of over 60%. This indicates a strong growth potential for DT in the construction industry (Liu et al., 2024).

The use of DTs in the construction industry is still in its early stages, primarily involving small-scale experiments and lacking mature practical applications (Amirthavarshan et al., 2023; Tuhaise, 2023). It should be noted that the industry lacks a clear understanding of the barriers posed by technology (Amirthavarshan et al., 2023). Furthermore, there is currently no consensus among researchers and industry practitioners on standardized approaches for integrating DT processes and data-centric technologies within building and civil infrastructure projects (Sacks et al., 2020). As such, a clear research gap exists in understanding how DT technologies can be effectively adopted and adapted to the specific needs and conditions of the Sri Lankan construction sector (Gunatilaka et al., 2021). Moreover, aligning system design with stakeholder preferences ensures that proposed DT frameworks are not only technologically feasible but also aligned with operational workflows and user capacities. This aligns with global perspectives, which emphasize stakeholder-driven DT development to ensure relevance and efficiency (Revolti et al., 2024). Bandara et al., (2024) stated future research should continue exploring these areas to provide further insights and recommendations for enhancing digital adoption in the construction sector.

Therefore, this research aims to explore the applicability of implementing DT technology in construction projects in Sri Lanka, and the study's aim has been achieved by accomplishing three objectives. Accordingly, the study will investigate the current state of DT technology implementation in Sri Lanka. Then study will identify potential benefits, and barriers to DT in construction in Sri Lanka. Ultimately, the research will suggest practical steps that can be taken to overcome common barriers associated with implementing DT technology in Sri Lankan construction projects.

2. LITERATURE REVIEW

2.1 OVERVIEW OF DT

DT technology is underpinned by advanced data processing and artificial intelligence (AI) applications such as machine learning, optimisation techniques, and search algorithms to assess project performance in real time, whether the project is under construction or in operation (Akomah et al., 2020; Radzi et al., 2024). A DT consists of three integral components: the physical system, its virtual counterpart, and the communication link that synchronises the two. This linkage is enabled by technologies including cyber-physical systems, sensors, communication networks, and mobile devices (Akomah et al., 2020; Amirthavarshan et al., 2023; Madubuike et al., 2022). DT operates as dynamic simulations, leveraging digital technologies such as Geographic Information Systems (GIS), Building Information Modelling (BIM), and Internet of Things (IoT) devices to create comprehensive, real-time representations of physical assets (Amirthavarshan et al., 2023; Omrany et al., 2025). Cloud-based platforms are used for data storage and real-time data exchange, enabling system integration.(Tuhaise, 2023). According to Madubuike et al. (2022), implementing DT technology involves a six-step process: imagining opportunities, identifying a suitable process, piloting the DT, industrializing the process, scaling the twin, and monitoring and measuring.

2.2 CURRENT STATE OF DT

The use of DT technology in the construction and real estate industries has the potential to revolutionize the management of assets and projects (Attaran & Celik, 2023). The De Soysa building on Slave Island and the Rangiri Dambulla Caves are prime examples where DTs can play a crucial role. For the De Soysa building, a DT can aid in preserving its legacy amid urban development. For the Rangiri Dambulla Caves, a DT focusing on microclimatic conditions can enhance preservation efforts by predicting and mitigating environmental impacts (Kudasinghe & Jeewananda, 2024). Another one such example is the creation of the Rankoth Vehera DT. This not only illustrates how DT applications are currently used in Sri Lanka, but it also shows how transformative DT technology can be, even in developing nations, where it can move major advancements and growth, and innovation in sectors with little experience with digital technology (Buddika et al., 2022). Despite its potential, in Sri Lanka, the adoption of DTs in the construction industry lags behind more technologically advanced countries (Kudasinghe & Jeewananda, 2024).

2.3 ADVANTAGES OF DT

Amirthavarshan et al., (2023) research indicates that DT has a high potential to solve the numerous challenges in construction site progress monitoring, rather than other current technologies in use. The benefits of integrating DT into construction processes are significant (Omrany et al., 2025). According to the literature review findings, the advantages of the DT to the Sri Lankan construction industry are given in Table 1.

Table 1: Advantages of DT

Advantage	References
Enhance the design and planning	Hämäläinen (2021); Wang et al. (2025); Acampa & Pino, (2023); Melesse et al. (2021); Singh et al. (2021)
Improve industrial production efficiency	Jiao et al. (2025); Wang et al. (2025); Tuhaise (2023); Bandara et al. (2024)
Improving management efficiency	Jiao et al. (2025); Amirthavarshan et al. (2023)
Ensuring sustainable development	Jiao et al. (2025); Wang et al. (2025); Madubuike et al. (2022)
Risk management	Wang et al. (2025); Amirthavarshan et al. (2023); Acampa & Pino (2023); Melesse et al. (2021); Singh et al. (2021)
Enhanced safety	Wang et al. (2025); Amirthavarshan et al. (2023); Bandara et al. (2024); Haron & Zafir, (2025); Madubuike et al. (2022)
Cost reduction	Wang et al. (2025); Madubuike et al. (2022); Acampa & Pino (2023); Melesse et al. (2021); Singh et al. (2021)
Improve the quality of decision-making	Wang et al. (2025); Amirthavarshan et al. (2023); Nagalingam et al. (2013); Haron & Zafir (2025); Madubuike et al. (2022)
Improve performance	Tuhaise (2023)
Monitor energy consumption	Amirthavarshan et al. (2023); Madubuike et al. (2022)
Remote monitoring	Amirthavarshan et al. (2023); Madubuike et al. (2022); Attaran & Celik (2023); Acampa & Pino (2023); Melesse et al. (2021); Singh et al., (2021)
Quality assurance	Madubuike et al. (2022)

2.4 IMPACT OF DT ON KEY CONSTRUCTION INDUSTRY ISSUES

The construction industry is under growing pressure to adopt digital technologies but continues to face challenges such as system instability, technology integration difficulties, and data security concerns (Tuhaise, 2023). A major barrier to digital transformation is the disconnect between stakeholders' expectations and the perceived impact on project outcomes, with many decision-makers failing to recognize the benefits of digital tools on performance (Jiao et al., 2025). Despite these challenges, DT technology is increasingly valued not only for its technical capabilities but also for its contributions to project efficiency, predictive maintenance, cost-effectiveness, and sustainability (Geekiyanage et al., 2025)

2.4.1 Lack of Reliable and Real-Time Data

This issue can arise from outdated reporting systems, manual data collection, and insufficient technology, leading to delays in decision-making, poor communication among stakeholders, and challenges in identifying potential problems early (Nagalingam et al., 2013). The DT has emerged as a solution that can update a BIM model with real-time data to achieve cyber-physical integration (Tuhaise, 2023). With the help of this technology, real-time monitoring and analysis can help mitigate these problems by

providing accurate and timely details for informed decision-making and improved coordination (Jiao et al., 2025; Nagalingam et al., 2013; Tuhaise, 2023)

2.4.2 Inefficient Building Systems and Poor Design

It can result in high energy consumption and maintenance costs, which can be particularly challenging for low-income households and small businesses (Emmanuel, 2004). One potential solution is DT technology, which can facilitate early simulation and testing of design options, as well as enhance collaboration and communication among project stakeholders (Hämäläinen, 2021; Parvin, 2021). This contributes significantly to national sustainability goals and fosters a greener construction industry (Hämäläinen, 2021; Jiao et al., 2025)

2.4.3 Safety

Safety is an ongoing concern in Sri Lanka's construction industry, with accidents and injuries being all too common. The lack of proper safety measures and training for workers can put them at risk of injury or even death (Priyadarshani et al., 2013). DT technology enhances safety on construction sites by offering real-time hazard analysis and suggesting preventive measures (Attaran & Celik, 2023b; Wang et al., 2025). This not only improves worker safety but also boosts productivity and reduces costs linked to work-related injuries (Priyadarshani et al., 2013). Chathuranga et al., (2025) findings stated key technologies like BIM, virtual reality, augmented reality, geographic information systems, and serious games provide various construction safety applications. Combining AI with video cameras, mobile devices, and sensors, DT creates a robust safety net for the construction industry by enabling virtual site reconstruction to monitor progress and detect safety hazards or deviations from the plan (Attaran & Celik, 2023).

2.4.4 Cost

The cost of construction projects is crucial to manage across the project life cycle, as cost overruns, differences between actual and estimated costs, are a key indicator of project success (Wijekoon & Attanayake, 2012). Geekiyanage et al. (2025) findings show that DT is commonly used in the design and planning phase in Sri Lanka's construction industry, but has minimal usage in construction, operations, and none in the end-of-life phase. By adopting Whole Life Cycle Costing (WLCC) and Life Cycle Costing (LCC) approaches, DT allows professionals to simulate entire building lifecycles, from design to demolition (Boussabaine & Kirkham, 2004). This facilitates more accurate forecasting of construction and maintenance costs, helping to make more informed decisions that balance short-term budgets and long-term value (Boussabaine & Kirkham, 2004).

2.5 BARRIERS FOR DT

According to the research studies, identified four main categories of barriers have been which are Stakeholder-Oriented (Li et al., 2025; Opoku et al., 2023), Industry-Related (Bandara et al., 2023; Opoku et al., 2023), Construction-Enterprise-Related (Opoku et al., 2023), and Technology-Related Barriers (Bandara et al., 2023; Li et al., 2025; Opoku et al., 2023). According to the literature review findings, the barriers to the DT in the Sri Lankan construction industry are given in Table 2.

Table 2 : Barriers for DT

Barriers		References
Main Category	**Sub Category**	
Stakeholder-Oriented Barriers	Level of maturity and experience	Aragón et al. (2025); Amirthavarshan et al. (2023); Sacks et al. (2020); Bandara et al. (2023); Geekiyanage et al. (2025)
	Limited understanding of potential benefits	Bandara et al. (2023); Geekiyanage et al. (2025)
	Lack of organizational support	Amirthavarshan et al. (2023); Melesse et al. (2021); Bandara et al. (2023); Madubuike et al. (2022); Haron & Zafir (2025)
Industry-Related Barriers	Fragmented nature	Amirthavarshan et al. (2023); Bandara et al. (2023); Madubuike et al. (2022); Geekiyanageet al. (2025)
	Lack of standards	Wang et al. (2025); Aragón et al. (2025); Madubuike et al. (2022); Melesse et al., (2021)
	Variability of projects	Aragón et al. (2025)
Construction-Enterprise-Related Barriers	Financial barriers	Aragón et al. (2025); Amirthavarshan et al. (2023); Madubuike et al. (2022); Melesse et al. (2021); Bandara et al. (2023)
	Time constraints	Amirthavarshan et al. (2023)
	Limited infrastructure and organisational culture	Bandara et al. (2023)
	Organisational resistance to change	Geekiyanage et al. (2025)
Technology-Related Barriers	Data challenges	Wang et al. (2025); Tuhaise (2023); Madubuike et al. (2022); Aragón et al. (2025); Melesse et al. (2021)
	Model maintenance challenges	Wang et al. (2025)
	Privacy and security risks	Wang et al. (2025); Tuhaise (2023); Madubuike et al. (2022)
	Visualization limitations	Tuhaise (2023)
	Technological compatibility	Aragón et al. (2025); Bandara et al. (2023); Sacks et al. (2020)

2.5.1 Stakeholder-Oriented Barriers

Stakeholder-oriented barriers refer to challenges faced by individuals and groups in the construction industry, including a lack of knowledge and acceptance of DT, misconceptions, and differing opinions on its value and potential for projects (Sacks et al., 2020).

2.5.2 Industry-Related Barriers

Industry-related barriers are specific to the characteristics of the construction industry itself. These challenges include the complexity of construction projects, difficulties in integrating various trades and components, the static nature of building data, and challenges related to managing data and technology in a fragmented industry (Lu et al., 2020).

2.5.3 Construction-Enterprise-Related Barriers

Construction-related barriers include challenges such as funding issues, lack of government support, legal and ethical concerns, and difficulties in coordinating infrastructure spending for digital technology use (West & Blackburn, 2017). Implementing DT technology involves significant financial investment in hardware, software, and training, which can be a barrier, especially for smaller firms or projects with limited budgets (Aragón et al., 2025; Geekiyanage et al., 2025).

2.5.4 Technology-Related Barriers

Technology-related barriers in digital transformation involve challenges like systems integration, data security and scalability issues, hardware and software limitations, concerns about data quality and reliability, and the necessity for constant internet connectivity.(Marocco & Garofolo, 2021).

3. METHODOLOGY

This study adopts a qualitative research method to identify and explore the barriers and potential solutions for implementing DT in the construction industry. Data collection integrates a systematic literature review and semi-structured interviews. Seven industry professionals were interviewed, and the interviews were semi-structured and open-ended to allow participants to provide detailed perspectives and insights. Thematic analysis was used to analyse the qualitative data.

3.1 QUALITATIVE DATA ANALYSIS

Qualitative research is a method that explores human experiences and social phenomena in depth using non-numerical data like interviews and texts, and it focuses on understanding meanings and context, providing detailed insights rather than numerical analysis (Christou, 2022). Thematic analysis is a flexible and accessible method that helps researchers identify, explore, and interpret patterns or themes within rich qualitative data, providing deep insights into participants' perspectives and social phenomena (Christou, 2022; Clarke & Braun, 2017).

3.2 EXPERTISE CORE DATA ANALYSIS

Table 3 represents the demographic data analysis of the interview.

Table 3 : Expertise core data analysis

Organization firm	Profession	No. of Interviewers	Years of experience
Construction Contracting firm	Project manager (R1, R2)	2	10-15 years
	Senior Engineer (R3)	1	10-15 years

Organization firm	Profession	No. of Interviewers	Years of experience
Construction Consultant firm	Architect (R4)	1	15-20 years
	Quantity Surveyor (R5)	1	15-20 years
	Engineer (R6, R7)	2	15-20 years

4. RESULTS AND DISCUSSION

4.1 CURRENT APPLICABILITY OF DT TECHNOLOGY AMONG THE SRI LANKAN CONSTRUCTION INDUSTRY PROFESSIONALS

Despite advancements, out of 7 interviewees, 4 experts mentioned that construction projects still rely on manual methods, primarily due to limited software experience and resistance to change stemming from traditional practices, while 3 experts indicated that projects utilized automated tools. Table 4 illustrates the current applicability of different digital technologies among Sri Lankan construction industry professionals, according to the interviewers' responses.

Table 4: Current applicability of digital technologies

Digital technologies	Awareness	Practical implementation
Digital Twin	1	1
Photogrammetry	2	1
BIM	2	3
LiDAR	2	1

Among the technologies, BIM showed the highest level of practical implementation, with 3 out of 7 participants confirming its use, while 2 participants indicated awareness of it. Photogrammetry and LiDAR were each mentioned by 2 participants in terms of awareness, but only 1 participant acknowledged actual implementation in practice for each. Digital Twin technology had the lowest overall recognition, with only 1 participant mentioning awareness and 1 noting practical use, indicating it is still relatively new or unfamiliar in the Sri Lankan context.

4.2 ADVANTAGES AND BARRIERS OF DT

Tables 5 and 6 represent a detailed overview of the barriers and advantages associated with the implementation of DT technology in the construction industry, incorporating insights from both the literature review and the interview findings

Table 5: Advantages of DT

	Advantages	Literature Review	Interviewers						
			R1	R2	R3	R4	R5	R6	R7
1	Enhance the design and planning	✓	✓	✓	✓	✓	✓		
2	Improve industrial production efficiency	✓			✓		✓	✓	✓
3	Improving management efficiency	✓	✓	✓			✓		

	Advantages	Literature Review	Interviewers						
			R1	R2	R3	R4	R5	R6	R7
4	Ensuring sustainable development	✓		✓					
5	Enhanced safety	✓						✓	
6	Cost reduction	✓			✓		✓	✓	✓
7	Improve the quality of decision-making	✓			✓		✓		
8	Improve performance	✓	✓	✓	✓			✓	✓
9	Monitor energy consumption	✓						✓	✓
10	Remote monitoring	✓	✓	✓		✓	✓	✓	✓

The analysis identified twelve advantages of DT implementation. Enhancing design and planning was widely supported, while improving performance and remote monitoring received unanimous backing from all seven interviewees. Other commonly cited benefits included improved management efficiency, cost reduction, and better decision-making quality, highlighting DT's practical value in project execution. Some advantages, like enhanced industrial production efficiency and energy monitoring, were recognized by the literature and certain respondents.

Table 6:Barriers for DT technology

	Barriers	Literature Review	Interviewers						
			R1	R2	R3	R4	R5	R6	R7
1	Limited Awareness & Understanding	✓	✓	✓	✓				✓
2	Lack of Skilled Workforce	✓	✓	✓	✓	✓	✓		✓
3	Low Adoption in Small Projects	✓		✓	✓				✓
4	Technical Complexity	✓						✓	✓
5	Lack of Tools for Maintenance Phase	✓	✓	✓	✓				✓
6	Financial barriers	✓			✓		✓	✓	

A total of 15 barriers were identified through the literature review. Notably, 6 of these barriers, as shown in Table 6, were also highlighted by experts during the data collection process, indicating alignment between the literature and professional insights. The most significant barrier is limited awareness, noted by four interviewees. Nearly all sources acknowledged a lack of skilled workforce, indicating a skills gap. Low adoption in small-scale projects was mentioned by three interviewees, suggesting resource constraints for smaller firms. Technical complexity was discussed by only two interviewees. Additionally, four noted the need for better tools for the maintenance phase, while three highlighted financial barriers and cost concerns related to advanced technologies.

4.3 PRACTICAL STEPS TO FACILITATE THE IMPLEMENTATION OF DT TECHNOLOGY IN SRI LANKAN CONSTRUCTION INDUSTRY

The Table 7 outlines the proposed practical steps to overcome the barriers of digital technology, according to the interviewees.

Table 7: Proposed practical steps

	Proposed Practical Steps	Interviewers						
		R1	R2	R3	R4	R5	R6	R7
1	Awareness Campaigns	✓		✓	✓	✓		
2	Standardized Framework		✓			✓		
3	Training Programs			✓	✓	✓		
4	Pilot Projects						✓	✓
5	Regulatory Support		✓			✓		
6	Collaboration			✓				✓
7	Education and Curriculum Development				✓	✓		
8	User-Friendly Platforms	✓					✓	✓

The key recommendations included awareness campaigns to improve understanding of DT, as supported by four interviewees. Training programs and curriculum development for capacity building were emphasized by three others. R6 and R7 suggested pilot projects, while R2 and R5 called for standardized frameworks and regulatory support. R3 and R7 highlighted the importance of collaboration among stakeholders, and R1, R6, and R7 stressed the need for user-friendly platforms to enhance adoption.

Figure 1 illustrates the suggested practical steps that can be taken to overcome common barriers associated with implementing DT technology in Sri Lankan construction projects.

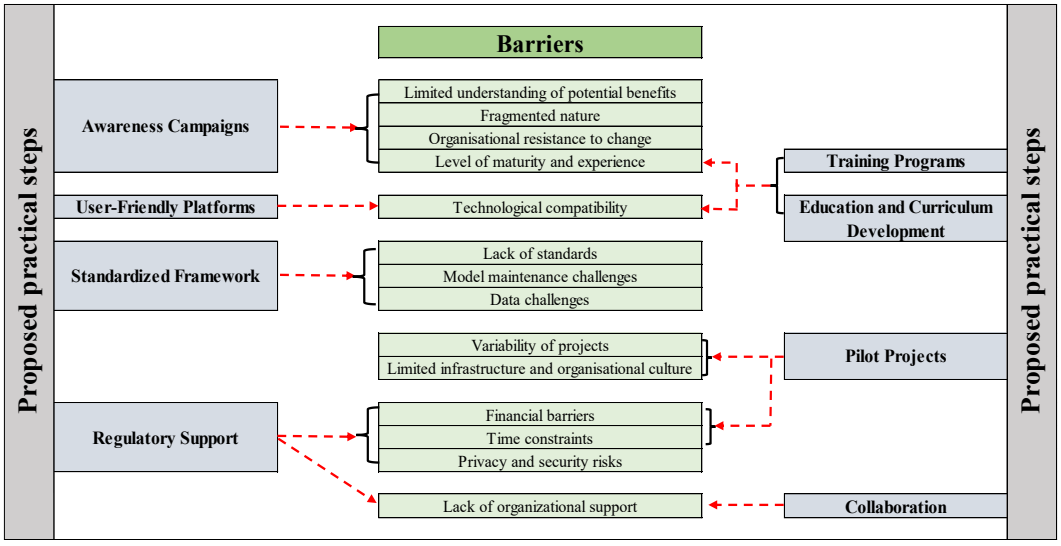


Figure 1 - Proposed practical applications to overcome the barriers of DT technology

Incorporating DT technologies into academic curricula equips future professionals with essential skills. This strategy promotes a culture that supports digital initiatives. A standardized framework enhances data sharing, model development, and integration, reducing fragmentation and improving interoperability, which is vital for effective DT applications. Creating user-friendly platforms encourages adoption, ensuring stakeholders engage with systems for smoother implementation and better data management. Pilot projects serve as test environments for DT solutions, helping identify issues, validate benefits, and build stakeholder confidence. Successful pilots demonstrate

viability and encourage broader investment. Government regulations can establish industry standards, provide financial incentives, and enforce security measures, lowering risks and costs while supporting digital innovation. Collaboration across government, academia, and industry fosters knowledge sharing, drives innovation, and establishes essential support systems for successful DT implementation.

5. CONCLUSIONS

This study assessed the applicability of DT technology in Sri Lankan construction projects by examining its current usage, potential benefits, and implementation barriers. It's important to recognize limitations in the research, as technology's dynamic nature may affect the generalizability of the findings. The research findings confirm that while DT remains an emerging concept in Sri Lanka, it holds considerable promise in addressing industry specific barriers, such as improving design accuracy, monitoring performance, enhancing safety, and managing LCC. Despite growing interest, the uptake of DT is hindered by limited stakeholder awareness, insufficient technical expertise, cost constraints, and lack of regulatory support. Addressing these barriers requires a multi-pronged approach, including targeted awareness programs, integration of DT concepts into academic and professional training, pilot implementations to demonstrate value, and the development of supportive policies and standardized frameworks. With proper strategic direction, Sri Lanka's construction industry can harness DT technology not only to modernize its practices but also to contribute to a more sustainable and digitally integrated future. Therefore, future research should incorporate stakeholder input to define the scope and functionalities of DT systems that best serve the practical needs of the industry.

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BARRIERS FOR TIME, COST, AND QUALITY MANAGEMENT IN POLYMER MODIFIED ASPHALT ROAD CONSTRUCTION IN SRI LANKA

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ABSTRACT

Polymer Modified Asphalt (PMA) offers improved durability, reduced maintenance, and helps mitigate plastic waste, making it a sustainable alternative to conventional asphalt in road construction. The successful implementation of PMA in road construction depends on effective time, cost, and quality management. This study explores the unique challenges faced in PMA road projects in Sri Lanka by identifying specific barriers and proposing tailored strategies to improve project outcomes. Using a qualitative research approach, data were collected through expert interviews supported by a comprehensive literature review. This study is based on 12 semi-structured interviews with industry experts whose experience ranged from 4 to 15 years in road construction, including PMA applications. The findings highlight common barriers such as scheduling inefficiencies, supply chain disruptions, high material costs, and limited availability of skilled personnel. PMA-specific challenges, including temperature sensitivity, complex quality testing, and variability in material standards, were also identified. To address these, the study presents a matrix of 34 barriers and 15 strategies, including advanced planning, real-time tracking, value engineering, standardized protocols, and capacity-building programs. These strategies directly enhance project performance across all three dimensions of the Iron Triangle: time, cost, and quality. The research provides actionable insights for industry practitioners and policymakers to support the broader adoption of PMA, particularly in high-traffic and climate-sensitive regions.

Keywords: *Polymer Modified Asphalt; Project Management; Road Construction; Sustainable Infrastructure; Time-Cost-Quality.*

1. INTRODUCTION

Road infrastructure is crucial for socio-economic development, enabling access to markets, resources, and services. In the UK, road transport accounted for 91% of passenger travel and 67% of goods transport in 2008 (Gibbons et al., 2019), highlighting the global reliance on road networks. However, increasing traffic loads, climate

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variability, and the environmental impact of traditional materials like asphalt pose significant challenges (Segui et al., 2023). Sustainable alternatives, such as recycled materials, are emerging as cost-effective, eco-friendly solutions. One such innovation is Polymer Modified Asphalt (PMA), which incorporates polymers, often from plastic waste, to enhance pavement durability, flexibility, and resistance to distress (Polacco et al., 2015). PMA contributes to longer road life, reduced maintenance, and plastic waste reduction (Nawela & Samaranayake, 2024). Despite its benefits, successful PMA adoption requires effective time, cost, and quality management (Walker & Kumar, 2005). This study investigates PMA implementation in Sri Lanka, identifies key barriers, and proposes strategic solutions to support the country's transition toward more sustainable and resilient road infrastructure.

2. LITERATURE REVIEW

2.1 GENERIC APPLICATIONS OF ASPHALT

Asphalt is a widely used paving material, with over 90% of European pavements utilising bituminous mixtures due to their smooth surface and rapid construction (Kowalski et al., 2016). These mixtures, composed of aggregates and bitumen, are produced via Hot Mix Asphalt (HMA), Warm Mix, and Cold Mix methods, differing by temperature requirements (Liu et al., 2017). Despite their advantages, asphalt pavements face challenges such as environmental degradation and high greenhouse gas emissions, with global asphalt production emitting approximately 46.08 million tons of CO_2 in 2007 (Shamoon et al., 2022). To improve sustainability and performance, the industry is adopting recycled aggregates and polymers. Polymers, both synthetic and natural, enhance asphalt properties but pose compatibility challenges (Alghrafy et al., 2021). The use of recycled plastics in asphalt offers a dual benefit: addressing plastic waste issues and improving pavement durability (Costa et al., 2019).

2.2 POLYMER MODIFIED ASPHALT

Plastic waste poses significant environmental challenges due to improper disposal, prompting interest in recycling plastics for asphalt modification (Dwivedi et al., 2019). Recycled polymers enhance asphalt's flexibility, durability, and mechanical properties, contributing to improved pavement performance (García-Morales et al., 2004; Behnood & Modiri Gharehveran, 2019). Various polymer types, including thermoplastic elastomers and plastomers, offer distinct benefits. Incorporation methods include dry and wet mixing, with the wet method promoting better chemical bonding (Chavez et al., 2019). This sustainable approach reduces emissions, diverts waste from landfills, and proves more cost-effective than conventional bitumen, supporting environmentally friendly road construction (Magar et al., 2022; Moughari & Daim, 2023).

2.3 POLYMER MODIFIED ASPHALT APPLICATION IN SRI LANKAN ROADS

In recent years, Sri Lanka has escalated its efforts to incorporate recycled plastic into asphalt for road construction. The Asset Group of Companies pioneered this approach, using shredded waste plastics in asphalt mixes to pave a 500 m pilot road from Ratmalana to Borupana (AGC innovate, 2021). Building on that early success, a government-backed initiative launched in late 2020 began converting the growing plastic waste stream into a raw material for roads (Kodithuwakku et al., 2023). This led to the first public road

section paved with plastic-modified asphalt (Meegoda–Dampe Road, Homagama) in November 2020. The private sector also joined in 2021, Cargills partnered with AGC Innovate to resurface a Food City supermarket car park with Plastic Modified Asphalt Concrete (PMAC), consuming approximately 200,000 waste plastic bags (AGC Innovate, 2021). By 2022, the Western Province Road Development Authority signed agreements to use PMAC for provincial highways, supported by policies like compulsory plastic recycling and a forthcoming ban on single-use plastics (AGC Innovate, 2021). Recent research affirms the suitability of PMAC under local conditions, highlighting improvements in pavement strength and longevity as well as reductions in landfill waste and reliance on virgin materials (Kodithuwakku et al., 2023; Nawela & Samaranayake, 2024).

2.4 IRON TRIANGLE OF PROJECT MANAGEMENT

Project success in construction is often measured using the 'Iron Triangle' framework—balancing time, cost, and quality (Walker & Kumar, 2005). In Sri Lanka and similar developing countries, time overruns in road projects are common, making effective scheduling and monitoring essential (Mohammed, 2023). Cost management enhances resource use, minimises design changes, and reduces risks (Khan & Chan, 2023). Quality management ensures infrastructure durability, safety, and performance, reducing future maintenance needs (Kim et al., 2012). Integrating these three elements supports sustainable, resilient, and efficient road construction outcomes that align with stakeholder expectations (Wandiri & James, 2020).

2.5 TIME, COST, AND QUALITY MANAGEMENT BARRIERS IN ROAD CONSTRUCTION

Since PMA road construction is a relatively new concept, specific studies on its time, cost, and quality management challenges are limited. Hence, this study refers to barriers identified in conventional road construction projects to inform PMA applications. Literature highlights delays in material delivery, poor site management, incomplete designs, and financial constraints as common challenges (Arulvel & Widisinghe, 2022; Abeysinghe & Jayathilaka, 2022; Elamah, 2011; Khan & Chan, 2023). Ineffective stakeholder coordination, resistance to new technologies, and lack of training further affect project performance (Kim et al., 2012; El-Maaty et al., 2018). These barriers, although derived from regular road projects, provide a critical foundation to anticipate and address similar risks in PMA road construction. A detailed summary of the identified barriers and their impacts is presented in Table 1.

2.6 STRATEGIES FOR MITIGATING BARRIERS

To overcome time, cost, and quality-related barriers in road construction, existing literature on conventional road projects offers several strategies. Time-related solutions include efficient planning, risk management, and technologies like Integrated Project Delivery (IPD) and real-time tracking to minimize delays. Weather adaptation and streamlined permitting also support timely delivery (Lashof & Neuberger, 2023). Cost challenges are addressed through resource optimization, Life Cycle Costing (LCC), and lean construction to enhance value (Santos et al., 2017). Quality barriers are mitigated through assurance protocols, stakeholder engagement, and supplier agreements. These strategies, while not specific to PMA roads, provide relevant insights.

Table 1: Barriers influencing time, cost and quality management of road construction

Barriers	Impact			Sources												
	Time	Cost	Quality	A	B	C	D	F	G	H	I	J	L	M	N	P
Delay in delivery	✓	✓		✓		✓	✓	✓					✓		✓	✓
Shortage or unavailability	✓	✓		✓												✓
Construction mistakes	✓	✓	✓	✓		✓		✓								✓
Poor site management	✓	✓	✓	✓		✓		✓							✓	✓
Poor-quality design documents	✓	✓	✓			✓	✓	✓		✓					✓	
Delayed decision-making	✓			✓		✓		✓							✓	
Slowness in approvals	✓			✓		✓		✓								✓
Stakeholder coordination and communication	✓	✓	✓								✓	✓				
Insufficient project information	✓	✓	✓		✓		✓						✓	✓		
Financial issues	✓	✓		✓		✓									✓	✓
Unrealistic contract durations	✓	✓					✓						✓	✓		
Inadequate time for estimation and planning	✓	✓					✓			✓			✓	✓		
Lack of experience	✓	✓	✓	✓		✓	✓	✓		✓			✓	✓		
Resistance to new technologies			✓						✓		✓					
Inadequate training			✓						✓		✓					
Lack of standardisation			✓						✓		✓					
Limited resources	✓	✓	✓						✓		✓	✓				
Ineffective quality control			✓						✓		✓					
Non-compliance			✓						✓		✓	✓				
Poor integration			✓						✓		✓	✓				
Price escalation of materials		✓			✓		✓			✓			✓	✓		
Frequent design changes	✓	✓			✓		✓			✓			✓	✓		

Barriers	Impact			Sources											
	Time	Cost	Quality	A	B	C	D	F	G	H	I	J	L	M	N	P
Poor direction of labour	✓	✓					✓			✓			✓	✓		
Poor site selection	✓	✓	✓		✓		✓						✓	✓		
Adverse weather	✓	✓		✓		✓		✓								✓

A - Abeysinghe & Jayathilaka (2022); B - Albtoush et al. (2020); C - Arulvel & Widisinghe (2022); D - Charoenngam & Sriprasert (2001); E - Elamah (2011); F - El-Maaty et al. (2018); G - Khan & Chan (2023); H - Kim et al. (2012); I - Karunasena et al. (2018); J - Koushki et al. (2005); K - Mahamid et al. (2012); L - Naveenkumar (2007); M - Negesa (2022); N - Olawale & Sun (2010)

3. RESEARCH METHODOLOGY

This study adopted a qualitative research approach to explore the barriers and strategies related to time, cost, and quality management in PMA road construction in Sri Lanka. Given the novelty of PMA technology in the country and the limited availability of experienced professionals, the qualitative approach was appropriate for capturing rich, contextual insights (Bryman et al., 2008; Ruffa & Evangelista, 2021). Semi-structured interviews were selected as the data collection method to allow flexibility in exploring emerging themes while maintaining focus on core research areas (Baxter & Jack, 2008). Respondents were selected using a convenience sampling with snowballing technique, targeting professionals with hands-on PMA experience. The final sample included 12 experts from consultancy and contracting sectors, each with over five years of general construction experience, road construction exposure, and at least one year of involvement in PMA projects. Details of the selected respondents are listed in Table 2 below.

Table 2: Profile of respondents

Respondent Code	Designation	Working Sector	Experience in Construction	Experience in Road Construction	Experience in PMA Road Construction
R1	Executive Engineer	Consultant	10	8	3
R2	Material Engineer	Consultant	8	5	1
R3	Project Manager	Contractor	12	10	5
R4	Planning Engineer	Contractor	7	6	2
R5	Executive Engineer	Consultant	6	4	2
R6	Project Manager	Contractor	8	6	2
R7	Engineer	Consultant	5	4	1

Respondent Code	Designation	Working Sector	Experience in Construction	Experience in Road Construction	Experience in PMA Road Construction
R8	Material Engineer	Contractor	9	7	3
R9	Material Engineer	Consultant	10	8	3
R10	Quantity Surveyor	Contractor	6	4	2
R11	Project Manager	Contractor	10	8	3
R12	Material Engineer	Consultant	15	12	1

Following this selection criterion ensured respondents were well-positioned to reflect on time, cost, and quality challenges in both traditional and PMA road projects. Interview data were manually analysed using manual content analysis to identify recurring patterns, themes, and strategies. This approach enabled the interpretation of varied perspectives, forming the basis for the effective implementation of PMA road projects in Sri Lanka.

4. RESULTS AND DATA ANALYSIS

This section presents findings on the use of conventional asphalt and its drawbacks, followed by the benefits of PMA. It also discusses PMA's implications on time, cost, and quality, and outlines key barriers and practical strategies identified through expert interviews to enhance implementation in Sri Lanka.

4.1 USE OF REGULAR ASPHALT CONCRETE IN SRI LANKA

4.1.1 Types and Usage Levels of Asphalt Concrete Mixes

In Sri Lanka, hot mix asphalt using 60/70 penetration grade bitumen is the predominant choice for road construction, valued for its durability and suitability for both binder and wearing courses. Industry professionals, including R1 and R5, affirm its widespread application. While hot mix asphalt remains the standard, gap-graded mixes are used for specific needs, and higher penetration grades like 80/100 are employed for applications such as bitumen emulsion production (R2). Cold mix asphalt, though less common, is essential for maintenance tasks like pothole patching, with R3 noting its practical use with CSS01 bitumen emulsion. This mix of diversity highlights the industry's flexible, performance-driven approach to material selection, optimizing durability, cost, and maintenance efficiency across Sri Lanka's road network.

4.1.2 Drawbacks of Regular Asphalt Concrete

Understanding the limitations of conventional asphalt is essential to justify the need for alternative solutions such as Polymer Modified Asphalt (PMA). These insights help frame the performance gaps that PMA technology may potentially address. Figure 1 illustrates the severity levels of selected drawbacks of conventional asphalt based on expert responses.

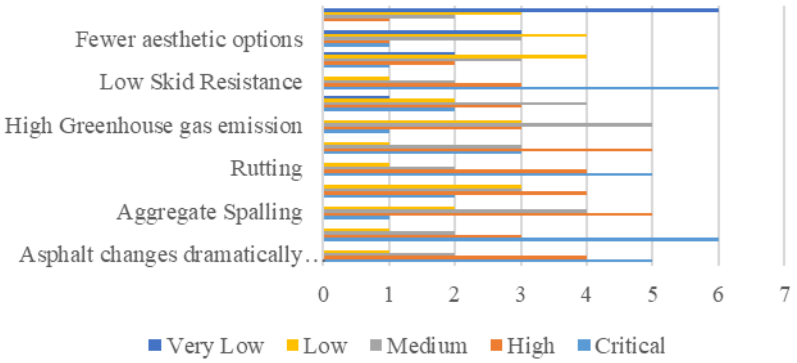


Figure 1: Impact level of drawbacks of asphalt

As shown in Figure 2, several issues are consistently rated as high or critical. "Rutting" and "Aggregate Spalling" were rated as significant challenges by multiple experts, linked to repetitive traffic loads and inadequate aggregate bonding. "High greenhouse gas emissions" and "Low skid resistance" also received medium to high concern, reflecting environmental and safety drawbacks. "Asphalt changes dramatically with temperature" emerged as a critical issue, particularly under Sri Lanka's tropical climate. Although "Fewer aesthetic options" was not widely seen as critical, the collective insights emphasize the need for enhanced materials like PMA that can overcome these performance limitations.

4.1.3 Solutions Adopted to Overcome Drawbacks of Regular Asphalt Concrete

This aimed to identify the current solutions adopted in Sri Lanka to overcome the performance limitations of conventional asphalt, as discussed in the previous section. Understanding these solutions is crucial to assess the extent to which Polymer Modified Asphalt (PMA) has been integrated into the local construction practices and to evaluate its perceived benefits relative to other alternatives. Figure 2 illustrates the various technologies currently used in Sri Lanka to address the common drawbacks of traditional asphalt, as per the respondents.

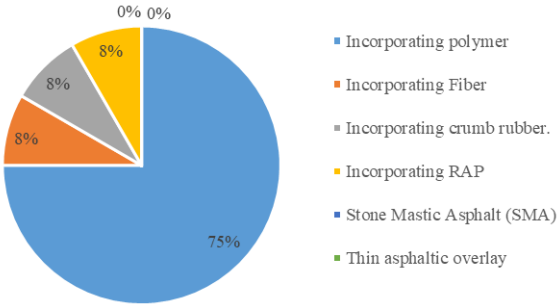


Figure 2: Solutions used in Sri Lankan context to avoid the drawbacks

As shown in Figure 3, 75% of respondents identified polymer incorporation as the primary solution adopted to enhance asphalt performance. This overwhelming preference underscores PMA's dominance in addressing issues like rutting, cracking, and aging. Other methods such as incorporating fiber, crumb rubber, and Reclaimed Asphalt Pavement (RAP) were each cited by 8% of the respondents, while Stone Mastic Asphalt (SMA) and Thin asphaltic overlays were not identified by any respondents. This trend highlights the Sri Lankan industry's strong reliance on polymer modification as the preferred performance-enhancing strategy.

4.2 USE OF POLYMER-MODIFIED ASPHALT

4.2.1 Benefits of Polymer Modified Asphalt (PMA) Usage

PMA offers significant advantages over conventional asphalt in enhancing road durability, performance, and lifespan. Traditional asphalt often suffers from rutting and fatigue cracking, particularly under heavy traffic and tropical climates. R3 highlights this, stating, "When using the penetration bitumen, several issues have occurred such as rutting and fatigue cracking," emphasizing the need for more resilient alternatives. PMA, classified under performance-grade (PG) bitumen, addresses these issues effectively. Grades such as PG 70-10 and PG 76-10, commonly used in Sri Lanka, provide superior resistance to temperature variations and mechanical stress. R9 notes that PMA requires careful temperature management during mixing, typically at 170–180°C. Despite its higher initial cost, PMA offers long-term value due to reduced maintenance and longer service life. As R11 states, "Polymer-based roads exhibit an extended estimated lifetime compared to conventional 60/70 bitumen-based roads," making PMA a reliable solution for sustainable and high-performance road infrastructure in Sri Lanka.

4.2.2 Polymer Types used for Asphalt Modification

This section examines the types of polymers used in PMA production in Sri Lanka, providing critical context to the material selection process and its implications for road performance and sustainability. Understanding the choice between virgin and recycled polymers is essential for evaluating the practical and environmental trade-offs involved in PMA usage. Figure 3 presents the proportion of virgin and recycled polymers used for asphalt modification.

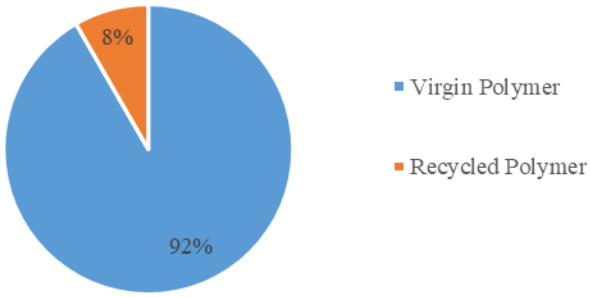


Figure 3: Polymer types used for polymer modification of asphalts in Sri Lanka

As shown in Figure 4, 92% of respondents indicated the use of virgin polymers, while only 8% reported using recycled polymers. Virgin polymers, particularly elastomers, are favoured for their consistency, flexibility, and superior performance in resisting fatigue and rutting under traffic and environmental stress. R1 highlighted that virgin polymers are preferred due to concerns over contamination in recycled materials, which affects quality and processing. However, PMA manufacturers have adopted an alternative by sourcing polymer waste directly from other manufacturers of polymer-based products. This allows access to high-quality polymer scrap free from contaminants, enabling environmental benefits by reducing landfill waste while maintaining performance standards.

4.3 BARRIERS FOR TIME, COST, AND QUALITY MANAGEMENT IN SRI LANKAN PMA ROAD CONSTRUCTION

The findings identified several unique barriers to PMA projects in Sri Lanka that arise due to the unique physical properties, handling sensitivities, and process requirements of PMA. As highlighted by respondents R1, R3, R5, R6, R8, R9, R10, and R11, the high initial cost of performance-grade bitumen and polymer additives, along with frequent price volatility, poses a major cost management barrier. Supply chain disruptions, including unreliable access to imported materials and delays in local production, often intensify these cost issues. R5 and R10 noted the temperature sensitivity of PMA during mixing and laying, which requires tight construction scheduling and coordinated material delivery to avoid cooling delays that can compromise pavement quality. In terms of quality management, R3, R6, and R9 pointed to complex and non-standardised testing protocols, as well as a shortage of trained personnel familiar with PMA technology, which negatively affects execution. Moreover, variability in testing methods and the absence of nationally standardised PMA guidelines further complicate quality assurance. The new barriers are presented in bold in Table 3 below.

4.4 STRATEGIES EMPLOYED TO OVERCOME BARRIERS IN SRI LANKAN PMA ROAD CONSTRUCTION

Key strategies include advanced planning and scheduling techniques, such as Gantt charts and critical path methods, emphasised by R6 and R10, which help anticipate potential delays and ensure timely project delivery. The integration of project management software and GPS tracking systems, highlighted by R3 and R5, enables real-time monitoring of site progress and allows for prompt decision-making to prevent schedule overruns.

Table 3: Strategies to overcome time, cost, and quality management barriers PMA road construction

Barriers	Impact			Strategy													
	Time	Cost	Quality	S1	S2	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Delay in delivery	✓	✓		✓	✓	✓											✓	
Shortage or unavailability	✓	✓					✓										✓	
Construction mistakes	✓	✓	✓								✓			✓	✓			
Poor site management	✓	✓	✓								✓		✓					
Poor-quality design documents	✓	✓	✓	✓												✓		
Delayed decision-making	✓			✓								✓						✓
Slowness in approvals	✓			✓								✓						✓
Stakeholder coordination and communication	✓	✓	✓									✓						✓
Insufficient project information	✓	✓	✓				✓			✓								
Financial issues	✓	✓					✓			✓								
Unrealistic contract durations	✓	✓		✓		✓	✓											

Barriers	Impact			Strategy														
	Time	Cost	Quality	S1	S2	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
Inadequate time for estimation and planning	✓	✓		✓			✓											
Lack of experience	✓	✓	✓									✓			✓			
Resistance to new technologies			✓										✓		✓			
Inadequate training			✓												✓			
Lack of standardisation			✓													✓		
Limited resources	✓	✓	✓						✓						✓			
Ineffective quality control			✓								✓			✓				
Non-compliance			✓								✓					✓		
Poor integration			✓									✓	✓					
Price escalation of materials		✓					✓										✓	
Frequent design changes	✓	✓				✓		✓										
Poor direction of labour	✓	✓							✓			✓						
Poor site selection	✓	✓	✓	✓				✓										
Adverse weather	✓	✓				✓												
High cost PMAC materials	✓	✓					✓	✓		✓								
Price volatility of materials		✓					✓										✓	
Supply chain disruptions affecting PMAC materials	✓	✓		✓	✓												✓	
Temperature sensitivity during handling and laying	✓		✓	✓	✓												✓	
Material procurement delays	✓	✓		✓								✓						✓
Regulatory compliance in sensitive areas	✓										✓					✓		
Complexity in quality assurance and testing for PMAC			✓												✓			
Lack of trained personnel for PMAC technology			✓													✓		
Variability in PMAC quality standards and testing protocols			✓															

S1 – Advanced planning and scheduling
S2 – Use of project management software
S3 – Effective risk management
S4 – Accurate budgeting and forecasting
S5 – Value engineering
S6 – Collaborative contracting and strong partnerships
S9 – Align quality expectations
S10 – Process refinement and issue resolution
S11 – Regular inspections and audits to ensure compliance
S12 – Training programs and capacity-building

S7 – Continuous financial planning and regular budget reviews	S13 – Standardization of quality protocols and testing
S8 – Quality assurance and control systems	S14 – Diversification of supply sources
	S15 – Improved communication and coordination

Collaborative contracting and improved communication among contractors, consultants, and suppliers, as recommended by R8, R11, and R12, were seen as essential for achieving cost efficiencies and minimising procurement delays. Additionally, targeted training programs and capacity-building initiatives were advocated by R2, R6, and R9 to address the skill gaps in handling PMAC technologies. The need for standardised testing procedures and clearly defined quality protocols was also stressed to ensure consistent performance and regulatory compliance across projects. The strategies are mapped against the identified barriers in Table 3.

5. CONCLUSION AND RECOMMENDATIONS

Effective time, cost, and quality management is vital for the successful implementation of Polymer Modified Asphalt (PMA) in road construction, particularly in the Sri Lankan context. This study identifies the key barriers hindering PMA integration, such as temperature sensitivity during application, high material costs, supply chain disruptions, and complexities in quality assurance and presents targeted strategies to address them. The research confirms PMA's superior performance in terms of durability, flexibility, and resistance to environmental stresses, making it an optimal choice for high-traffic and climate-challenged regions in Sri Lanka.

A matrix linking 34 identified barriers to 15 practical strategies provides a comprehensive decision-support tool for practitioners and policymakers. Implications of this study include improved planning, procurement, training, and regulatory coordination, all of which can accelerate the safe and efficient adoption of PMA. However, the study is limited by its qualitative scope, reliance on a relatively small group of experts, and the current lack of long-term performance data on PMA roads in Sri Lanka. Future research should include quantitative validation, field performance monitoring, and integration of emerging technologies. Overall, this study provides critical insights for enhancing the sustainability and cost-effectiveness of Sri Lanka’s road infrastructure through optimised PMA application.

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BARRIERS TO ADOPTING DIGITAL TWIN TECHNOLOGY FOR CONTRACT ADMINISTRATION IN SRI LANKAN CONSTRUCTION SECTOR

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ABSTRACT

The construction industry in Sri Lanka faces growing pressure to improve sustainability, efficiency, and transparency across project lifecycles. Digital Twin Technologies (DTT) offer real-time, data-driven digital representations of construction processes, opening an avenue for enhancing contract administration practices and supporting sustainable construction. However, the implementation of DTT remains limited within the Sri Lankan context. This study investigates the organisational and technological barriers hindering the adoption of DTT for contract administration in Sri Lanka's construction sector. A qualitative research design was employed, incorporating a thematic analysis of semi-structured in-depth interviews with industry professionals. The findings reveal that key organisational barriers include resistance from organisational culture, generational divide, and skills shortages. The key technological challenges encompass cybersecurity risks, interoperability issues, infrastructure gaps, and data quality issues. Despite these constraints, the study identifies actionable insights to support DTT adoption, including variation management programs and pilot projects, Mentorship programs and hybrid workflows, university partnerships, and provides certification incentives, robust data encryption, and localized cybersecurity protocols. The paper contributes to the body of knowledge on digital innovation in contract administration and offers practical recommendations for policymakers, practitioners, and researchers seeking to foster digital transformation in emerging construction markets.

Keywords: *Barriers; Contract Administration; Digital Twin Technology; DTT; Construction Industry; Sustainable Development.*

1. INTRODUCTION

Digital Twin Technology (DTT) is an emerging innovation for developing real-time virtual models of physical systems beyond the current state of the art (Grieves & Vickers, 2016). On the other hand, Contract Administration (CA) refers to the administrative functions related to dealing with contracts including issuing instructions, managing change procedures, dealing with completion and possession issues, resolving disputes, assessing entitlement for extension of time, advising all parties of their contractual rights

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and obligations, dealing with payment provisions, implementing contract, contract monitoring and quality assurance (QA), and contract interpretation (Davison & McCue, 2022). Nowadays, DTT is enabled in CA processes, such as compliance tracking and dispute resolution in sustainable projects. For example, DTT is used in Singaporean smart cities (Ai & Ziehl, 2024) and BIM based infrastructure monitoring in the United Kingdom (Li et al., 2019). CA in Sri Lanka remains predominantly manual, relying on paper-based documentation (Dunleavy et al., 2005), fragmented stakeholder communication via emails/ad-hoc meetings (World Bank, 2020), and reactive dispute management with 40% of projects delayed by contractual ambiguities (Hewage & Ruwanpura, 2021). BIM adoption is limited to <15% of design phases, hindering digital integration.

DTT have been repeatedly mentioned in the literature of asset management in the modern era as a conceptual enhancement (Grieves & Vickers, 2016). Using this developing body of knowledge, the current study offers empirical data on the operational integration of DTT into CA, thus re-engineering the two paradigms into a synchronised, data-driven compliance tracking and dispute resolution system. The practice of this real-time, data-driven transformation can be seen in two contexts: Singapore smart-city development and large-scale infrastructure projects in the United Kingdom (GovTech Singapore, 2022). Nevertheless, Sri Lanka's construction industry has been mostly limited to manual CA practices, fragmented stakeholder collaboration, and the lack of digital literacy (Dunleavy et al., 2005). Apart from the studies on DTT in design automation (Sobhkhiz et al., 2021) and CA with AI (Bolhassan et al., 2021), there are no previous studies regarding the DTT and CA integration in Sri Lanka. Naji et al (2024) highlighted that there are digitalization hindrances in Sri Lanka in addressing the construction issues. Thus, this study aims to identify the barriers to implementing DTT for CA processes in Sri Lanka and develop ways to overcome them.

2. LITERATURE REVIEW

2.1 WHAT IS DIGITAL TWIN TECHNOLOGY?

DTT involves creating a virtual implementation of a physical system, process, or asset that synchronises in real-time with data from sensors, Internet of Things (IoT) devices, and analytic platforms (Saad et al., 2025). By mirroring the physical entity's behaviour and lifecycle, it enables predictive modelling, simulation, and decision-making based on the entity's characteristics (Tao et al., 2018). DTT is an emerging field in the construction industry, aiming to provide solutions and improvements in various aspects of construction projects (Akanmu et al, 2019). Furthermore, DTT supports the construction industry's advancement toward the 5th industrial revolution and presents new opportunities to enhance the performance of construction projects throughout their entire life cycle (Moshood et al., 2024).

2.2 IMPLEMENTATION OF DIGITAL TWIN TECHNOLOGY FOR CONSTRUCTION CONTRACT ADMINISTRATION

DTT is useful for enhancing the contract administration in construction with transparency for monitoring, analysis, and communication, as well as enabling real-time worker and stakeholder interaction (Ammar et al., 2022). Further, Tao et al. (2018) highlighted that DTT helps to reduce risks, enhances compliance tracking, and improves the CA through real-time data sharing and automation of Workflows. For example, in Singapore smart

infrastructure project, DTT has been used to pave the ground via automated progress monitoring and claims resolution with an immutable audit trail in the aspect of designing and CA (Shishehgarkhaneh et al., 2022). DTT digitises documentation and facilitates collaboration among stakeholders, updates in a single platform that reduces ambiguities in contractual terms, and helps to hold people accountable (Tao et al., 2018).

2.3 BENEFITS OF IMPLEMENTING DTT FOR CA

Table 1 provides ten (10) key benefits of implementing DTT in construction CA with supported verifiable academic references from global case studies from the UAE, Germany, and Hong Kong. By linking each benefit (i.e., greater transparency, cost savings, and sustainability alignment) to empirical evidence, which demonstrates DTT's prevention of disputes, improving compliance, and maximising the use of available resources. These findings collectively highlight the possibility of DTT capabilities to assist CA practice by combining real-time data analytics with contractual governance to achieve efficiency and accountability in CA within projects.

Table 1: Benefits of DTT adoption

Ref	Benefit	Description	Sources
A1	Transparency	With DTT, stakeholders can have a real time access to project data and that decreases information asymmetry and increase trust. With virtual models, clients and contractors have an opportunity to collaborate in monitoring progress, compliance and resource allocation.	(Lu et al., 2020)
A2	Enhanced efficiency	Automated workflows eliminate time-wasting documentation, approval and change order cycles. AI based analytics reduces the reporting time by up to 30–40 percent in the Australian infrastructure projects.	(Alnaser et al., 2024)
A3	Mitigation of risks	Predictive analytics predict with high certainty when contractual obligations are not met (such as delay, overrun) prior and in advance of corrective action, when possible. In U.S. transportation projects, it reduced the disputes by 25%.	(Management Association, Information Resources, 2022)
A4	Alignment with sustainable development	SDG 9 and 11 are the goals supported by DTT as we optimize material use and reduce waste. In the case of UAE, real time resource tracking reduced the site waste by 18%.	(Tao et al., 2018)
A5	Enhanced collaboration	Real time collaboration is possible on cloud based DTT platforms. In Singapore, shared virtual models led to 15% reduction in rework once rework was counted, for the contractual deliverables.	(Bado et al., 2022)
A6	Cost reductions	It contributes to savings in the long term because rework and delays are reduced. German study also showed that DTT cut project overruns by 20%, by following a budget correctively.	(Serugga, 2025)

Ref	Benefit	Description	Sources
A7	Monitoring compliances	DTT automates compliance checks of contractual terms. For example, DTT was used in UK projects to enforce the sustainability certification with 100% compliance with the standard.	(Boje et al., 2020)
A8	Improved decision-making techniques	Stakeholders can evaluate scenarios (design changes), test before implementation and improve the accuracy of decisions by 35% in Japanese megaprojects.	(Pal et al., 2023)
A9	Building maintenance	Maintenance needs predictions through a lifecycle of a project can be made by DTT.	(Kaewpoonsuk, 2024)
A10	Dispute resolution activities	Immutable audit trails reduce the number of ambiguities in contractual claims.	(Gupta & Jha, 2023)

2.4 BARRIERS TO IMPLEMENTING DTT IN CA

The barriers to DTT adoption in Contract Administration (CA) identified from the literature sources are presented in Table 2. Fifteen (15) barriers were identified and categorised using thematic analysis technique. Accordingly, five groups emerged, namely technological, organisational, economic, regulatory and cultural barriers for implementing DTT in construction CA.

According to the table, key technological barriers are fragmented data integration (USA), cybersecurity risks (Australia), human and procedural limitations (India and Australia), and resistance to digitization (Sri Lanka and Australia). Further, systemic and policy related barriers are reflected in economic barriers such as high costs (South Africa) and unclear ROI (Canada), regulatory gaps (Europe), and legal ambiguities (Singapore). Therefore, the need for holistic strategies becomes stronger because cultural resistance to abandoning traditional practices is a barrier to DTT adoption that could be consistent with global best practices and local contexts. The survey of the reported global barriers to digitalisation, shown in Table 2, is exhaustive, but the existing literature shows heterogeneity in context.

Edmundson (2022) focuses on cybersecurity issues in the context of high technologies, and Çetin et al. (2021) on the problem of interoperability in regulatory fragmentation, particularly in Europe. However, existing literature does not pay much attention to interdependencies: economic limitations B10-B12, say, often compound human-capital shortages B7 in developing economies. An obvious gap is the sociotechnical analysis that would help understand the way such barriers are formed; the digital-maturity models (Kaewpoonsuk, 2022) could be used to understand why such barriers as cultural resistance B15 in Sri Lanka are rooted in systemic digital immaturity, not individual attitudes. Theoretical anchoring is required to translate lists of descriptive barriers into diagnostic tools to enable specific interventions.

Table 2: Barriers to implementing DTT

Code	Category	Barrier	Description	Global example	Source
B1	Technological	Complexity in data integration	Data formats across tools, with different data formats across BIM vs. legacy systems (fragmented formats).	Infrastructure projects in USA	(Lucchi, 2023)
B2		Cybersecurity issues	Risks related to data breaches in IoT devices and cloud platforms.	Smart cities in Australia	(Edmundson, 2022)
B3		Limitations in interoperability	Incompatibility between DTT tool and other CA tools.	Construction sector in Europe	(Çetin et al., 2021)
B4		Issues in accuracy and data quality	Getting error sensor data on virtual models.	Automotive projects in Germany	(He & Mao, 2023)
B5		Limitations in available infrastructure	No infrastructure at all for the existing IoT/sensor systems in developing regions.	Housing projects in South Africa	(World Bank, 2020)
B6	Organizational	Refusal to accept digitalization	Contractors prefer manual CA processes.	Mega projects in Sri Lanka	(World Bank, 2020)
B7		Existing skill gaps to DTT adoption	Missing professionals with the knowledge to integrate DTT and CA.	Construction firms in India	(Çetin et al., 2021)
B8		Issues in stakeholder collaboration	Silos between contractors, clients, regulators, and work functions.	Infrastructure projects in Brazil	(Hewage & Ruwanpura, 2021)
B9		Lack of team spirit and leadership support	Absence of commitment in other senior management to programs to fund DTT initiatives.	Renewable energy projects in UK	(McKinsey & Company, 2023)
B10	Economic	Higher implementation costs	Sensors, software license, training	Renewable energy projects in South Africa	(Lucchi, 2023)
B11		Minimum ROI (Return on Investment)	Uncertainty about long-term financial benefits of DTT adoption.	Smart cities in Canada	(McKinsey & Company, 2023)

Code	Category	Barrier	Description	Global example	Source
B12		Maintenance costs	Updating and maintaining DTT systems expenses	Transportation projects in USA	(Lucchi, 2023)
B13	Regulatory	Insufficient standardized frameworks	Absence of global protocols for DTT-CA integration.	Construction sector in Europe	(McKinsey & Company, 2023)
B14		Legislative uncertainties	Ambiguities in liability for DTT-generated decisions.	Smart contracts in Singapore	(World Bank, 2020)
B15	Cultural	Preference for traditional practices	Lack of willingness to stop using CA processes based on paper.	Construction contracts in Sri Lanka	(Hewage & Ruwanpura, 2021)

3. RESEARCH METHODOLOGY

Research methodology refers to the principles and procedures of logical thought processes that are applied to a scientific investigation (Fellows and Liu, 1997). Research methods, on the other hand, are merely tools. This research requires an in-depth exploration of implementing DTT technologies to improve CA. This can be achieved through examining the lived experiences of stakeholders. Qualitative methods are particularly appropriate for the capture of stakeholder views, contextual and unexpected themes (Creswell and Poth, 2018). Thus, a qualitative research approach was conducted to explore the subjective multiple barriers to DTT adoption.

Ten purposively sampled experts were interviewed using a semi-structured method, with thematic saturation reached when no new insights emerged. This methodology agrees with the rules of qualitative methodology, which do not give priority to breadth, but rather to depth, especially in the case of an expert panel that is homogeneous and explores a specialized subject (DTT-CA implementation). The collected data were analysed using thematic analysis. The analysis adopted a top-down approach, whereby pre-established themes derived from the literature synthesis initially guided the data interpretation process. Table 3 provides the profile of respondents, including their designation, years of experience, and the selection criteria for selecting them as experts for the study. The principles of ethical compliance were followed in the study. Ethics approval was sought and granted by the institution, and all the participants gave written informed consent. The data processing involved anonymization of participants and participation was voluntary. Information was stored safely to avoid unauthorized access, as it is the case with standard qualitative research procedures that involve human subjects.

Table 3: Participants' profile

Expert Code	Designation	Years of Experience	A	B	C	D
E1	Senior Quantity Surveyor	10	√	√	√	√
E2	Contract Administrator	12	√	√	√	√
E3	Commercial Manager	8	√	√	√	√
E4	Researcher	15	√	√	√	√
E5	Academic	14	√	√	√	√
E6	Construction Manager	18	√	√	√	√
E7	BIM Specialist	9	√	√	√	√
E8	Commercial Manager	11	√	√	√	√
E9	Civil Engineer	7	√	√	√	√
E10	Contract Specialist	13	√	√	√	√

A – Experience in Construction Contract Administration > 5 years

B - Awareness on DTT/ Experience on DTT

C – Minimum educational qualifications - at least a construction related degree

D - Possessing professional qualifications ‐ at least one among IQSSL, RICS, IESL, CIOB, LEED

4. FINDINGS

Even though, there were identified 15 barriers of adoption of DTT in Construction Contract Administration (CCA), the data analysis confirmed 13 critical barriers of adoption. The findings of the study uncover important pieces of information regarding the development of barriers to DTT adoption in the context of CCA in Sri Lanka. The barriers to implementing DTT for CA identified from the literature (15 barriers) were contextualized to the Sri Lankan context using in-depth interviews. Accordingly, a few barriers were modified, merged, or newly added. The research findings identified 13 barriers to implementing DTT in CA for the Sri Lankan construction industry, as outlined in Table 4. Further, the solutions were provided for the barriers through the thematic analysis of the in-depth interviews. These solutions provide actionable insights to the Sri Lankan construction industry.

From the thematic analysis of expert interviews, critical updates to the barrier framework were identified, such as the identification of new barriers and additional refinements to existing categories of barriers. According to Table 4, none of the barriers were removed from the literature findings while contextualizing to the Sri Lankan context. However, the modified barriers and newly added barriers are formatted as italicised and bolded. Thus, 6 barriers were modified by renaming, such as SLB2, SLB3, SLB4, SLB5, SLB6, and SLB7. In addition, the barriers B10, B11, and B12 have been merged as one barrier called financial constraints (SLB10). Further, the barriers B9 and B15 were merged and renamed as resistance from organisational culture (SLB9). One barrier was newly added for the SL context, specifically as vendor Lock-in (SLB13). Potential solutions for these barriers were proposed as shown in the last column of Table 4, based on the researcher's impetus and emerged from the expert discussions.

Among the 13 barriers to implementing DTT for CA in Sri Lanka, 3 barriers were overwhelmingly identified by the experts in the technological barrier category, such as cybersecurity risks, interoperability issues, and infrastructure gaps. Accordingly, the cybersecurity risks were considered most vulnerable because most firms panic about hackers accessing sensitive contract terms, as stated by E3. This was further explained by E1, recalling one of their past experiences, stating, "*the altered sensor data concealed an LKR 75 million (USD 250,000) concrete shortfall, resulting in a severe erosion of stakeholder trust in the digital system*". In further explaining, "*this incident underscores how DTT's data-dependent nature creates new attack vectors that malicious actors can exploit to manipulate contractual evidence*". This demonstrated the real-world consequences of cybersecurity risks. Like cybersecurity risks, equally problematic are interoperability issues in merging disparate digital ecosystems. E6 and E7 highlight the immense difficulties in reconciling different regional standards, whether combining Hong Kong's HKT specifications with the EU's ISO 19650 protocols or aligning the UK's BSI standards with international frameworks. These compatibility issues create significant friction in cross-border projects and even domestic operations using imported technologies. E4 adds that Sri Lanka's lack of a national digital engineering framework exacerbates these problems, resulting in fragmented data systems that cannot communicate effectively. Thus, the study proposes robust data encryption and localized cybersecurity protocols as the potential solution to the above two barriers. The next emphasized technological barrier is the infrastructure gap. The limitations in the electricity infrastructure in Sri Lanka were presented by E4 as follows: "*60% of rural construction sites lack stable internet connectivity fundamentally constrains real-time*

DTT functionality". These infrastructure gaps create a vicious cycle, where limited connectivity discourages DTT investment, which in turn slows digital infrastructure development. Therefore, the study proposes initiating a public-private infrastructure partnership and generating a DTT model through offline, capable methods as a solution to overcome the barrier.

In addition to the technological barrier category, the other three most stated barriers to implement DTT in SL CA in other barrier categories are financial constraints, generational divide, and skill shortage. When considering the financial constraints, E6 and E7 highlighted "*DTT consumes 5-7 % of project budgets in emerging markets, thus it is not unique to Sri Lanka among the competing priorities. We cannot afford it without subsidies*". Therefore, the provision of a subsidy by the government and the initiation of the adoption of the DTT model for a pre-determined phase of the construction project's CA would be the potential solutions for the barrier. Next, the resistance to technological change was pointed out by experienced professionals. This resistance is compounded by the generational divide and is significant to Sri Lanka as like financial constraints. It can be supported by a statement given by E6, *"I've used paper for 30 years—I won't trust a machine".* Adding on to that, E4 describes a pervasive attitude as *"why fix what isn't broken?".* Provision of mentorship programs for the staff of the organisation and allowing a hybrid workflow could be potential solutions to overcome the generational divide. Then, the acute skill shortage was noted as the most indicated barrier to implementing DTT in SL CA. The critical human resource limitation to implement DTT in Sri Lanka was mentioned by E5 as "*only two hundred (200) BIM-certified professionals are available nationwide in Sri Lanka*". Reinforce that statement, E7 indicated "*just 12% of local engineers have that BIM certification*". The skill gap extends beyond basic BIM competency to more advanced DTT applications, where E3 noted "*only 12% of Asian contractors have DTT-trained staff*". Thus, workforce development must accompany technological investment for successful adoption. Provision of incentives as a certification for DTT users and enhancing the partnership with the higher educational institute to incorporate the practical knowledge on DTT for construction will overcome the skill shortage to implement DTT for CA in Sri Lanka.

In addition to the above-mentioned six key barriers, there are other barriers to implementing DTT for CA in SL. Accordingly, creating protocols for sensor calibration and development of a framework for quality assurance and quality control for sensors could be a potential solution for data quality issues, which are mainly caused by errors in sensors. Further, pilot projects are suggested as solutions for the resistance that emerges from the organisational culture. Another considerable issue is the data privacy and government related barriers, where reforming the legal framework and developing laws for standardized digital evidence could be a solution. Besides, vendor-lock-in was identified as a new barrier while contextualizing the literature findings to the Sri Lankan context. E8 explained it as "*once a company chooses a specific vendor or platform to build and operate their digital twin, it becomes very difficult, expensive, or time-consuming to switch to another vendor or system later on*".

The barrier experience from this on the implementation of DTT for CA is highlighted by E9 as "*organizations may hesitate to adopt a digital twin solution if they fear they'll get locked into a system that restricts flexibility, innovation, or cost control in the future*". Therefore, the solution to this barrier, which stems from dependence on expensive proprietary software, could be to first implement the DTT in open-source DTT tools and

software. In addition, findings suggest utilizing the government-led platforms rather than those from a private vendor, which could significantly reduce the risk.

In the sociotechnical systems (STS) tradition, obstacles to the adoption of DTT are traditionally categorised into five broad categories: Technological, Organisational, Economic, Regulatory and Cultural. This schema is justified by the fact that effective implementation of DTT is based on the dynamic interplay of technological (tools, infrastructure) and social (people, structure, context) aspects (Clegg, 2000). Technological barriers (SLB1-SLB5) include shortcomings in hardware, software or connectivity as well as poor interoperability between DTT solutions. Organisational barriers (SLB6-SLB9) concentrate on the intra-firm features like capacity, cultural attitudes and governance arrangements. Economic barriers (SLB10) are based on the distribution of resources and profitability. Regulatory barriers (SLB11-SLB12) are based on external regulatory regimes that are unable to keep up with technological innovation or fail to leave legitimate policy gaps. Lastly, cultural barriers are part of organisational barriers, and they include deep-seated norms, practices and worldviews that hinder transformative change. Analytically, these classifications are helpful in that they allow the development of interventions that are specific to the subsystem that needs to be remediated; technical solutions can be designed to overcome technological barriers, and policy reform can be designed to overcome regulatory barriers. As a result, the framework provides both practitioners and scholars with a consistent, holistic view of DTT-CA adoption, softened by the realization that resistances are complex.

Technological barriers (SLB1-SLB5) were the most common, and the cybersecurity risks were the most significant constraint because of such incidents as maliciously altered sensor data that can create significant financial damage and reduce the trust of the population. Infrastructure deficiencies were also acute, with 60% of rural construction sites having no stable internet connection, thus fundamentally restricting the real-time capability of DTT.

The solutions to these technological problems are the creation of local cybersecurity standards and the creation of public-private partnerships that will modernize infrastructure. Organizational and cultural barriers (SLB6-SLB9) pointed to a significant generational gap, i.e., the reluctance of veteran professionals to digital workflows (e.g., I used paper all my life, I am not going to trust a machine), as well as to acute skills gaps, such as the fact that there are only 200 Building Information Modelling (BIM) certified professionals in the entire country. In this regard, suggestions include hybrid processes and industry incentives relating to university certification programs.

Economic and regulatory impediments (SLB10-SLB12) revolved around financial constraints, with DTT taking up 5-7 % of total project costs, encouraging firms to adopt a phased approach to adoption, with specific subsidies. The issue of data privacy highlighted the necessity of legal reforms that would help to standardize digital evidence. Vendor lock-in (SLB13) presented a new obstacle, as the use of proprietary software limited flexibility. The corresponding mitigation strategy suggests developing open-source platforms led by the government.

The current discussion contextualizes empirical results in the existing literature in a systematic way. It supports the diagnosis of Edmundson (2022) of cybersecurity vulnerabilities in high-tech environments with the measurement item SLB2 (Cybersecurity Risks). Simultaneously, it complements the work of Çetin et al. (2021)

regarding the interoperability by recognizing Vendor Lock-in (SLB13) as a poorly studied economic limitation in emerging economies. In addition, The Generational Divide (SLB6) situates the cultural barriers described by Hewage and Ruwanpura (2021) within the systemic digital immaturity of the Sri Lankan context, thus expanding the focus beyond the personal attitudes and questioning the direct transferability of global North models. The argumentation that follows hence establishes the need of sociotechnical ecosystem adaptations.

Moreover, the inclusion of potential solutions transforms Table 4 from purely diagnostic to prescriptive. The link between the barriers and proposed potential solutions is presented in the following Figure 1.

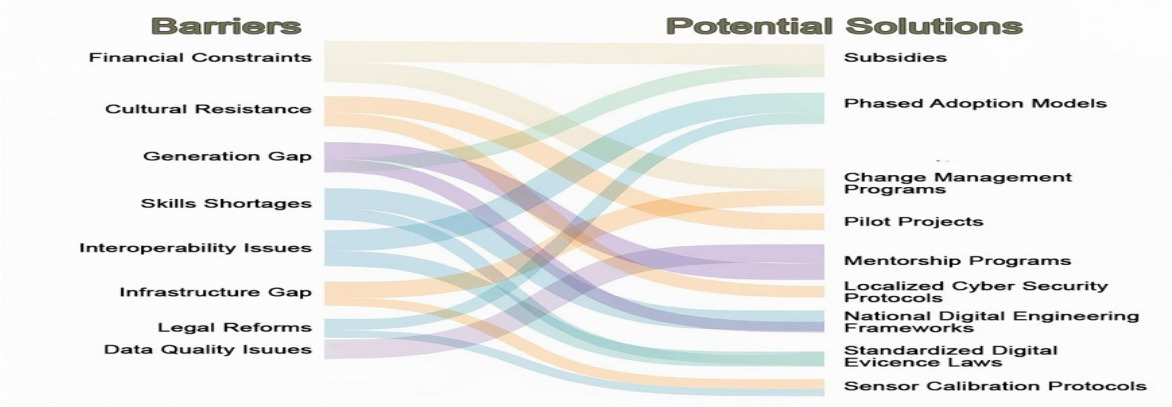


Figure 1: Barrier- Solution Pairing for DTT implementation for CA in Sri Lanka

In these findings, it is further shown that barriers are not static and evolve with changing technological/ contextual shifts. Sri Lanka's problems are unique socio-cultural and regulatory dynamics that compound the problem, global studies focus on skills gaps. Crossing the gap of awareness as a barrier to DTT adoption and introduction of vendor lock in or data quality issues indicate that the mission and purpose of DTT have been clearly understood better, and operators are increasingly advised to adopt a more tailored strategy that considers interaction between financial, technical and human components of DTT adoption.

Table 4 : Barriers to implementing DTT in CA in Sri Lanka

Literature review Findings			Expert Interview Findings		
Category	**Initial Code**	**Barrier in global context**	**Barrier in Sri Lankan context**	**Final code**	**Potential solutions**
Technological	B1	Complexity in data integration	Complexity in data integration	SLB1	Introducing Open BIM Standards - Adopt strategies and methodologies that enable data formats of different tools (e.g., BIM, IoT, legacy systems) to be unified using SDO or ISO 19650 compliant frameworks.
	B2	Cybersecurity issues	*Cybersecurity Risks*	SLB2	Robust data encryption and localized cybersecurity protocols.
	B3	Limitations in interoperability	*Interoperability Issues*	SLB3	Robust data encryption and localized cybersecurity protocols.
	B4	Issues in accuracy and data quality	*Data Quality Issues*	SLB4	Sensor calibration protocols and Quality Assurance and Quality Control (QA/QC) frameworks.
	B5	Limitations in available infrastructure	*Infrastructure Gaps*	SLB5	Offline-capable DTT model generation and public-private infrastructure partnerships.
Organisational	B6	Refusal to accept digitalization	*Generational Divide*	SLB6	Mentorship programs and hybrid workflows.
	B7	Existing skill gaps to DTT adoption	*Skills Shortages*	SLB7	University partnerships and provide certification incentives.
	B8	Issues in stakeholder collaboration	Issues in stakeholder collaboration	SLB8	Use tools such as BIM 360 or Procore to share real-time documents, track progress, and provide role-based access. IPD (Integrated project delivery) contracts Digital Twin Dashboards - Develop the dashboards based on roles (for instance, clients viewing milestones,

Literature review Findings			Expert Interview Findings		
Category	**Initial Code**	**Barrier in global context**	**Barrier in Sri Lankan context**	**Final code**	**Potential solutions**
					or contractors viewing compliance) to improve transparency.
	B9	Lack of team spirit and leadership support	*Resistance from organisational culture*	SLB9	Variation management programs and pilot projects.
Economic	B10	Higher implementation costs	*Financial Constraints*	SLB10	Subsidies and phased adoption models.
	B11	Minimum ROI (Return on Investment)			Offer tax breaks or bidding advantages to firms that use certified DTT-CA frameworks.
	B12	Maintenance costs			
Regulatory	B13	Insufficient standardized frameworks	Insufficient standardized frameworks	SLB11	National Digital Engineering Mandates Co-Developing Protocol Scalability refinement by Test frameworks on government-funded projects
	B14	Legislative uncertainties	Data Privacy and government concerns	SLB12	Legal reforms and standardized digital evidence laws.
Cultural	B15	Preference for traditional practices	*Resistance from organisational culture*	SLB9	Training, Government Backed - Educate people in Revit and Navisworks to enable cross-platform data management
			Vendor Lock-in	SLB13	Open-source DTT tools and software, and government-led platforms.

Bold: Newly identified barriers from Expert interviews | *Italicised*: Slightly modifies barriers during expert interviews

5. DISCUSSION

This research explains the multivariate barriers to the adoption of Digital Twin Technology (DTT) in the Sri Lankan construction industry, examining technological, economic, organisational, cultural, and regulatory barriers. Major limitations are high financial costs- DTT licences are said to absorb about 20 % of the profit margin of small and medium enterprises (SMEs), skills shortage, and legal reforms. The results also point out the fact that importing global models is constrained by contextual factors including generational gaps and the newly discovered obstacle of vendor lock-in which shows a mature awareness of the complexity of adoption. Besides, these challenges are compounded by local issues, such as cultural legacies, established practices, and infrastructure gaps (especially in rural settings) as well as data-quality risks and systemic policy issues related to data privacy and digital evidence.

Methodologically, the research was a qualitative one using expert interviews (n 10, mainly large organisations/government) which may have under-represented SME and subcontractor views, which are vital in diffusion. Thematic analysis with a top-down approach might have limited emergent themes, and the lack of quantitative data does not allow ranking barriers and modelling interdependencies, which makes generalisation to other emerging economies and highlights the necessity of mixed-methods research in the future.

The empirical evidence indicates that there is a high level of interdependence between the identified barriers and therefore isolated interventions are ineffective. Economic constraints are compounded by technological constraints, e.g. estimated LKR 75 million losses due to data/connectivity problems preventing return on investment, and cybersecurity threats, and infrastructure shortages. The organisational obstacles such as lack of skills and cultural resistance also work in self-reinforcing loops. Since the confidence and feasibility of cybersecurity vulnerabilities and labour shortages have multiplier effects, sequential strategies that are coordinated are more suitable than standalone strategies.

The current study goes beyond the traditional cost-skill dichotomies by putting vendor lock-in into the forefront as a relevant, under-researched constraint in emerging economies. Sri Lankan empirical evidence shows that the use of off-the-shelf platforms by managers increases dependency on Western providers, which hinders local digital transformation (DT). Based on this, the paper critically examines standalone licensing models and finds viable, situational, culturally relevant solutions: hybrid workflows that can narrow the generational gap; phased adoption that can assist SMEs through subsidisation; and open-source platforms that the government can lead to minimise reliance on proprietary systems and promote standardisation. Adoption, in turn, is redefined as the organisation of local sociotechnical ecosystems instead of the complete imitation of Global North patterns. Finally, the paper supports a holistic approach that involves both hybrid workflows and adaptive legal architectures to align local realities with global innovation, which supports sustainable DT in the resource-limited environment in Sri Lanka.

6. CONCLUSIONS

The current research identified 13 context-specific barriers to DTT adoption in the CCA practices of the Sri Lankan construction industry. These barriers were financial, organisational culture resistance, and a severe BIM skilled labour shortage. Several solutions generated by the respondents were suggested to reduce these obstacles including phased adoption models with subsidies, hybrid workflows, and government-led, open-source platforms. Because Sri Lanka is a developing country, the sustainable construction industry of the country presents an opportunity-rich field of CA development through DTT. The current study responds to a topical scientific demand, as no previous empirical research has assessed this integration in the environment of Sri Lanka with its unique socioeconomic and regulatory environment. Future studies ought to aim at empirically supporting the recommendations made and systematically analyse the interdependencies of the related barriers. The research thus equips policymakers with contextual approaches in which they can negotiate adoption complexities. The concept of lack of knowledge in the main construct studies means that there is no previous empirical study on DTT-CA integration in Sri Lanka, and thus there is no direct comparability. In line with this, further studies are justified to empirically support the suggested solutions as well as to investigate interdependencies of the identified barriers.

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BARRIERS TO ADOPTION OF AUTOMATION IN INDIAN CONSTRUCTION PROJECTS

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ABSTRACT

The construction industry, while a critical economic sector, is characterized by inherent inefficiencies and a relatively low adoption rate of automation technologies. The present research investigates the barriers impeding the adoption of automation in Indian construction projects. A mixed-methods approach was employed, integrating a critical literature review, semi-structured interviews, and questionnaire surveys to investigate the barriers. Initially, a critical review of the existing literature was conducted to identify pertinent barriers. Subsequently, semi-structured interviews with construction professionals were carried out to contextualize these barriers within the Indian construction landscape. The findings from these qualitative phases informed the development of a questionnaire survey, which was pilot-tested and subsequently distributed to construction professionals across India. Statistical methods were utilized to rank the identified barriers. The principal barriers were identified as the need for enhanced training programs, high initial investment costs, and limited stakeholder awareness. Principal Component Analysis (PCA) facilitated the grouping of these barriers into five key components that include industry-related, economic, operational, technical, and human-related barriers. These results underscore the potential of automation to address critical barriers within the construction sector while simultaneously highlighting the necessity of developing targeted strategies to overcome the identified adoption barriers. The present research also offers actionable insights for stakeholders, aimed at promoting the effective adoption of automation and enhancing overall productivity within the Indian construction industry.

Keywords: *Automation Adoption; Automation Barriers; Construction Automation; Indian Construction.*

1. INTRODUCTION

The construction industry significantly contributes to global GDP, yet struggles with persistent issues of productivity, efficiency, and technology adoption. Unlike manufacturing, which has embraced automation, construction remains labour-intensive and fragmented (Bock, 2015). Productivity gains in construction have been negligible compared to manufacturing (McKinsey Global Institute, 2017). Large projects often suffer delays of up to 20% and cost overruns of 80% (McKinsey Global Institute, 2017). Defects account for 10%–25% of construction costs (Get It Right Initiative UK, 2024),

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and the industry saw an 11% increase in workplace fatalities from 2021 to 2022 (US Bureau of Labor Statistics, 2024). These issues underscore the need for innovation through automation. In India, construction remains largely dependent on traditional practices, leading to inefficiencies and delays (Fellows et al., 2012). Fragmentation and a severe shortage of skilled labour exacerbate cost escalations. Though automation can potentially address some of these challenges, its adoption is hindered by multifaceted barriers (Bock, 2015). While countries such as the USA, Japan, China, and Malaysia have made progress, the Indian construction context is relatively slower with regard to adopting automation. Also, there is a paucity of literature on India-specific analysis of automation adoption barriers in construction. To address these gaps, the present study aims to identify and prioritise the barriers to the adoption of automation in Indian construction projects, particularly in the context of large water and effluent treatment projects. By analysing the barriers, the present study seeks to generate insights that can guide policymakers, industry leaders, and technology providers toward effective automation strategies, thereby enhancing safety, quality, productivity, and cost-efficiency in Indian construction projects.

2. LITERATURE REVIEW

Automation in construction refers to technologies that reduce human intervention in executing construction tasks (Groover, 2016). These technologies fundamentally transform conventional methods, including machine-centred approaches, real-time sensing and robotic execution. With Industry 4.0, the scope of automation now includes digitalization and information modelling (Oesterreich & Teuteberg, 2016), supported by CAD-robotics integration and digital fabrication. This study adopts Davis's (2022) definition, encompassing tools and processes that automate construction workflows.

Technologies such as building component manufacturing (BCM) automate off-site fabrication of structural components like floors, walls, and full modules using materials such as steel, concrete, and wood (Bock, 2015). Additive manufacturing (3D printing) is increasingly used for producing customized parts and on-site repairs, although it faces challenges related to material reliability and performance (Delgado et al., 2019). Despite ongoing material development, large-scale component printing is becoming viable. On-site automation includes Single-Task Construction Robots (STCRs) like scaffold-mounted arms, wall-painting robots, and concrete sprayers to perform repetitive tasks (Groover, 2016). However, safety and integration challenges remain, prompting the development of networked robotic factories. Additionally, wearable exoskeletons enhance worker capacity but face barriers of cost, safety, and usability (Chen et al., 2018).

The literature review was conducted using Google Scholar, Scopus, Web of Science, and Science Direct. A total of 114 sources, including 80 journal articles, 20 conference papers, 5 book chapters, and 9 industry reports, were reviewed. This comprehensive review ensured a balanced academic and industry perspective on automation barriers. A systematic approach such as PRISMA was not adopted due to the scoping and exploratory nature of the research, which aimed to broadly map themes and insights across heterogeneous sources rather than evaluate a specific intervention or clinical outcome. The flexibility of the scoping approach allowed for inclusion of diverse publication types and contextual understanding relevant to Indian construction. The literature review revealed that most studies focus on specific automation technologies rather than general barriers, and there is a notable absence of credible research addressing barriers to

automation adoption in Indian construction projects. Table 1 represents the barriers identified from the literature review.

Table 1: Identified barriers

Code	Barriers	Indicative Sources
B1	High initial cost	Tafazzoli et al., (2024), Waqar et al., (2024), Aghimien et al. (2024), Oke et al., (2023), Espinoza et al., (2023), Huang et al. (2022), Jäkel et al., (2022), Boya et al., (2022), Pradhananga et al., (2021), Delgado et al., (2019), Kamaruddin et al., (2016), Bock (2015), Mahbub (2008)
B2	High operation and maintenance cost	Waqar et al., (2024), Aghimien et al., (2024), Oke et al., (2023), Espinoza et al., (2023), Huang et al., (2022), Boya et al., (2022), Kamaruddin et al., (2016), Mahbub (2008)
B3	Easy access to low wage labour	Pradhananga et al., (2021), Delgado et al., (2019)
B4	Lack of government initiatives and support	Aghimien et al., (2024), Oke et al., (2023), Jäkel et al., (2022), Huang et al., (2022), Delgado et al., (2019)
B5	Lack of skilled operator and expertise	Tafazzoli et al., (2024), Liu et al., (2024), Waqar et al., (2024), Aghimien et al., (2024), Oke et al., (2023), Espinoza et al., (2023), Jäkel et al., (2022), Huang et al., (2022), Boya et al., (2022), Bademosi and Issa (2021), Pradhananga et al., (2021), Delgado et al., (2019), Kamaruddin et al., (2016)
B6	Need for training and retraining	Liu et al., (2024), Aghimien et al., (2024), Jäkel et al., (2022), Huang et al., (2022), Bademosi and Issa (2021), Delgado et al., (2019), Mahbub (2008)
B7	Job loss concerns	Tafazzoli et al., (2024), Liu et al., (2024), Oke et al., (2023), Boya et al., (2022), Pradhananga et al., (2021), Bademosi and Issa (2021), Delgado et al., (2019)
B8	Conservative work culture	Liu et al.. (2024), Aghimien et al.. (2024), Huang et al., (2022), Pradhananga et al., (2021), Delgado et al., (2019)
B9	Low level of awareness	Mahbub (2008), Jäkel et al., (2022), Aghimien et al., (2024)
B10	Product complexity	Liu et al., (2024), Aghimien et al., (2024), Oke et al., (2023), Boya et al., (2022), Huang et al., (2022), Pradhananga et al., (2021), Bock (2015), Mahbub (2008)
B11	Immature technology and unproved effectiveness	Aghimien et al., (2024), Liu et al., (2024), Espinoza et al., (2023), Jäkel et al., (2022), Huang et al., (2022), Pradhananga et al., (2021)
B12	Easily and locally not available	Aghimien et al., (2024), Huang et al., (2022), Boya et al., (2022), Kamaruddin et al., (2016), Mahbub (2008)
B13	Fragmented nature of supply chain	Liu et al., (2024), Aghimien et al., (2024), Oke et al., (2023), Huang et al., (2022), Bademosi and Issa (2021), Pradhananga et al., (2021), Delgado et al., (2019), Mahbub (2008)

Code	Barriers	Indicative Sources
B14	Project-based and task-based industry	Liu et al., (2024), Tafazzoli et al., (2024), Espinoza et al., (2023), Jäkel et al., (2022), Huang et al., (2022), Bademosi and Issa (2021), Delgado et al., (2019)
B15	Low level of digitalization	Liu et al., (2024)
B16	Lack of R&D	Liu et al., (2024), Espinoza et al., (2023), Huang et al., (2022), Pradhananga et al., (2021), Delgado et al., (2019), Bock (2015)
B17	Lack of relevant codes and standards	Liu et al., (2024), Waqar et al., (2024), Espinoza et al., (2023), Jäkel et al., (2022), Huang et al., (2022), Bademosi and Issa (2021), Pradhananga et al., (2021)
B18	Safety concerns	Waqar et al., (2024), Tafazzoli et al., (2024), Liu et al., (2024), Aghimien et al., (2024), Espinoza et al., (2023)
B19	Inadequate technical infrastructure	Tafazzoli et al., (2024), Oke et al., (2023), Espinoza et al., (2023), Bademosi and Issa (2021)
B20	Regulations limiting the use	Tafazzoli et al., (2024)
B21	Limited flexibility of automation technologies	Liu et al., (2024), Tafazzoli et al., (2024)

**B1- Barrier Number 1*

3. METHODOLOGY

The present study adopted a mixed-methods approach to examine barriers to automation adoption in Indian construction projects. The methodology integrated qualitative and quantitative techniques to ensure a comprehensive analysis. A critical literature review and semi-structured interviews with industry professionals informed the development of a structured questionnaire, which was pilot tested by 4 experts (3 from industry and 1 from academia). The finalised survey was circulated among construction professionals across India. This triangulated approach combining literature, expert opinion, and field data enabled robust identification of key automation barriers. Such integrative frameworks are recognized as effective for addressing complex AEC challenges, especially where socio-technical resistance exists. Statistical tools were applied to rank and prioritise the barriers, ensuring conclusions were evidence-based and practically relevant. Principal Component Analysis (PCA) was used to group barriers into thematic categories, providing structured and scalable insights.

3.1 DATA COLLECTION

Barriers identified from the literature review guided the design of the initial questionnaire. Semi-structured interviews were conducted with 12 professionals from various sectors of the Indian construction industry (Table 2). These online and offline interviews validated literature findings in the Indian context and identified any additional country-specific barriers. Open-ended questions encouraged respondents to share insights based on their experience. These responses helped refine and expand the questionnaire. A pilot survey

was conducted to check the instrument's clarity and completeness, and feedback led to minor adjustments to improve reliability. The final survey was distributed via Google Forms to 75 professionals with direct or related experience in construction automation, resulting in 66 completed responses. The respondent profile is shown in Table 3. Each barrier was rated on a five-point Likert scale. The survey reached professionals across India, enabling diverse, representative results to support nationally relevant conclusions.

Table 2: Profile in interviewees

Code	Role	Experience	Location (India city)	Duration (min)
P1	P&M Engineer	13	Trichy	26
P2	Site Engineer	10	Trichy	10
P3	Quality Engineer	25	Hyderabad	15
P4	Site Engineer	5	Trichy	10
P5	Contractor	30	Hyderabad	10
P6	Planning Engineer	5	Delhi	20
P7	Project Manager	13	Hyderabad	24
P8	Site Engineer	14	Guwahati	10
P9	Planning Engineer	5	Guwahati	20
P10	Project Manager	28	Hyderabad	15
P11	Automation team	20	Chennai	40
P12	Automation team	8	Chennai	14

**P1-Professional Number 1*

Table 3: Profile of survey respondents

Category	Parameter	Percentage	Category	Parameter	Percentage
Education	Diploma	28.78	Experience	1-5 Years	22.72
	Graduate	43.93		5-10 Years	39.39
	Postgraduate	27.27		10-15 Years	31.81
State	Madhya Pradesh	12.12		15-20 Years	6.06
	Rajasthan	13.63	Department	Execution	27.27
	Karnataka	6.06		Planning	34.84
	Tamil Nadu	25.75		Safety	4.54
	Odisha	42.42		Design	22.72
				Quality	10.6

3.2 DATA ANALYSIS

Statistical techniques were employed to derive meaningful insights. Cronbach's Alpha (α) assessed internal consistency, with values above 0.7 indicating strong reliability (Nunnally & Bernstein, 1994). Shapiro-Wilk and Kolmogorov-Smirnov tests tested data normality (Shapiro & Wilk, 1965), using a p-value > 0.05 as the threshold. Since most

data were non-normal, non-parametric methods were adopted. The Kruskal-Wallis H test evaluated variations across demographic groups (Kruskal & Wallis, 1952). Barriers were ranked using mean and standard deviation, with ties resolved based on lower standard deviations. The dataset's suitability for factor analysis was verified using the KMO test and Bartlett's sphericity test. Principal Component Analysis (PCA) was then applied to reduce dimensionality, extracting factors with eigenvalues above one and using Varimax rotation to enhance interpretability. These components informed the development of strategies to address automation barriers in the Indian construction context.

4. RESULTS AND DISCUSSIONS

The subsequent sections present the findings derived from analysis of the data collected. The identified barriers are ranked and categorized, providing a structured understanding of their relative importance and interrelationships.

4.1 SEMI- STRUCTURED INTERVIEWS

Semi-structured interviews of 12 construction professionals were conducted in offline and online modes to identify the barriers to the adoption of construction automation in the Indian context. The semi-structured interviews gave insights into the barriers based on practical ongoing Indian conditions. The interviews helped in selecting the most critical barriers in the Indian context. Newly identified barriers that were unidentified in the literature and are included in the questionnaire are "need for manual rework (finishes) even after automation" and the "lowest bidder system in awarding contracts". Changes in wordings were made in the survey according to interviews, for instance, identifying barriers from "easy access to labour" to "easy access to low-wage labour", considering the Indian context. The summary of the perceived barriers (as extracts from the interviews), as derived from the semi-structured interviews, is presented in Table 4. A total of 35 barriers to automation adoption were initially identified through literature review, from which 21 barriers were synthesized based on their repetitiveness and their applicability in the Indian context. Two additional barriers derived from interviews were selected for the survey, bringing the total count to 23 barriers. Pilot testing with three industry professionals ensured clarity and design adequacy, leading to finalization of the questionnaire based on their feedback. The main survey was administered using Google Forms, where participants rated each barrier on a five-point Likert scale, and responses were collected widely across Indian construction professionals to ensure robust representation.

Table 4: Summary of semi-structured interviews

Code	Summary (perceived barriers)
P1	Physically active skilled operator required, need for training and retraining, complex to use, high initial, maintenance, operation cost, job security concern, manual work required even after automation, easy availability of low-wage labour, aversion to change, project-based industry, lack of client awareness, complexity of the product.
P2	Need for training, need for skilled operators, high initial, maintenance, and operational costs, lack of government initiatives, lowest bidder system.
P3	Easy availability of low wage labour, low level of awareness, inadequate technical infrastructure supporting implementation, and job security concerns.

Code	Summary (perceived barriers)
P4	Lack of skilled operators and expertise, safety concerns, inadequate technical infrastructure supporting implementation, low level of digitalization, high initial cost, and maintenance costs.
P5	changing site conditions, uniqueness of projects, need for training and retraining, lack of skilled operators, lack of awareness, low project budgets, lack of client support, high initial, maintenance and operation costs, and easily not available.
P6	Lack of R&D, project-based industry, low level of digitalization, poor database management, some projects lack internet connectivity, initial cost, unproven effectiveness, need for training, lack of awareness.
P7	Changing needs for every task, need for training, lack of operators and expertise, low level of awareness/exposure, high initial, maintenance, and operation cost.
P8	High initial cost, easy availability of low wage labour, need for training, lack of skilled operators and expertise, job security concerns.
P9	High initial, maintenance, and operation costs, manual work required even after automation, easy availability of low wage labour, lack of support from top management, need for training, training will not give ROI when workmen are rotated due to sub-contractor, lack of skilled operators and expertise, job security concerns.
P10	High initial cost, inadequate technical infrastructure, job loss for labourers, need for training, lack of skilled operators and expertise, and complex nature of automation technology.
P11	Easy availability of low wage labour, aversion to change, unproven effectiveness, high initial cost, maintenance, low flexibility, need for training, challenging to update, need for training, lack of skilled operators and expertise, lack of codes and standards.
P12	Initial cost, sometimes manual work (finishes) required even after automation, special materials needed (e.g. 3d printing), safety concerns, unproven effectiveness, limited flexibility of automation technologies.

**P1- Professional Number 1*

4.2 RANKING OF BARRIERS

The barriers were ranked according to their Mean Item Score (MIS) and Standard Deviation (SD). Descriptive statistics were done using SPSS software, and Mean Item Score (MIS) and Standard Deviation were calculated. Table 5 represents the final ranking of barriers.

Table 5: Ranking of barriers

Code	Barrier	MIS	SD	Rank
B6	Need for training and re-training	4.015	0.953	1
B1	High initial cost	3.833	1.075	2
B9	Low level of awareness (exposure) among stakeholders	3.712	1.12	3
B5	Lack of skilled operators and expertise	3.697	1.176	4
B12	Easily and locally not available	3.652	1.116	5
B8	Conservative work culture and resistance to change	3.53	1.07	6
B19	Inadequate technical infrastructure supporting implementation	3.485	0.996	7

Code	Barrier	MIS	SD	Rank
B2	High operation and maintenance cost	3.47	1.14	8
B4	Lack of government initiatives and support	3.455	1.01	9
B10	Product complexity	3.455	1.112	10
B23	Lowest bidder system in awarding contracts	3.455	1.139	11
B20	Regulations limiting the use	3.424	0.993	12
B18	Safety concerns	3.364	1.172	13
B11	Immature technology and unproved effectiveness	3.348	1.015	14
B16	Lack of R&D	3.318	1.098	15
B17	Lack of relevant codes and standards	3.318	1.152	16
B7	Job loss concerns	3.303	1.007	17
B14	Project-based and task-based industry	3.303	1.189	18
B21	Need for manual rework (finishes) even after automation	3.303	1.24	19
B3	Easy access to low wage labour	3.288	1.31	20
B22	Limited flexibility of automation technologies	3.273	1.001	21
B15	Low level of digitalization	3.182	1.136	22
B13	Fragmented nature of supply chain	3.121	1.089	23

B1-Barriers Number 1

The barriers with the same MIS value were ranked according to their standard deviation; the factor with the lower standard deviation will be given a higher rank (Delgado et al., 2019), as the lower standard deviation represents a more consistent rating by the respondents to a particular factor.

Reliability analysis yielded a Cronbach's Alpha of 0.925, confirming excellent internal consistency (Nunnally & Bernstein, 1994). Normality tests using Shapiro-Wilk and Kolmogorov-Smirnov methods revealed p-values < 0.05 for all barriers, indicating non-normal distribution (Shapiro & Wilk, 1965), and necessitating the use of the Kruskal-Wallis H-test for further non-parametric analysis (Kruskal & Wallis, 1952). The Kruskal-Wallis H-test showed no statistically significant difference in opinions across different groups of construction professionals, with p-values above 0.05 for all 23 barriers. This indicated a general consensus regarding the barriers affecting automation adoption. For critical ranking, barriers were prioritized based on Mean Item Score (MIS) and Standard Deviation (SD) calculated through SPSS, following methodologies suggested by Olanrewaju et al., (2020). The systematic ranking provided clear insights into the industry's key concerns regarding automation, forming the foundation for subsequent recommendations and strategy development. Need for training and re-training, high initial cost of technologies related to construction automation, low level of awareness (exposure) among construction stakeholders, lack of skilled operators and expertise, and unavailability of automation-related technologies locally and in an accessible manner are top-ranked barriers.

4.3 CATEGORIZATION OF BARRIERS

The categorization of barriers was conducted to condense the number of factors into identifiable subscales using Principal Component Analysis (PCA) (Field, 2013). A minimum of 15 variables is recommended for PCA, which this study satisfied. The Kaiser-Meyer-Olkin (KMO) value achieved was 0.814, which exceeds 0.6 threshold (Kaiser, 1974), while Bartlett's Test of Sphericity produced a significant result ($p < 0.05$) with a chi-square value of 779.616 and 253 degrees of freedom, confirming the dataset's suitability for PCA (Bartlett, 1954). Exploratory Factor Analysis (EFA) using PCA with varimax rotation extracted five principal components explaining a cumulative variance of 62.96%, surpassing the recommended 50% threshold. Two barriers, B8 and B10, were removed for having factor loadings below 0.3 (Field, 2013). The naming of the components was guided by theoretical reasoning and researcher judgment as suggested by Williams et al. (2010), providing a structured categorization of the barriers affecting automation adoption in the Indian construction sector. The categorization derived from this study is presented in Table 6 and discussed below.

Table 6: Categorization of barriers

	Categories	C1	C2	C3	C4	C5
Industry-related barriers						
B12	Easily and locally not available	0.617				
B13	Fragmented nature of supply chain	0.549				
B14	Project-based and task-based industry	0.692				
B16	Lack of R&D	0.524				
B22	Limited flexibility of automation technologies	0.803				
B23	Lowest bidder system in awarding contracts	0.810				
B9	Low level of awareness (exposure) among stakeholders	0.512				
Economic barriers						
B1	High initial cost		0.783			
B2	High operation and maintenance cost		0.684			
B4	Lack of government initiatives and support		0.469			
B6	Need for training and retraining		0.592			
Technical barriers						
B5	Lack of skilled operator and expertise			0.399		
B11	Immature technology and unproved effectiveness			0.338		
B15	Low level of digitalization			0.713		
B19	Inadequate technical infrastructure supporting implementation			0.520		
Operational barriers						
B17	Lack of relevant codes and standards				0.822	
B18	Safety concerns				0.394	
B20	Regulations limiting the use				0.455	

	Categories	C1	C2	C3	C4	C5
B21	Need for manual rework (finishes) even after automation				0.571	
Human-related barriers						
B3	Easy access to low wage labour					0.611
B7	Job loss concerns					0.779
Extraction Method: Principal Component Analysis.						
Rotation Method: Varimax with Kaiser Normalization.						

**C1- Category Number 1*

4.3.1 Industry-Related Barriers

The Indian construction industry encounters several distinct barriers that hinder automation adoption. A major challenge, ranked third, is the "Low level of awareness (exposure) among stakeholders" (B9). Many remain unaware of automation's potential benefits, limiting informed decisions and investment (Jäkel et al., 2022; Mahbub, 2008). Ranked fifth, "Easily and locally not available" (B12) reflects the lack of a domestic supply chain for automation tools, resulting in dependence on costly imports (Boya et al., 2022; Huang et al., 2022). The "Fragmented nature of the supply chain" (B13) adds further complexity, as subcontracting and disjointed workflows make integration difficult (Delgado et al., 2019; Mahbub 2008; Oke et al., 2023). The "Project-based and task-based industry" (B14) also limits ROI on automation, since each project and task is unique—unlike the automotive sector—restricting the reuse of specialized tools (Espinoza et al., 2023; Huang et al., 2022). The "Lack of R&D" (B16) constrains local innovation and adaptation of automation technologies. Similarly, "Limited flexibility of automation technologies" (B21) highlights the inability of current systems to meet diverse construction needs (Liu et al., 2024; Tafazzoli et al., 2024). Finally, the "Lowest bidder system in awarding contracts" (B23) prioritizes short-term cost savings over innovation, discouraging investments in long-term automation solutions.

4.3.2 Economic Barriers

Economic constraints are a major hindrance to automation adoption in India. The top-ranked barrier is the "Need for training and retraining" (B6). This highlights the financial burden of continuously upskilling the workforce to operate and manage advanced systems (Jäkel et al., 2022; Liu et al., 2024). With a predominantly unskilled and semi-skilled labour pool, Indian companies must allocate substantial resources to training, which can discourage automation initiatives. Ranked second, "High initial cost" (B1) of automation technologies remains a primary concern for most stakeholders (Oke et al., 2023; Tafazzoli et al., 2024). Additionally, the eighth-ranked "High operation and maintenance cost" (B2) deters adoption, as many companies lack the financial resilience to bear recurring expenses related to automated equipment (Mahbub, 2008; Oke et al., 2023). "Lack of government initiatives and support" (B4) further exacerbates the problem (Delgado et al., 2019; Oke et al., 2023). Despite India's focus on infrastructure development, policies and subsidies promoting automation adoption remain limited, leaving stakeholders to bear the financial burden entirely. This gap underscores the urgent need for government intervention to incentivize automation adoption through tax benefits, grants, or low-interest loans.

4.3.3 Technical Barriers

The Indian construction sector also grapples with significant technical hurdles. Ranked fourth, "Lack of skilled operators and expertise" (B5) is a major obstacle (Boya et al., 2022). Operating automated machinery and implementing digital systems requires specialized knowledge, which is scarce in India. The seventh-ranked barrier, "Inadequate technical infrastructure supporting implementation" (B19) (Bademosi & Issa, 2021; Oke et al., 2023), further compounds the problem. In many parts of India, such infrastructure is either underdeveloped or entirely absent, making the deployment of automation systems impractical. Another key barrier is the "Immature technology and unproved effectiveness" (B11). Given that automation in construction is still emerging in India, many stakeholders are hesitant to adopt unproven technologies (Aghimien et al., 2024; Espinoza et al., 2023). Moreover, the "Low level of digitalization" (B15) in the construction sector reflects the lack of foundational digital infrastructure required for implementing automation solutions effectively (Liu et al., 2024).

4.3.4 Operational Barriers

Operational barriers also play a significant role in limiting automation adoption. The “Lack of relevant codes and standards” (B17) reflects the regulatory vacuum in India concerning automation in construction. Without clear guidelines and standards, stakeholders are uncertain about the legal and procedural requirements for deploying automated systems (Huang et al., 2022; Pradhananga et al., 2021). "Safety concerns" (B18) remain another critical issue. Despite the potential of automation to improve safety, stakeholders often perceive advanced machinery as risky due to the lack of proven safety protocols and training (Waqar et al., 2024). Similarly, "Regulations limiting the use" (B20) underscore the restrictive policies that hinder the application of automated technologies, particularly in sensitive sectors such as water infrastructure and urban development (Tafazzoli et al., 2024). The "Need for manual rework (finishes) even after automation" (B22) reflects persistent operational inefficiencies, as many automated systems lack the precision needed for certain tasks, requiring manual touch-ups and diminishing automation's overall effectiveness.

4.3.5 Human-Related Barriers

Finally, human-related barriers are deeply rooted in India's socio-economic context. The "Easy access to low-wage labour" (B3) reflects a fundamental barrier to automation adoption (Delgado et al., 2019; Pradhananga et al., 2021). With abundant and inexpensive labour readily available, many contractors see little incentive to invest in costly automation technologies that replace manual work. "Job loss concerns" (B7) further deter automation adoption. The fear of widespread unemployment due to automation is a significant concern in a country with high labour dependency. Stakeholders often prioritize social stability over technological advancement, choosing to maintain traditional practices that ensure job security for unskilled and semi-skilled workers (Delgado et al., 2019; Tafazzoli et al., 2024).

In summary, the barriers identified across industrial, economic, technical, operational, and human dimensions present a comprehensive view of the multifaceted challenges facing automation in Indian construction. Recognizing and addressing these barriers is crucial for developing effective strategies to foster wider technology adoption and drive industry transformation.

5. CONCLUSIONS

The present study critically explored the barriers to the adoption of automation in Indian construction through a mixed-methods approach involving literature review, semi-structured interviews, and a questionnaire survey. A total of 23 distinct barriers were identified and grouped into five core categories: industry-related, economic, technical, operational, and human-related. Among these, the most significant barriers were the need for training and retraining, high initial costs, low stakeholder awareness, and lack of skilled operators. These findings reveal the complex interplay of challenges faced by a traditionally operated industry, where socio-economic diversity and infrastructural limitations continue to impede technological adoption.

The research contributes theoretically by offering a structured, empirically validated framework tailored to India's unique construction landscape. While studies including Delgado et al. (2019) and Mahbub (2008) have assessed global contexts, the present study localizes those findings, accounting for India's infrastructural and policy environment. Practically, it delivers insights regarding construction automation for stakeholders across the sector. Top-ranked barriers, such as high costs and inadequate government support, suggest the need for incentives like subsidies and public-private partnerships. R&D and modular automation can address technical gaps, whereas awareness campaigns can reduce resistance among workers and decision-makers.

The sample, though diverse, may not fully capture regional disparities or micro-level project complexities, representing a limitation. While PCA effectively grouped barriers into themes, it did not examine causal relationships, which future studies could address using SEM or system dynamics. Further research could explore sector-specific automation, cross-country comparisons, and the integration of emerging technologies like AI, BIM-robotics, and digital twins. Overall, a holistic approach addressing technological, economic, operational, and human factors is essential. This study offers a foundation for steering India's construction industry toward a more automated, efficient, and future-ready paradigm.

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BEYOND EFFICIENCY: RETHINKING OFF-SITE CONSTRUCTION FOR POST-DISASTER HOUSING RECONSTRUCTION

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ABSTRACT

The rising frequency and severity of natural hazard-induced disasters has heightened the need for reconstruction strategies that are rapid, yet resilient and responsive to long-term community needs. Off-site construction (OSC) has emerged as an effective approach to post-disaster reconstruction (PDR), offering accelerated delivery, enhanced quality control, and reduced on-site disruption. However, existing research is found to distort OSC's potential by primarily emphasising technical efficiencies while overlooking major barriers such as standardisation issues, cultural insensitivity, and inadequate policy integration. This paper addresses this distortion by conducting a systematic scoping review, supplemented by scientometric analysis. The scientometric review analyses 113 peer-reviewed publications across the years 2004–2025, retrieved from the Scopus database, identifying dominant research themes including modular construction, sustainability, and resilience. Concurrently, the systematic review highlights OSC's key advantages—most notably, time and cost efficiencies—as well as persistent challenges such as high initial investment, logistical constraints, limited policy integration, and insufficient community involvement. Critically, the review suggests that OSC's effectiveness cannot be measured solely by technical efficiency, as the delivery of standardised, culturally disconnected housing may undermine broader recovery goals. For OSC to contribute meaningfully to sustainable reconstruction, it must be integrated within a holistic framework that values local context, supports community agency, and fosters a transition from shelter to home. This study underscores the need for more adaptive, inclusive, and policy-aligned models of OSC in post-disaster settings.

Keywords: *Disaster Resilience; Housing; Off-Site Construction (OSC); Post-Disaster Reconstruction (PDR); Systematic Review.*

1. INTRODUCTION

The global incidence of natural hazard-induced disasters has increased markedly in recent decades, both in frequency and severity (Guha-Sapir et al., 2013). This escalation is

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compounded by the persistent rise in global temperatures and sea levels, which continues to pose profound and increasingly unmanageable challenges for many nations (Huang et al., 2018). Even if the most ambitious climate mitigation pledges are fully implemented, they are still projected to be insufficient to stop further global temperature rise (IPCC, 2023). Consequently, extreme weather events are expected to become more frequent and more destructive. These climatic threats are further intensified by rapid population growth and expanding infrastructure, which together have elevated global exposure and vulnerability to natural hazards (Bournay, 2007). As reported by the International Displacement Monitoring Centre, approximately 14 million individuals are displaced annually due to natural disasters (Rashidi & Ghalambordezfooly, 2025).

In response to this growing crisis, governments, policymakers, and humanitarian organisations are increasingly prioritising disaster resilience and preparedness as core policy concerns (Thurairajah et al., 2019). Recognising that no nation is immune to disaster risks, strategic improvements in disaster management—grounded in coordination, foresight, and logistical capability—have become imperative (Guha-Sapir et al., 2013). Within this broader landscape, post-disaster reconstruction (PDR) of houses emerges as one of the most complex yet critical dimensions of recovery (Siriwardhana et al., 2021). Unlike conventional housing projects, PDR of houses must contend with severe time constraints, limited resources, logistical bottlenecks, and the often-fragile socio-environmental contexts of affected areas (Rathnasinghe et al., 2021).

PDR is frequently hindered by chronic delays (Tas et al., 2010), with slow reconstruction prolonging displacement, heightening human suffering, and escalating costs (Weerakoon et al., 2007). On the other hand, financial limitations are acute (Lloyd-Jones, 2006), exacerbated by weak insurance mechanisms and disproportionate emphasis on short-term relief (Ginigaddara et al., 2023). Disrupted supply chains, resource shortages, and labour constraints, further impede progress and compromise construction quality (Rapone et al., 2024). Moreover, fragmented governance, inadequate inter-agency coordination, and top-down planning continue to undermine the effectiveness of reconstruction efforts (Rashidi & Ghalambordezfooly, 2025). At the same time, the pursuit of sustainable and resilient reconstruction—though increasingly recognised as essential—remains constrained by logistical, institutional, and contextual barriers (Rathnasinghe et al., 2024). Conventional construction typically operates within predictable and controlled environments with established timelines, budgets, and logistics, whereas PDR must navigate significant uncertainty, accelerated timelines, resource scarcity, and compromised infrastructure. These unique constraints amplify the relevance and potential of alternative construction techniques in addressing the pressing demands characteristic of disaster recovery contexts (Rathnasinghe et al., 2024).

Amid these challenges, interest in alternative construction strategies has grown, with particular attention to the potential of off-site solutions. Recent efforts have focused on proactive measures such as the deployment of prefabrication and decentralised logistics hubs to support emergency response and reconstruction (Shahzad et al., 2022). Off-site construction (OSC), defined as the manufacturing of prefabricated and non-prefabricated components in controlled factory environments (Rashidi & Ghalambordezfooly, 2025), has gained recognition for its capacity to enhance speed, quality, and efficiency in the built environment. Notably, modular approaches have demonstrated advantages including reduced material waste (MBI, 2010), enhanced quality assurance (Liu et al., 2021), reduced environmental impact (Rathnasinghe et al., 2024), and improved health and safety (MBI, 2010). Other frequently cited benefits include time and cost savings,

decreased dependency on manual labour, and decreased resource depletion (Won et al., 2013). As a premise, OSC represents a promising means for addressing both the speed and quality imperatives of PDR, with potential contributions to more adaptive and resilient recovery systems (Goulding & Rahimian, 2019).

Yet, while OSC has demonstrated clear technical and logistical benefits, its effectiveness in post-disaster contexts cannot be deduced to construction efficiency alone. Research suggests that the provision of standardised, prefabricated dwellings—absent community input, cultural sensitivity, or long-term integration—can undermine the social objectives of reconstruction (Rathnasinghe et al., 2021). Accordingly, a critical appraisal of OSC's potential, limitations, and future pathways when deployed in the PDR of houses is needed. Thus, this study addresses the following research question:

How has Off-Site Construction (OSC) evolved and contributed to post-disaster reconstruction (PDR) of houses, and what are the knowledge gaps, challenges, and future opportunities in its application?

To answer this, the study presents a scientometric and systematic scoping review of 113 peer-reviewed publications from 2004–2025. By synthesising thematic trends, identifying gaps, and evaluating practical implications, this study aims to reposition OSC not as a mere technical fix for PDR of houses, but as a component of a more holistic, inclusive, and policy-aligned reconstruction paradigm.

2. METHODOLOGY

The study adopted a two-phase review methodology integrating scientometric and systematic review techniques. The process involved identifying, screening, and analysing relevant literature, guided by a transparent and replicable methodology.

2.1 LOCATING BIBLIOMETRIC DATA

Scopus was selected as the primary database due to its broader source coverage compared to alternatives such as Web of Science (Rathnasinghe et al., 2024). The search strategy was designed around three interrelated thematic areas: *Off-Site Construction, the Construction Industry, and Post-Disaster Reconstruction*. Specifically, the search utilised comprehensive Boolean logic, systematically combining keywords as follows: ("off-site construction" OR "modular construction" OR "industrialised building systems" OR "prefabricated construction" OR "prefabricated housing" OR "modular building" OR "factory-built housing") AND ("post-disaster" OR "disaster recovery" OR "emergency housing" OR "temporary housing" OR "reconstruction"). The keyword combinations were consistently applied across all database searches to ensure replicability and transparency.

2.2 SELECTION OF THE MOST RELEVANT BIBLIOMETRIC DATA

To ensure methodological rigour, a defined set of inclusion and exclusion criteria was applied during the screening process. These criteria are presented in Table 1.

Table 1: Inclusion and exclusion criteria of research publications

Inclusion Criteria	Exclusion Criteria	Rationale
Publications in English language	Non-English publications	English was adopted for consistency and accessibility in global academic discourse
Publication years 2004–2025	Publications before 2004	The 2004 Indian Ocean tsunami was a turning point in global PDR discourse
OSC and PDR addressed jointly or partially in scope	Studies focusing solely on OSC without disaster context	The study is scoped specifically around OSC's role within post-disaster reconstruction
Peer-reviewed journals or indexed conference proceedings	Non-indexed publications	Ensures academic quality, reliability, and traceability

In determining eligibility, conceptual and theoretical papers were included only if they explicitly provided empirical evidence, rigorous analytical insights, or detailed case-study discussions related to OSC in post-disaster contexts. Purely theoretical or opinion-based articles lacking empirical substantiation or specific practical implications were excluded to maintain analytical rigour. Following this, the selection process adhered to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009), as depicted in Figure 1. Using the initial keyword search, a total of 152 studies were retrieved from Scopus databases.

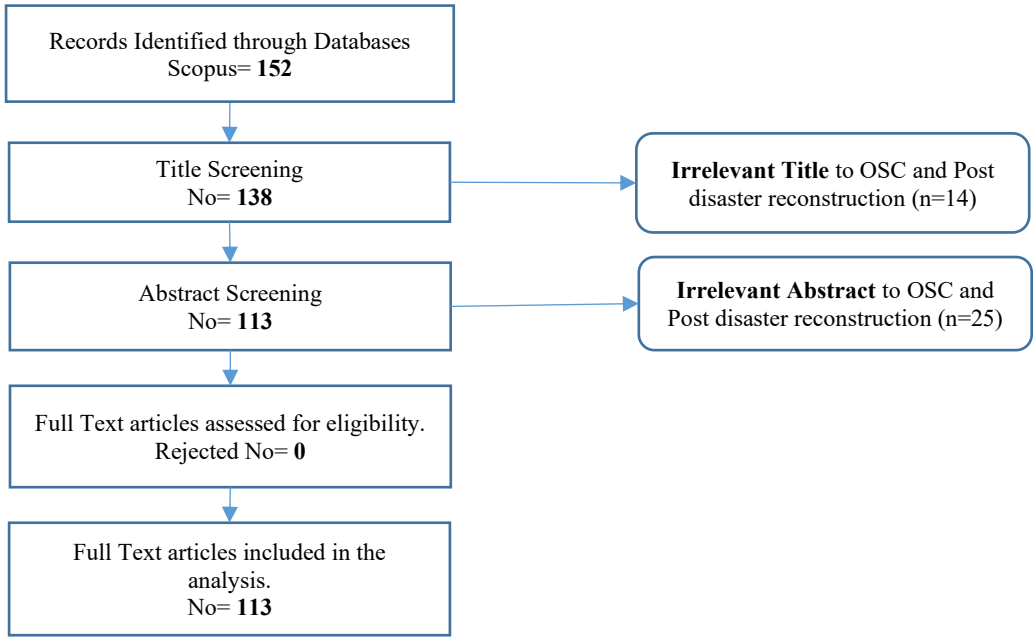


Figure 1: PRISMA guideline for evaluation and screening of retrieved articles from database search

After examining for duplicates and screening abstracts, 39 studies were excluded. The remaining 113 studies met all inclusion criteria and were retained for full-text review and analysis.

2.2.1 Scientometric Review

Rathnasinghe et al. (2024) emphasised scientometric review as an effective mapping tool for visualising connections between keywords, as well as collaborations among researchers, institutions, and countries. In this study, the VOS viewer software was used to generate co-occurrence networks of keywords from the selected 113 publications, allowing the identification of thematic clusters and emerging trends. Overlay visualisation further facilitated the temporal analysis of keyword prominence, revealing how the academic discourse has evolved over the period.

2.2.2 Systematic Review

As part of the review methodology, a systematic review was conducted to delve into the content of the 113 selected publications and assess the depth of knowledge on OSC in PDR. Although scientometric review method effectively maps research networks, it offers limited depth in content interpretation. Therefore, each included article was read in full and critically analysed to extract pertinent information focusing on three core aspects reported in the literature: (1) the advantages/benefits of utilising OSC for post-disaster reconstruction, (2) the challenges or barriers encountered in implementing OSC in such contexts, and (3) the outstanding knowledge gaps or research needs identified.

While the methodological design ensured both breadth and depth, several limitations must be acknowledged. First, the exclusivity of Scopus as the source database may have introduced a degree of publication bias, excluding relevant studies indexed elsewhere or published in non-English languages. Second, the scientometric analysis was purposely scoped to focus on keyword co-occurrence and thematic mapping, excluding dimensions such as author collaboration networks or geographic spread. Finally, although the systematic review aimed to extract and synthesise themes rigorously, it inevitably involved interpretive judgement. Nonetheless, these limitations were mitigated by transparent selection criteria and a reflexive review process, thereby ensuring a robust and credible foundation for the findings presented.

3. FINDINGS OF THE SCIENTOMETRIC REVIEW

This section discusses the scientometric review findings facilitated by VOS Viewer. The trajectory of publications over the studied period and keyword-occurrence are discussed.

3.1 THE ANNUAL PUBLICATION TREND

Figure 2 presents the annual output of research on OSC in PDR, revealing a clear upward trajectory over the past two decades.

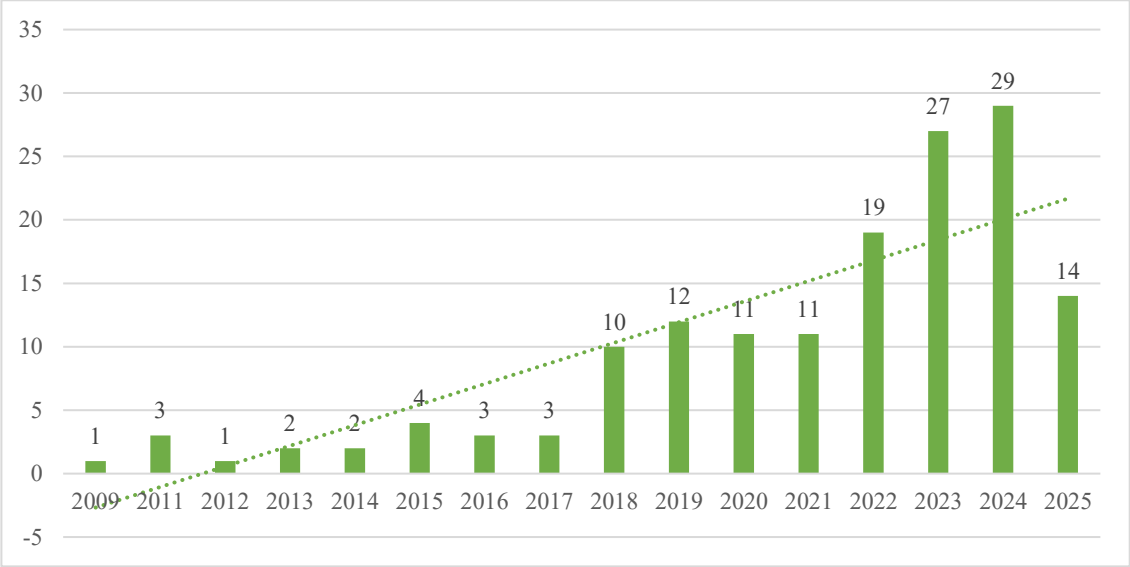


Figure 2: Annual research publications on off-site construction in the context of post disaster reconstruction

From the mid-2000s through the mid-2010s, publication counts remained modest (on the order of 1–4 per year), indicating that OSC in PDR was a niche focus during that period. A pronounced inflection occurs around 2018, after which the volume of publications accelerates markedly – rising to about 10 papers in 2018 and continuing to climb to a peak of 29 in 2024. This steady growth in output suggests that OSC in PDR of houses has moved into the mainstream of scholarly attention. The surge after 2018 likely reflects a confluence of factors: the escalating frequency of climate-induced disasters heightening the urgency for faster reconstruction methods, and technological advances (e.g. modular design, digital fabrication) that made off-site approaches more feasible and appealing. While a slight drop in 2025 (14 publications as of data collection) is observed, this is likely due to incomplete data for that year or a natural stabilisation after the 2024 peak. Overall, the publication trend underscores an increasingly vigorous research focus on OSC within disaster resilience discourse, marking the transition of this topic from a fringe interest to a prominent scholarly domain.

3.2 CO-OCCURRENCE NETWORK OF KEYWORDS

The VOSviewer's keywords co-occurrence mapping (Figures 3–4) offers a holistic view of the scholarly discourse of OSC research in PDR, highlighting which themes have been most prevalent and how the discourse has evolved. From an initial pool of over a thousand distinct keywords across the 113 publications, roughly fifty high-frequency (Freq=3) keywords meet the inclusion threshold of three times frequency to form a network visualisation (refer to Figure 3 (a)).

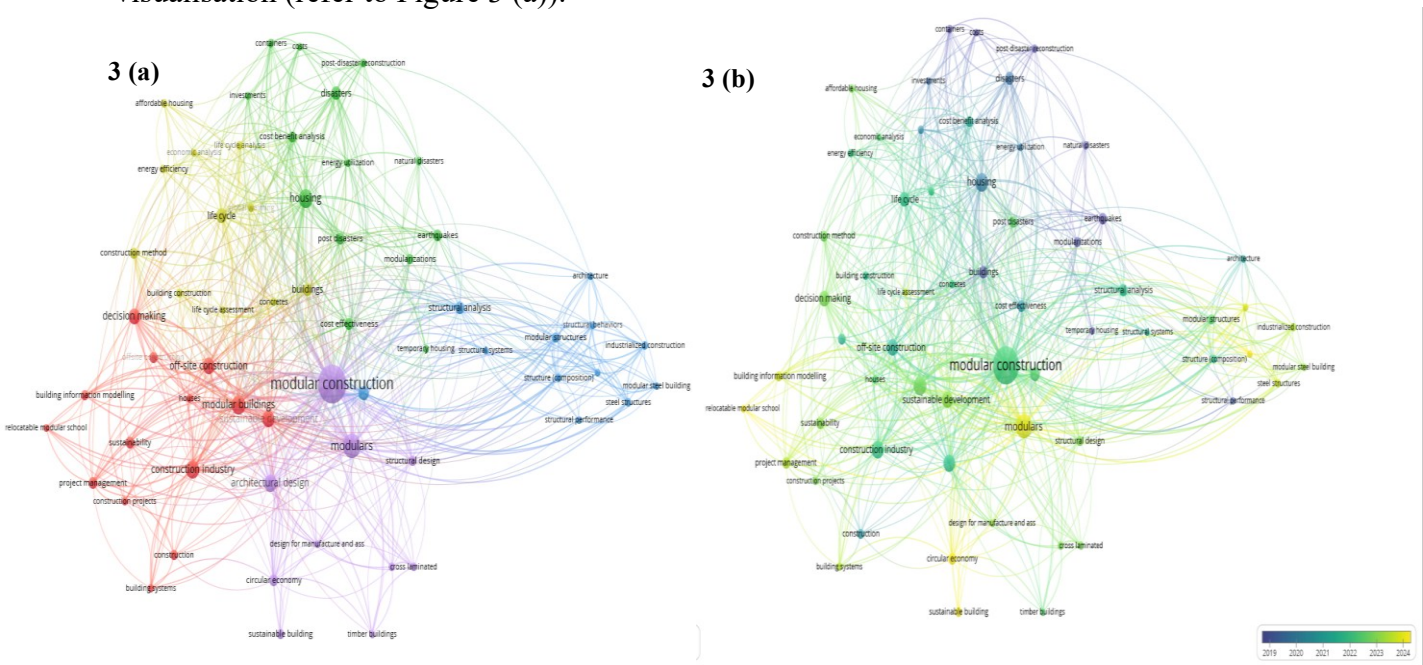


Figure 3: Keywords co-occurrence map for the OSC research in PDR context; (a) network visualisation; (b) overlay visualisation.

Several thematic clusters emerge in this network, each cluster comprising tightly interconnected keywords that denote key research strands. Notably, three overarching themes stand out as focus areas of the literature: *modular construction*, *sustainability*, and *resilience*. The prominence of these clusters suggests that the technical and strategic merits of modular/off-site building methods, as well as considerations of long-term sustainability and hazard resilience, have been focal points driving the OSC-PDR research agenda.

Crucially, the keyword network in Figure 3 informs how tightly OSC research is coupled with the PDR of houses context. The most connected and frequent terms in the network are those directly related to disasters and reconstruction. For instance, keywords such as "*disasters*," "*post-disaster reconstruction*," and similar variations form the core hubs of the map, possessing the highest link strengths (i.e. they co-occur with many other terms). This is evident in Figure 3(b), which shows OSC's robust associations with these disaster-related terms, underlining that nearly all discourse in this field is anchored to the post-disaster context. Figure 4 zooms in on the networks surrounding these pivotal terms: for instance, in the sub-network for "*disasters*" (Figure 4(a)), one observes strong links connecting the disaster theme to practical OSC concepts like "*modular construction*," "*modular buildings*," and "*housing*." Such linkages reveal that a significant portion of research has focused on leveraging modular/off-site building techniques to address the pressing needs of housing reconstruction after disasters. Similarly, the sub-network for "*post-disaster reconstruction*" (Figure 4(c)) is richly connected with OSC-related terms,

reaffirming that off-site construction is increasingly seen as integral to modern reconstruction strategies.

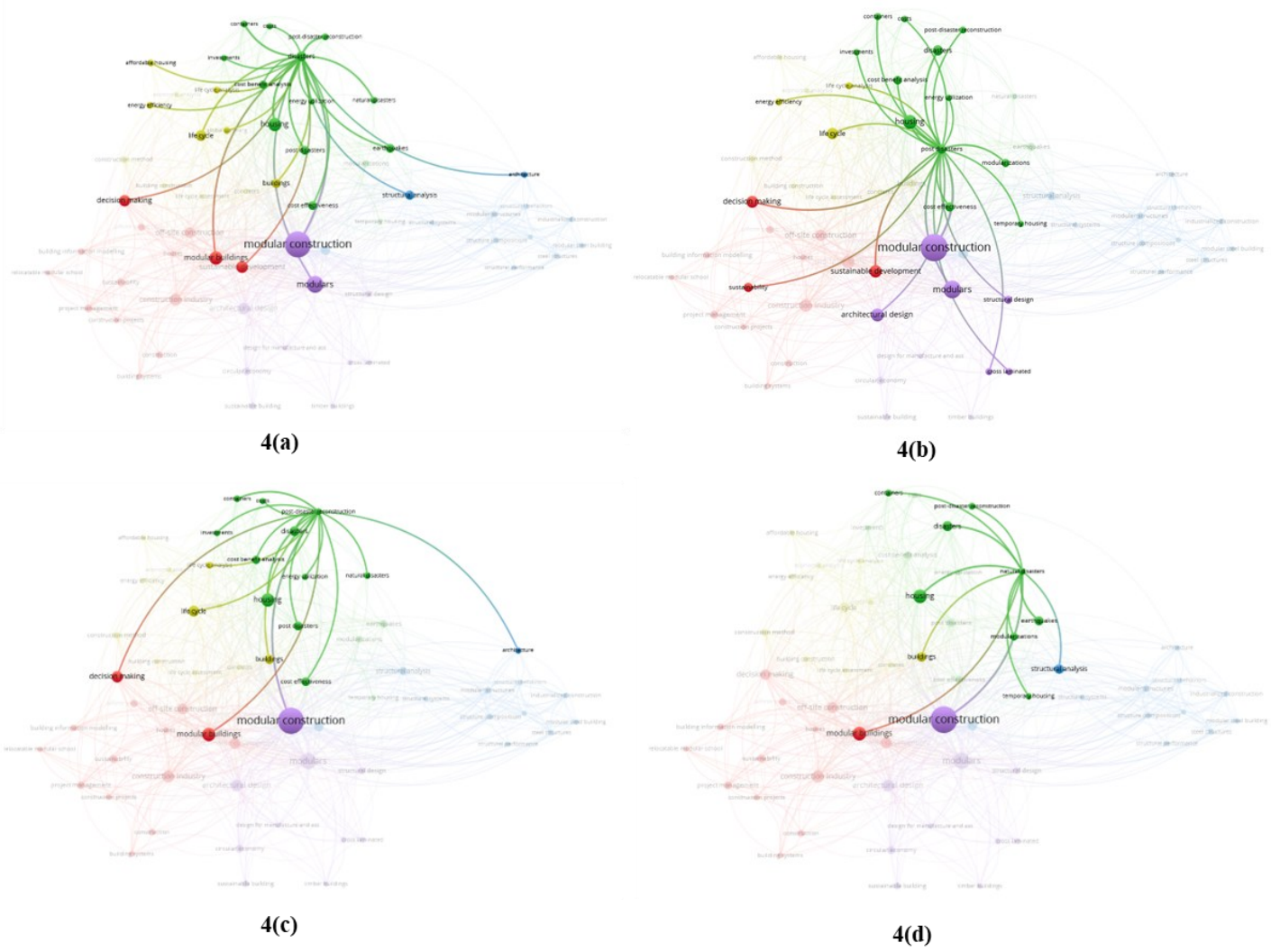


Figure 4: The keywords co-occurrence map of: (a) disasters; (b) post disasters; (c) post disaster reconstruction; (d) natural hazards

The ***evolution of research priorities over time*** is reflected in the changing weight and connectivity of certain keywords. Early in the timeline (mid-2000s), the literature appears to have centred on immediate, logistics-driven concerns – for instance, delivering temporary housing or expediting construction to shelter affected populations. As the field progressed into the 2010s and beyond, the vocabulary of research broadened. Terms related to sustainability and resilience grew more prominent, indicating a shift from purely rapid deployment of OSC towards ensuring that rebuilt communities are safer, greener, and more durable in the long run. This temporal shift, captured by the VOS viewer overlay analysis (Refer to Figure 3(b)), suggests that the academic discourse has matured: recent studies place greater emphasis on the quality and longevity of off-site solutions (e.g., energy-efficient modular units, resilient design for repeat hazards) rather than solely on speed and efficiency. In parallel, we see the emergence of keywords hinting at innovation and integration – for instance, concepts adjacent to OSC like circular economy or building information modelling (BIM) start appearing as the field interfaces

with advancements in construction practice. Such developments point to a research domain that is not only expanding in volume but also deepening in complexity, connecting with broader trends in construction and disaster management.

Another notable pattern in the co-occurrence map is the ***disparity in thematic density between technical and socio-cultural facets of OSC in PDR***. The clusters around engineering and construction-process terms are highly populated and interconnected, reflecting intensive study and a possibly high degree of saturation in those areas. By contrast, keywords that would signify social, community, or policy-oriented aspects (i.e., "community engagement," "policy frameworks," or "governance") are relatively sparse in the network, if present at all. This gap implies that while the engineering and operational benefits of off-site construction have been well documented in the literature, the softer dimensions – such as community acceptance, cultural fit of prefabricated housing, and integration of OSC into policy and institutional arrangements – have not yet received equivalent attention. The current map therefore not only charts what has been extensively studied but also reveals under-explored niches that persist. The lack of dense clusters for these social dimensions highlights an opportunity for future research to balance the discourse, as the field moves toward a more holistic understanding of OSC's role in post-disaster recovery.

4. FINDINGS OF THE SYSTEMATIC REVIEW

While the scientometric analysis offers an overview of thematic structures and publication trends, it does not capture the nuanced content of the existing literature (Rathnasinghe et al., 2024). To address this limitation and enhance the analytical depth, a systematic review was conducted. This review aimed to critically synthesise empirical findings and theoretical insights concerning the use of OSC in PDR of houses. The analysis focused on two central areas: (1) the documented advantages of OSC, and (2) the key challenges or barriers impeding its effective implementation in disaster settings.

4.1 ADVANTAGES OF OFFSITE-CONSTRUCTION IN PDR

The literature reveals a broad consensus on the benefits of OSC, particularly in time-sensitive and resource-constrained post-disaster contexts. As shown in Table 2, these advantages span four main categories: time management, financial efficiency, construction quality, and sustainability.

Table 2: Advantages of using OSC in post disaster reconstruction of houses.

Categories	Advantages	Description	Sources
Time Management	Faster deployment	Enables quick response in emergency reconstruction contexts	[1] [2]
	Time intervals are shorter	Minimises the total project timeline from initiation to completion	[3] [4]
	Parallel construction	Allows simultaneous site preparation and module fabrication	[5] [6]
	Reduced weather delays	Indoor fabrication is less susceptible to adverse weather conditions	[7] [8]

Categories	Advantages	Description	Sources
Financial	Savings on expenses	Lowers long-term project costs through efficiency and standardisation	[1] [2] [3]
	Provide low-cost mass housing	Supports affordable housing scale-up for large, displaced populations	[2] [10]
Quality	Error reduction	Improves precision through factory-controlled processes	[11]
	Enhanced component customisation	Allows design flexibility within modular production constraints	[12] [13]
	Improving productivity and performance	Streamlines construction activities through process optimisation	[9] [14]
Sustainability	Mitigation of environmental impacts	Reduces on-site pollution and supports greener construction practices	[6] [15]
	Enhanced material reuse and recycling	Promotes circular economy through planned material recovery	[4] [15]
	Promotes health and safety	Minimises on-site risk by shifting work to safer factory environments	[9] [13]
	Labour-intensive activities reduction	Reduces reliance on large on-site workforce	[4] [16]

Sources: [1] (Gibb & Isack, 2003) [2] (Aburas, 2011) [3] (Hwang et al., 2018)[4] (Xu et al., 2020) [5] (Wong et al., 2017) [6] (Kamali & Hewage, 2016) [7] (Schuldt et al., 2021) [8] (Lu, 2009) [9] (Abanda et al., 2017) [10] (Pan & Goodier, 2012) [11] (Pan et al., 2012) [12] (Nawari, 2012) [13] (Liu et al., 2021) [14] (Kamali & Hewage, 2016) [15] (Jang et al., 2021) [16] (Razkenari et al., 2020)

One of the most cited and strategically significant advantages is the capacity of OSC to accelerate construction delivery (Aburas, 2011; Gibb & Isack, 2003). In humanitarian settings, reducing time to occupancy is a critical metric of success, particularly where vulnerable populations face prolonged displacement (Shahzad et al., 2022). These expedited timelines are critically beneficial within post-disaster scenarios, directly addressing the urgent need for rapid rehousing to mitigate prolonged displacement and community destabilisation (Rathnasinghe et al., 2021).

Studies such as Rapone et al (2024) have demonstrated the reuse potential of modular units with advanced building envelopes, enabling not only immediate shelter provision but also adaptable responses in repeated disaster cycles. Additionally, OSC's process efficiency translates into tangible environmental benefits through reduced waste, controlled emissions, and safer working conditions—hallmarks of sustainable recovery models.

4.2 CHALLENGES AND LIMITATIONS OF OFF-SITE CONSTRUCTION IN PDR

Despite these strengths, the review also highlights a range of systemic and operational challenges that constrain the broader implementation of OSC in PDR of houses (Refer to Table 3). These are grouped into four overarching categories: technological constraints,

workforce-related barriers, operational inefficiencies, and financial limitations. A critical issue emerging from the literature is the lack of interoperability between OSC systems and local planning or regulatory regimes (Gan et al., 2018; Wuni & Shen, 2020). Without design standardisation, logistics coordination, and clear performance frameworks, the efficiencies promised by OSC are often compromised. This logistical complexity is notably intensified following disasters, as damaged infrastructure, compromised transportation routes, and limited accessibility significantly elevate costs and operational challenges of module delivery and on-site assembly (Gan et al., 2018).

Table 3: Challenges of using OSC in post disaster reconstruction of houses.

Categories	Challenges/ Limitations	Description	Sources
Technological	Damage during transport	Modules may suffer from structural compromise in transit	[1] [2] [3]
	Inferior imports	Low-quality materials or units may undermine long-term durability	[4] [5] [6]
	Rigid for last-minute design modifications	Design changes in post-fabrication are limited or costly	[4] [5] [6]
	Absence of acceptable size and repetition options	Limits adaptability to site-specific needs	[3] [7]
Resource	Early commitment from contractors	Requires upfront planning before full project scope may be clear	[8] [9]
	Inventory control challenges	Difficulty tracking prefabricated units during storage or shipping	[4] [5] [6]
Human	Training for current professionals and courses for new entrances	Demands specialised upskilling in modular systems	[6] [9]
	Lack of competent and professional labour	Shortage of trained workforce hampers quality and speed	[4] [10]
	Inadequate incentives	Lack of policy or financial motivation for industry adoption	[3] [4]
Operational procedures	No standardised design	Fragmented design frameworks delay implementation	[4] [9]
	Lack of standards	Absence of regulatory benchmarks complicates compliance	[2] [3]
	Lack of logistics	Weak transport and storage networks hinder module delivery	[2] [9]
	Intense emphasis on lowest bid price	Cost-cutting undermines quality and innovation	[2] [9]
Financial	High capital expenses	Upfront costs for facilities and technology are substantial	[8] [10]
	Larger initial capital expenditure	Initial funding requirements can discourage uptake	[4] [10]
	Transportation costs	Modules/ panels are costly to move over long distances	[5] [9]

Sources: [1] (Boyd et al., 2013) [2] (Gan et al., 2018)[3] (Hwang et al., 2018) [4] (Lou & Kamar, 2012) [5] (Rahman, 2014) [6] (Aburas, 2011) [7] (Kamali & Hewage, 2016) [8] (Razkenari et al., 2020) [9] (Wuni & Shen, 2020) [10] (Gumusburun & Ay, 2021)

Furthermore, while the technological infrastructure for prefabrication has advanced considerably, the institutional and policy infrastructure to support its widespread application in disaster contexts remains underdeveloped. This results in a fractured implementation landscape, where innovation is often isolated and under-leveraged.

5. DISCUSSION OF FINDINGS

Drawing on both scientometric and systematic reviews, this section reveals the critical trajectories of OSC, with attention to its role in addressing urgent reconstruction needs and its constraints in enabling long-term, socially grounded recovery.

5.1 PERSISTENT GAPS AND STRUCTURAL CONSTRAINTS

Despite clear benefits, the effective deployment of OSC in disaster contexts continues to face substantial implementation and knowledge barriers. In theory, OSC holds transformative potential for disaster recovery—moving beyond simply rapid shelter provision towards sustainable, adaptable housing that can evolve with community needs, supporting both short-term relief and long-term recovery. However, realising this potential remains challenging due to persistent structural constraints. These include bureaucratic delays, inconsistent application of building codes, and a lack of standardised frameworks, all of which significantly diminish OSC's intended advantages of speed and coordination (Rahman, 2014). Operational difficulties related to procurement logistics, transportation, and on-site assembly are particularly under-explored, especially in disrupted infrastructure environments. Social limitations compound these technical issues. A majority of OSC interventions adopt top-down delivery approaches, marginalising local input and often disregarding cultural, spatial, and social contexts (Thurairajah et al., 2019). Consequently, although delivered units might satisfy technical specifications, they frequently fail to support psychosocial recovery effectively. Furthermore, research into the long-term performance and adaptability of modular structures within multi-hazard environments remains limited, casting uncertainty over their sustained resilience (Ginigaddara et al., 2023). Studies exploring the transition of temporary shelters into permanent housing solutions are notably lacking. Few assessments rigorously evaluate life-cycle costs, modular reuse potential, environmental impacts, or post-occupancy performance (Pan & Sidwell, 2011). At the policy level, the transformative potential of OSC remains under-realised. Currently, OSC is often treated merely as a technical fix rather than as a comprehensive and transformative reconstruction approach. Fragmented governance systems and the absence of pre-approved modular standards further restrict its scalability and long-term impact (Zhai et al., 2014).

5.2 INNOVATION PATHWAYS AND RESEARCH FRONTIERS

Recent research trends point toward promising developments that seek to address these limitations. Technologies associated with Industry 4.0—including digital twins, BIM-based DfMA, and AI-driven generative design—are being investigated for their potential to enhance project planning, design flexibility, and resource efficiency (Ginigaddara et al., 2023). Yet, their performance in chaotic, uncertain post-disaster conditions remains largely theoretical, with limited empirical validation to date. Sustainability and circular

construction are also gaining prominence. Modular units embedded with renewable energy systems and reusable components are emerging as conceptual models, though current OSC literature continues to under-represent green design in practice (Abdul & El-adaway, 2020). At the material level, innovations such as seismic-resistant connections and high-performance composites are being trialled to improve the structural integrity of prefabricated buildings. However, these technologies require further testing across varied geographic and hazard contexts to establish their reliability and transferability. Overall, the future of OSC innovation within PDR lies not only in advancing isolated technological or material solutions but also in exploring the interdependencies between physical innovations (materials and modular technologies), information innovations (digital systems and data-driven methods), and cognitive innovations (stakeholder integration, policy alignment, and community-driven design). Therefore, future research should prioritise these integrated pathways, fostering comprehensive frameworks that leverage technological advancements while also emphasising adaptability, contextual sensitivity, and community resilience.

5.3 REPOSITIONING OSC IN THE LONG-TERM RECOVERY CONTINUUM

Of particular significance is a conceptual shift emerging in the literature: a rethinking of OSC housing across its lifecycle. Recent studies increasingly advocate for OSC, particularly modular systems that serve not merely as short-term shelters but as transitional assets capable of evolving into permanent infrastructure (Goulding & Rahimian, 2019). This direction calls for research into modular flexibility, participatory planning, and institutional arrangements that enable OSC to bridge the relief-to-recovery continuum. Taken together, these findings reinforce the view that the value of OSC in PDR cannot be assessed by construction speed or efficiency alone. As the study reveals, rapid deployment often comes at the cost of adaptability and local fit. Without mechanisms to embed OSC within broader recovery strategies, it risks delivering technically competent yet socially disconnected solutions. What emerges instead is the need for a paradigm shift: from viewing OSC as a logistical fix to understanding it as a platform for sustainable, inclusive reconstruction. The construction of housing units must not be conflated with the creation of homes. The latter requires design and delivery processes that are attuned to the lived realities of disaster-affected populations—supporting not only their immediate shelter needs but also their long-term recovery, identity, and community cohesion. This critical reframing of OSC will form the basis for the concluding section, which outlines the policy and research implications of treating OSC not as an end, but to support enduring, culturally responsive, and socially embedded post-disaster housing solutions.

6. CONCLUSION

This study underscores the rising prominence of OSC as a technically capable and logistically agile strategy in PDR. Yet, despite its operational strengths, OSC remains constrained by fragmented policy support, insufficient standardisation, and a persistent disconnect from the social realities of recovery. As it stands, OSC too often delivers structures, not solutions. If OSC is to serve as more than a temporary fix, it must be reframed as a transformative mechanism for recovery—one that not only addresses shelter deficits but actively contributes to rebuilding lives. This requires reimagining the modular unit not as an end-product, but as a platform for social continuity, cultural adequacy, and long-term resilience. In this light, the challenge is not to produce faster

housing, but to co-create '*transformational homes*' that can evolve with the needs and aspirations of displaced communities. Only then can OSC realise its full potential as an enabler of sustainable, dignified, and future-oriented recovery.

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BIM IMPLEMENTATION BY INTEGRATING LEAN CONSTRUCTION AND IDT (LCIDT)

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ABSTRACT

The construction industry, which makes a significant contribution to the country's GDP, continues to grapple with rising costs and project delays. While multiple factors contribute to such overruns one contributing factor is the underutilization or limited deployment of new innovative technologies and procedures. BIM is one such technology/process which have numerous benefits throughout the lifecycle of a project. However, the construction sector is still behind the rate at which innovation should be adopted due to many barriers and a heavy reliance on frameworks based on innovation adoption theories (IDT, TAM, etc.). The study utilized a systematic literature review (SLR) and a document analysis approach to seek answers for the current status of BIM and the hurdles faced by Indian construction stakeholders in its implementation. The shortlisted articles and documents underwent quantitative and qualitative content analysis. The study found that the BIM maturity in India is still very low due to various barriers, which can be eliminated by using a combination of theoretical and practical strategies. Hence, the study proposes a framework ("LCIDT") based on an integrated approach of lean construction (LC) and innovation diffusion theory (IDT) for enhancing BIM implementation. IDT can primarily help in eliminating technical and cost-related barriers, whereas LC can overcome organizational, people, and government-related barriers affecting the utilization of BIM. This framework significantly provides stakeholders with a new perspective on the barriers and integrates theoretical guidance with practical LC applications. However, future research should focus on validating the developed framework across different organizations and geographical locations.

Keywords: *Building Information Modelling (BIM); Innovation Diffusion Theory (IDT); Lean Construction (LC).*

1. INTRODUCTION

The Government of India (GOI) initially allocated ₹111 trillion towards infrastructure development between 2020 and 2025, which further increased substantially to ₹168.93 trillion indicating expanded scope and ambition (Ministry of Finance Government of India, 2020), resulting in huge demand for infrastructure construction as well as maintenance in the country due to the increasing population (Machnoor, 2021). However, as of March 2025, projects worth ₹31.1 trillion have been completed, achieving 28% of the original target. Though pace of construction in the country has tremendously increased with the applications of advanced tools and techniques, however recent studies show that a considerable number of projects overshoot budgets and anticipated timelines (Pal & Nassarudin, 2020; Shendurkar et al., 2022) and encounter difficulties with

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cooperation and coordination among the stakeholders throughout the process (Shendkar & Patil, 2017). A significant number of construction projects in India have higher cost-overruns amounting to 63%–141% of the initial budgeted cost and delays up to 79% of preliminary project milestones as compared to the worldwide average (Rajan et al., 2014). As per the June 2024 report by the Ministry of Statistics and Programme Implementation (MoSPI), among a total of 1,817 projects (with a value exceeding INR 150 crores), 458 projects have overshot the initial cost budgets, whereas 831 projects were experiencing time overruns. Some of the most common and important factors for such delays include failure to share relevant project information, lack of collaboration and communication, low productivity of people involved, disagreements among stakeholders, and lack of use of innovative technology, dearth of research on delay factors that are specific to the sector, the impact of delay factors, and the absence of standardization of innovative technologies (PMI and KPMG India, 2019; Saxena et al., 2023).

The increased need for an intelligent and environmentally friendly constructed environment only adds to the complexity of the task (Gupta et al., 2022). Utilization of novel and innovative construction techniques, including digitalization and automation are specific way to enhance the efficiency, value, and administration of construction projects and should be adopted to unleash the industry's enormous potential (Gao et al., 2019). Building Information Modelling (BIM) has been introduced with this objective from the perspective of the construction industry. However, the industry has been slower than other industries in adopting these technologies (Sepasgozar et al., 2019). BIM is widely recognized as a crucial facilitator for effectively identifying risks and achieving the intended construction management objectives among various stakeholders (Aghimien et al., 2022). BIM is revolutionizing the way in which various stakeholders in the construction industry collaborate on projects as a diverse array of BIM software applications is employed during the design, construction, operation & maintenance, and demolition phases (Patel et al., 2021). BIM has been integrated more deeply into various lifecycle phases of construction projects, further facilitating greater digitized industrialization (Gavali & Halder, 2020; Singh et al., 2021) and enhanced project delivery conditions. This has resulted in a notable enhancement in the overall performance of construction projects, from their delivery to management throughout their lifecycle (Raya & Gupta, 2022). Therefore, the Indian construction industry should embrace BIM to reduce project delays and achieve cost-effectiveness in project delivery (Shendurkar et al., 2022).

2. RESEARCH PROBLEM

The adoption of BIM has significantly transformed the processes involved in designing, constructing, delivering, and operating building projects on a global scale. BIM has seen widespread adoption in developed nations, whereas it is rarely put into practice in the context of developing nations (Arokiaprakash & Aparna, 2018). Regarding developing nations, specifically India, it can be observed that the implementation of BIM is still in its initial stages (Ahuja et al., 2020). BIM has been in circulation for a significant duration; however, its level of dissemination is inadequate (Arunkumar et al., 2018), and its application is restricted to visualization (Mohanta & Das, 2022), design management, clash detection, and automatic generation of bill of quantities (BoQs), resulting in low BIM maturity in India (Ahuja et al., 2017; Koul et al., 2023; Sood & Laishram, 2022). Nevertheless, a limited number of studies have endeavoured to leverage BIM tools

beyond traditional applications. These studies have focused on techniques such as integrating linear structures with 3D geometric surfaces to enhance the precision and efficiency of 3D reconstruction in smart city initiatives, thereby streamlining construction and maintenance procedures (Kurup & Bhise, 2024), and a framework to mitigate geometric discrepancies during segmental casting alignment of bridge elements (Babanagar et al., 2023). Additionally, the use of BIM in India is restricted only to urban and large-scale megaprojects, with rare implementation in rural or low-budgeted residential projects (Raya & Gupta, 2022; Surya & Tom, 2022). There have been few studies of BIM implementation in India at different project levels (Bhat et al., 2018; Charlesraj & Dinesh, 2020; Gaur & Tawalare, 2022; Gavali & Ralegaonkar, 2019; Mohanta et al., 2019; Pakhale & Pal, 2020; Rafi & Chari, 2019; Ralegaonkar et al., 2017) and the implementation rate is found to be very low in comparison to other countries owing to various barriers (Dhopte & Daga, 2022; Saxena et al., 2023). Therefore, it can be inferred that even after conducting various studies, BIM implementation among construction firms in India is very low and is attributable to inadequate investigation into the barriers impeding its adoption, as well as the absence of frameworks to address them.

It is recommended that the adoption of BIM in different construction organizations be handled through the lens of innovation (Murphy, 2014). There have been studies across the globe that developed and utilized frameworks based on Innovation Diffusion Theory (IDT) and Technology Acceptance Model (TAM) to understand the process of implementation of such novel and innovative technologies in the construction sector (Fakhimi et al., 2021; Gledson, 2022; Hosseini et al., 2016; Kim et al., 2016). However, even after utilizing such frameworks, the construction sector is still behind the rate at which innovation should be adopted, as these integrations are constrained to the creation of theoretical frameworks that primary stakeholders do not fully comprehend. Therefore, to address the limitations of theoretical models and improve the implementation of BIM through a practical approach, this study attempts to modify the existing frameworks by integrating them with Lean Construction (LC) principles. This approach draws inspiration from the conclusions of a few of the studies that lean construction principles, tools, and techniques can be used to enhance BIM implementation (Barkokebas et al., 2021; Demirdöğen et al., 2021; Mahalingam et al., 2015; Michaud et al., 2019; Piroozfar et al., 2019; Weerasinghe et al., 2023). Few studies that have integrated lean and BIM, with a specific emphasis on BIM as a means to achieve lean goals, have been carried out (Andújar-Montoya et al., 2020; Bhattacharya & Mathur, 2023; Ismail et al., 2023; Moballeghi et al., 2023; Tezel et al., 2020; Uvarova et al., 2023) but these studies lack a holistic framework. Hence, to address these gaps and enhance BIM implementation, the study conducted a systematic literature review to understand the current level of BIM implementation, barriers in its implementation by considering the case of the Indian construction sector and proposed a framework that combines LC and IDT.

3. RESEARCH METHODOLOGY

The research employed a combination of systematic literature review (SLR) and document analysis approach to shortlist academic literature and other documents, respectively, to gain answers to our research problem.

3.1 SYSTEMATIC LITERATURE REVIEW

The systematic review protocol is essential for the identification, screening, and critical assessment of pertinent studies. This procedure also entails the gathering and examining data that will be integrated into a review led by specific research inquiries and explicit methodologies. To organize the literature, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method is used (Moher et al., 2009), which involves evidence-based (minimum set) items for conducting systematic reviews and meta-analyses. The aforementioned methodology was instituted in the year 2009 and has gained traction across various research domains in science and technology, owing to its replicability and efficacy in enabling the development of superior processes (Sidani et al., 2021). It involves a four-step process (Shahruddin & Zairul, 2020) and has been adopted by various studies (Charef et al., 2018; Safikhani et al., 2022; Shahruddin & Zairul, 2020; Sidani et al., 2021).

3.1.1 Stage 1: Identification of Database and Keywords

Scopus database served as the primary source of data due to its free accessibility for the authors through their university and is widely recognized as a reputable database engine for academic data. This is because Scopus has indexed a greater number of journals in comparison to other data sources: PubMed, WOS, and Google Scholar (Chadegani et al., 2013). Scopus encompasses a range of data structures, such as keywords, abstracts, article types, authors, journals, institutes, languages, countries, and references, which facilitate the execution of four fundamental search techniques (Khan et al., 2021). Based on our research problem, different keyword blocks such as “BIM”, “barrier”, and “critical success factor”, and their synonyms, the following search syntax was adopted by utilizing Boolean operators "AND" and "OR":

[TITLE-ABS-KEY (“BIM” OR “Building Information Model”) AND (“Barrier” OR “Challenge” OR “Hurdles” OR “Driver” OR “CSF” OR “critical success factor*”)] AND [LIMIT-TO (AFFILCOUNTRY, “India”)].

3.1.2 Stage 2: Screening

Following the database search, 94 articles were retrieved and were further filtered by language and document type. Only journal and conference articles written in the English language were kept for the next stage, as conference papers serve as a convenient means to enhance an inclusive knowledge of the latest developments in a particular field, thereby facilitating the acquisition of up-to-date knowledge. This step resulted in a list of 78 articles which were downloaded into an MS Excel file.

3.1.3 Stage 3: Eligibility using Inclusion and Exclusion Criteria

The abstracts of the articles from the previous stage were analysed to determine their eligibility based on inclusion and exclusion criteria. The study revealed that a total of 20 articles were sourced from disciplines outside of the construction industry, while 8 articles were deemed irrelevant to the investigation of BIM in India.

3.1.4 Stage 4: Included

During the final stage, an analysis of full-text availability was conducted, revealing that four articles were not present in the database. Therefore, a finalized list of 46 articles was selected to undertake both quantitative and qualitative content analysis.

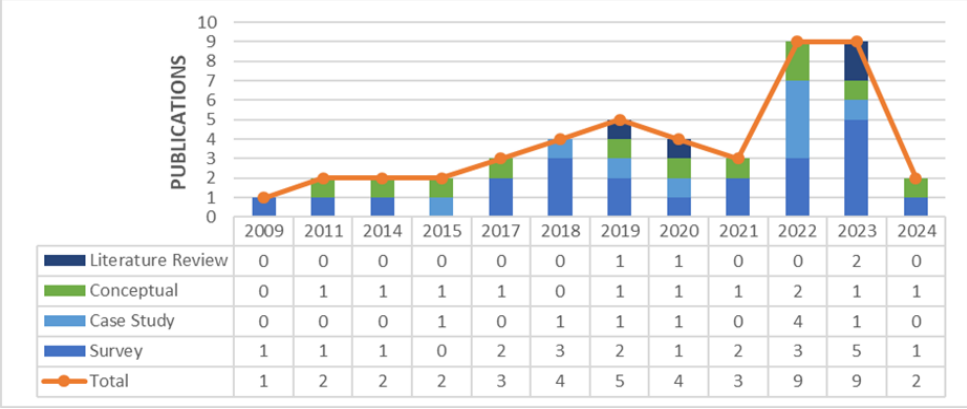
3.2 DOCUMENT ANALYSIS

Document analysis is a qualitative research methodology that involves the evaluation of many types of documents, including printed and electronic archives (Bowen, 2009). The primary objective of this approach is to generate empirical information and foster a comprehensive understanding of a specific topic. After establishing the study's background and shortlisting academic papers, further analysis was conducted on different documents obtained from online sources (such as blogs, webpages and reports) to enhance the existing knowledge about BIM implementation in India as well as validate the findings of the shortlisted papers (Bagalkotkar & Narain, 2022; Machnoor, 2021; Shetty & Narain, 2021; Verma, 2023).

4. CONTENT ANALYSIS

4.1 QUANTITATIVE ANALYSIS

The quantitative analysis classified the articles based on the year of publication as well as the method of research opted for (Figure 1). The graphical representation illustrates that the emergence of publications about BIM in India commenced in 2009 and has exhibited a favourable upward trend. The year 2009 saw the minimum number of publications, with only one article being published, while the maximum number of publications, with nine articles being published, was observed in the years 2022 and 2023. This indicates a growing interest in BIM-related studies among various researchers in the Indian construction sector. However, the aggregate quantity of BIM-centric scholarly articles published in the years 2020 and 2021 has exhibited a decline in comparison to the corresponding figure for 2019 which could potentially be due to COVID-19 impact. The articles were also classified based on the methods adopted by the authors and are classified into literature review, conceptual, case study, and survey based. The result shows that survey-based methodology that involves online/offline questionnaires, as well as interviews with construction experts, is the most preferred methodology that has been opted for by Indian researchers. Additionally, these 46 selected articles, were also classified based on the type of publications (journal/conference). It was found that 28 articles (61%) were published in various journals whereas the remaining 18 articles (39%) were part of national and international conferences. Among these journal publications, the top 3 journals with a total of 11 articles include Asian Journal of Civil Engineering



	2009	2011	2014	2015	2017	2018	2019	2020	2021	2022	2023	2024
Literature Review	0	0	0	0	0	0	1	1	0	0	2	0
Conceptual	0	1	1	1	1	0	1	1	1	2	1	1
Case Study	0	0	0	1	0	1	1	1	0	4	1	0
Survey	1	1	1	0	2	3	2	1	2	3	5	1
Total	1	2	2	2	3	4	5	4	3	9	9	2

Figure 1: Publications based on year and research method

having 5 articles followed by Buildings having 4 articles, and Institution of Civil Engineers with 2 articles.

4.2 QUALITATIVE ANALYSIS

The qualitative analysis helps to conduct the content analysis of the selected articles and other documents. Three different themes/categories for in-depth analysis have been identified.

4.2.1 Geographical Location

A study in Rajasthan (a Northern state of India) modified the BIM based on the needs of rural infrastructure development (Raya & Gupta, 2022). Based on a case study of a rural water management (RWM) project, a rural BIM (R-BIM) model was developed. This model delved into multiple facets, with particular emphasis on the BIM cloud operations, incorporating the active involvement of pertinent stakeholders. In another study conducted in Kerala (a Southern state of India), a methodology that advocates for the integration of Indigenous architectural features into the structural framework was proposed (Surya & Tom, 2022). This approach aims to facilitate the uptake of BIM within the context of residential construction projects. In addition, (Kalidass et al., 2023) conducted a questionnaire survey-based study to investigate the state of occupational safety, health, and environmental standards within the construction sector of Chennai, a major city in southern India. The study aimed to comprehend the existing conditions and assess the integration of BIM for regulatory compliance in these domains. Additionally, various infrastructure projects such as personal rapid transit in Amritsar, Bangalore international airport, Mumbai international airport, Chenab bridge in Kashmir, metro rail in Delhi, and Nagpur have witnessed successful BIM implementation in India (Shetty & Narain, 2021; Verma, 2023).

4.2.2 N-Dimensional BIM

The research on adopting BIM was further refined by incorporating multiple dimensions of BIM into the analysis. In a study conducted in Eastern India, it was determined that BIM was predominantly confined to creating 3D BIM models, primarily due to a variety of technical barriers (Mohanta et al., 2019). Similarly, Charlesraj and Dinesh (2020) surveyed to explore the prevailing level of 4D BIM usage in Indian construction projects. The results revealed that the practical implementation of 4D is very low due to the absence of in-house trained staff, reliance on traditional construction management and contracts, and scarcity of 4D BIM experts. Pakhale and Pal (2020) analyzed the Nagpur Metro Rail Project through a case study approach, with specific attention directed towards assessing both the challenges and benefits entailed in the deployment of a 5D integrated BIM system. The researchers identified the absence of a proficiently trained team, difficulties in converting from 2D drawings to 3D models, and the initial lack of a BIM contract at the project's outset. Similar conclusions have also been drawn by Gaur and Tawalare (2022) from their study of a large-scale project in India that utilized 5-D BIM technology, whereas Sood et al. (2025) emphasizes the importance of sustainability within the construction industry and the potential of 6D BIM for attaining sustainable design for buildings.

4.2.3 Barriers and Action Plans

One of the studies on barriers and action plans influencing Indian construction stakeholders' preference to adopt BIM has investigated the technological, organizational, and environmental factors affecting BIM adoption among different architectural organizations in India (Ahuja et al., 2020). The findings indicate that these firms are currently in the experimentation stage of BIM implementation, primarily due to their inability to identify critical BIM capabilities (Ahuja et al., 2017). Among the most recent studies, Gaur and Tawalare (2022) identified eight primary challenges affecting the implementation of the 5D BIM, Srikanth et al. (2023) identified cultural, legal, financial, lack of skill sets and competence, and management-related factors, whereas Umaapathy & Sundarrajan (2023) did a systematic study based on seven significant factors influencing BIM adoption in India. In another study by Mohanta & Das (2022), an online and interview survey approach was used to rank and find the significance of 14 BIM applications and 12 BIM adoption challenges. Additionally, cost-based factors (such as high costs for software, licenses, hardware, security, staff training, etc.) were found to be major barriers in the majority of studies conducted in India (Arokiaprakash & Aparna, 2018; Gaur & Tawalare, 2023; Sreelakshmi et al., 2017; Verma, 2023). However, a few other significant barriers were related to a lack of collaboration among stakeholders, insufficient resources, limited awareness and knowledge of BIM and ISO 19650 standards, cultural reluctance to adopt new technologies, legal barriers, and dependence on conventional methods (Gaur & Tawalare, 2023; Hire et al., 2021; Machnoor, 2021; Malla et al., 2024; Sawhney, 2014; Singh & Kumar, 2023; Srikanth et al., 2023; Verma, 2023).

Furthermore, a few studies have also suggested various action plans to enhance the adoption and implementation of BIM. To foster broader adoption and implementation of BIM in India, it is imperative to undertake a comprehensive analysis of both the advantages and disadvantages linked to the incorporation of BIM capabilities within organizational frameworks, along with the formulation of ways to overcome the barriers through significant adaptations at both the individual and disciplinary levels (Ahuja et al., 2016). Few studies have suggested that academic measures through BIM education at the university level (Hire et al., 2021), corporate staff training (Patel et al., 2021), organizational support (Umaapathy & Sundarrajan, 2023), social media campaigns (Surya & Tom, 2022), forming BIM groups such as the Indian BIM association (Machnoor, 2021), policy recommendations (Roy & Pawar, 2022), enhanced collaboration and transparent communication between the stakeholders (Gaur & Tawalare, 2022; Singh & Kumar, 2023) can enhance BIM implementation. Moreover, the adoption of BIM in India is often propelled by government mandates, governance models, and standards (Patel et al., 2021; Singh & Kumar, 2023; Verma, 2023), alongside the aspiration of stakeholders to get a tangible return on their investments (Bagalkotkar & Narain, 2022; Charlesraj & Dinesh, 2020; Umaapathy & Sundarrajan, 2023). Few studies have also tried to examine the role of lean construction (LC) principles, tools, and techniques as one of the most suitable strategies for mitigating coordination and collaboration-related challenges, particularly concerning metro projects (Mahalingam et al., 2015) and off-site housing construction in India (Sreeja et al., 2023).

5. CONCEPTUAL FRAMEWORK INTEGRATING LC AND IDT ("LCIDT")

A novel conceptual framework utilizing the "concept mapping" approach has been proposed based on the six-step methodology: preparation, generation of statements, structuring of statements, representation of statements through a concept map, interpretation, and utilization (Kane & Trochim, 2007). This methodology entails the use of visual representations, such as diagrams or pictorial maps, to convey concepts and ideas. The framework incorporates five categories of barriers and demonstrates the role of IDT and LC in eliminating various categories of barriers, as highlighted in Figure 2.

According to academic literature, the diffusion of an innovation approach refers to the transmission of a novel idea disseminated through targeted communication channels within a social system over a defined timeframe, whereas adoption is distinguished by a conscious choice to completely accept an innovation as the best feasible course of action (Rogers, 2003). Innovation Diffusion Theory (IDT) delves into understanding the workings, motivators, and trends of the dissemination of novel ideas and advancements in technology within different societal contexts (Rogers, 2003). The utilization of this concept has been extensive within the realm of Information Technology (IT) research, as it offers valuable perspectives on the uptake, execution, integration, and expansion of IT innovations (Fakhimi et al., 2021). The methodology offers a comprehensive set of quantitative and qualitative instruments to evaluate the probable pace of technology diffusion, while also identifying the factors that either promote or hinder the acceptance and deployment of a given technology. There exist apprehensions regarding the potential assimilation of BIM within the industry, as novel technologies do not invariably yield their anticipated transformative impact and may exhibit a slower-than-expected adoption rate or fail to gain traction altogether (Gledson, 2022). The diffusion of innovation is a phenomenon that is observed throughout society; however, the construction industry experiences a relatively low rate of innovation. As per Rogers (2003), within a given population, the initial 50% of individuals who reach a critical point of innovation adoption are comprised of innovators (2.5%), early adopters (13.5%), and the early majority (34%), while the remaining are composed of the late majority (34%) and laggards (16%). Several scholarly investigations have employed these theoretical frameworks to comprehend the BIM implementation in diverse nations. The utilization of IDT in investigating the BIM adoption among SMEs in Australia (Hosseini et al., 2016), Oil, Gas, and Petrochemical Industry in Iran (Fakhimi et al., 2021), and the UK industry (Gledson, 2022) was observed, whereas, Xu et al. (2014) and Kim et al. (2016) employed an integrated approach that combined the Innovation Diffusion Theory with the Technology Acceptance Model (TAM-IDT), to investigate BIM adoption in China and Korea, respectively.

However, in contrast to the above theoretical perspectives, Lean construction (LC) serves as an overarching term encompassing a blend of operational research and practices customized for the AEC industry, with its origins traced back to the lean production system pioneered by Toyota, a leading Japanese automobile manufacturer (Ballard, 2000; Koskela, 1992; Sacks et al., 2010). The main goal of LC is to eliminate various forms of waste from a process, thereby maximizing the value delivered to the customer (Heigermoser et al., 2019). By leveraging the principles of LC, construction processes can undergo continuous improvement and standardization (Zhang et al., 2016). This suggests that integrating principles from lean concepts can also elevate the maturity level

of BIM within organizations. There have been various studies that consider the use of various lean tools such as the Last Planner System (LPS), Integrated Project Delivery (IPD), Value Stream Mapping (VSM), and the Big Room concept as potential techniques to enhance innovation acceptance across various construction projects (Mahalingam et al., 2015; Michaud et al., 2019; Piroozfar et al., 2019).

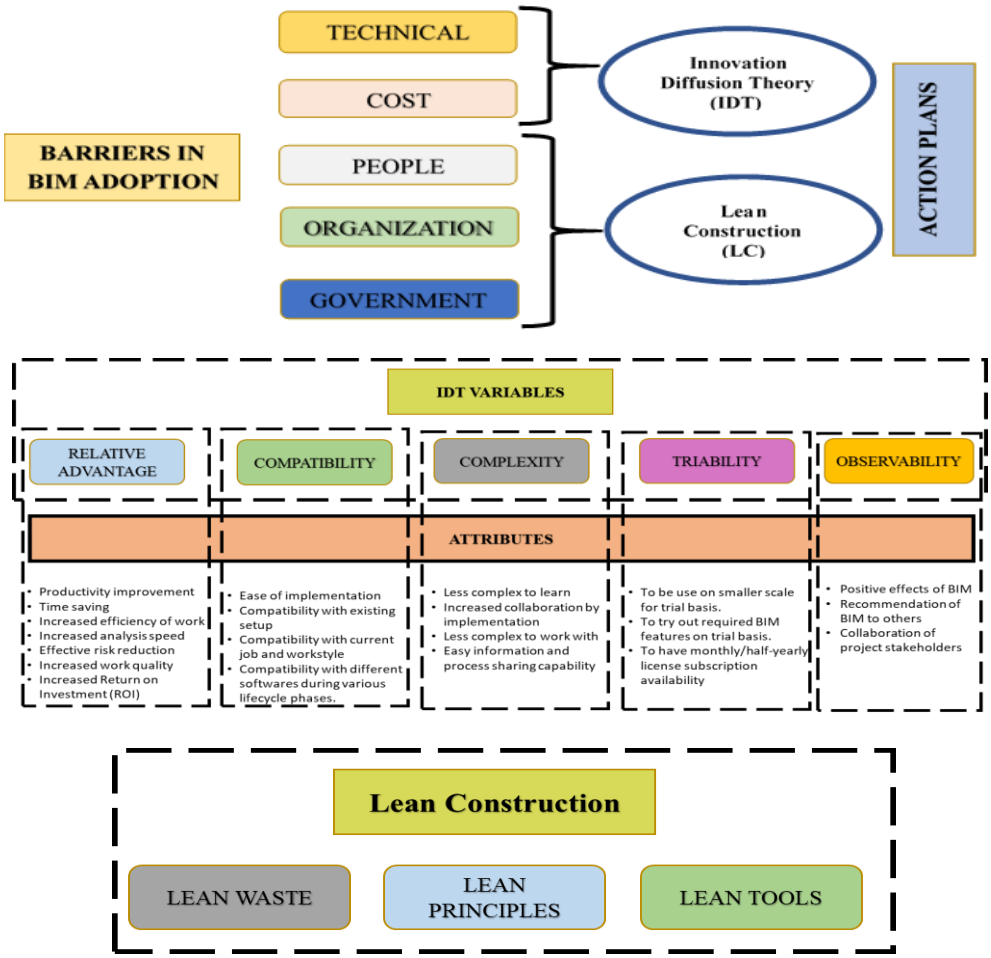


Figure 2: LCIDT - A conceptual framework

Hence, "LCIDT" has been formulated by integrating LC with IDT to demonstrate effective strategies to overcome the barriers. The barriers are classified into five different categories: Technical, People, Organization, Cost, and Government barriers, based on similar other studies (Ahuja et al., 2020; Gaur & Tawalare, 2022, 2023) and demonstrates the role of IDT and LC in eliminating various categories of barriers. As shown in the framework, IDT involves five categories of variables including innovation's relative advantage (perception of the innovation's superiority above current practice), compatibility (extent to which an innovation aligns with prior concepts, and/or perceived necessity.), complexity (level of understanding associated with the utilization or comprehension of an innovation), trialability (the extent to which the innovation can be tried intermittently) and observability (extent to which prospective adopters can perceive the outcomes of an innovation). These five variables include different attributes related to the technical and cost aspects of BIM-related software and can be utilized to select multiple BIM software during various lifecycle phases of a project, depending upon varying levels of necessity. Hence, the IDT variables can be a useful method for

stakeholders to select appropriate BIM software based on their technical requirement and purchasing power, hence eliminating technology (interoperability issues, data privacy/security issues, availability of multiple BIM software, etc.) and cost-related barriers (high cost of software, hardware, risk of low ROI, etc.).

On the other hand, LC cultivates a philosophy of improved coordination and collaboration among different project teams, further establishing a new cultural environment which will consequently amplify the adoption of BIM (Mahalingam et al., 2015). It helps in enhancing organizational learning, which aids companies in value addition through the promotion of innovations (Salehi & Yaghtin, 2015), training and standardization of processes (Schimanski et al., 2021). Furthermore, it improves the early involvement of key participants and increases the level of trust among influential stakeholders (Piroozfar et al., 2019). Additionally, few studies have suggested that enhanced BIM maturity level, as well as integrated BIM implementation (called Level 3 BIM), would not have been achievable without a thorough comprehension and use of LC principles (Barkokebas et al., 2021; Hamdi & Leite, 2012; Koseoglu et al., 2018). Hence, it can be inferred that LC can help in eliminating various organizational (lack of top management support, resistance to change, etc.), people (lack of collaboration, lack of knowledge and BIM training, etc.) and government (lack of standards and mandatory BIM contracts, lack of involvement and initiatives).

6. CONCLUSION

The study developed a framework to enhance the adoption of BIM by integrating the theoretical and practical lenses of IDT and Lean construction, respectively. In this regard, a systematic review of 46 papers (using the PRISMA technique and the SCOPUS database) along with an analysis of various online available documents was done. The authors identified 46 articles that underwent quantitative analysis based on their year of publication, research method employed, and type of article (journal or conference). Based on the qualitative analysis, the studies were analysed based on different geographical locations in India as well as various dimensional applications of BIM. It was found that BIM and other digital technologies have not yet been fully adopted by the Indian construction sector, shedding light on the current status of BIM development as well as the barriers affecting its successful implementation. It was also ascertained from the study that there is a paucity of research on the deep understanding of BIM implementation in India due to various socio-cultural and geographical factors. Furthermore, no prior investigation has employed Innovation Diffusion Theory (IDT) to analyse BIM adoption in the Indian context. Additionally, no framework has depicted the impact of Lean Construction (LC) on improving BIM implementation. Thus, the novelty of this study arises from the development of the framework "LCIDT" by integrating LC with IDT. The IDT can deal with technology and cost-related barriers by comprehending and selecting the necessary BIM tools required for different project trades and applications. Similarly, LC can help to eliminate people, organizations, and government-related barriers through the engagement of lean principles and tools. Utilizing the conceptual framework can help in the pragmatic execution of diverse emerging technologies across different infrastructure domains. Moreover, the framework can be customized according to the specific technology being considered and can be beneficial for implementing different innovations in the AEC Industry. Although the stakeholders are reluctant to deviate from

conventional construction approaches, existing literature strongly supports the implementation of LCIDT in the construction industry for effective technology adoption.

The study focuses on the implementation of LC within project organizations. However, LC applications are presently being utilized by designers, contractors, and consultants, whereas client organizations, which are one of the primary stakeholders for BIM use, remain largely unaware of its potential benefits and implementation. In addition to the contribution of this study to the body of knowledge, as part of future work, the framework can also be further enhanced by categorizing the barriers into distinct lean waste categories, and appropriate lean tools, techniques, and principles can be applied to eliminate them. Additionally, empirical research and surveys can be conducted with different lean implementing organizations and stakeholders to enhance the understanding of the applications of LC for improving the digitalization of the global construction sector. Lastly, the study selected articles from a single database, and to increase the study's comprehensiveness and validity, document analysis from other sources such as webpages, blogs, and reports was also performed. However, the study recommends the use of multiple databases as part of future studies to enhance data reliability.

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BRIDGING THE GAP: ENABLING A SECONDARY MATERIAL MARKET FOR CONSTRUCTION AND DEMOLITION WASTE

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ABSTRACT

Reintroducing construction and demolition waste (C&DW) to the construction supply chains in the form of secondary materials (SMs) has been in the global limelight over the past decades. However, the underdevelopment/non-existence of SM markets in developing countries stands as a significant barrier. Thus, this study aims to facilitate the widespread reuse of C&DW by reinforcing the SM market in Sri Lanka. The aim was accomplished by conducting an explanatory sequential mixed method research following the survey strategy. Initially, a quantitative questionnaire survey was conducted with 92 respondents, followed by a qualitative survey in the form of semi-structured interviews with 13 experts. Data were analysed through descriptive statistics and content analysis, respectively. Findings revealed that in Sri Lanka, C&DW are directed to landfills on 75% of the occasions, and only 14.47% are directed for reprocessing. Concrete, steel, and timber are the most used C&DW types as SMs. In Sri Lanka, using SMs is limited to post-disaster reconstruction, green buildings, and a few signature projects due to the absence of an established SM market. Therefore, it is crucial to overcome the limited scope and application of SMs and ensure widespread adoption across the CI by establishing a SM market characterised by a web-based digital database. Accordingly, this research contributes the realm of C&DW management, both practically and theoretically by scrutinising the role of the SM market in realising the closed loop and substantiating the ability of the SM market to bridge the gap.

Keywords: *Construction and Demolition Waste (C&DW); Recycling, Repurposing; Reusing; Secondary Material (SM) Market.*

1. INTRODUCTION

The construction industry (CI) constitutes one of the main consumers of raw materials and producers of waste worldwide (Papamichael et al., 2023). Particularly, CI consumes about 50% of the global raw material, accounting for over 35% of the energy-related greenhouse gas emissions and generates about 35% of the world's solid waste (Nawaz et al., 2023). For example, in the European Union (EU), CI is responsible for over 35% of its solid waste (Gherman et al., 2023). The fundamental reason behind the accelerated

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construction and demolition waste (C&DW) generation is the reliance upon the linear economic model of "take–make–dispose" (Shooshtarian et al., 2022).

C&DW can be defined as "A resource material that arises from construction, renovation and demolition activities, which needs to be transported from the site and has the potential to be repurposed through downcycling or upcycling" (Caldera et al., 2020, p. 7). It often consists of materials such as concrete, wood, metals, plastics, and bricks, as well as hazardous substances such as asbestos and lead (Bokarde, 2021). Traditionally, C&DW have ended up in landfills, leading to environmental degradation, pollution, inefficient utilisation of lands, unnecessary depletion of natural resources, and habitat destruction (Lindhard et al., 2023). In response, the CI adopted the concept of reverse logistics (RL) to divert C&DW from landfills (Tennakoon et al., 2021). RL supply chain (RLSC) of C&DW is "a chain of activities followed in introducing salvageable material from DW, back to the forward supply chain" (Rogers & Tibben-Lembke, 1998, p 262). It consists of five stages, namely dismantling, sorting and segregation, reprocessing, secondary market operations, and residue disposal (Jayasinghe, Rameezdeen, & Chileshe, 2019). As C&DW passes through the RLSC, recoverable C&DW are converted into value-added resources and introduced to the secondary material (SM) markets, while unrecoverable C&DW are disposed methodically (Tennakoon et al., 2021).

A SM market refers to a structured and often digitalized system that enables the trade, procurement, and reuse of materials recovered from construction, demolition, and restoration activities. These markets serve as intermediaries connecting suppliers of recovered materials with potential users, thereby supporting reverse logistics and promoting circular economy practices in the construction industry (Victar & Waidyasekara, 2023). Using SMs decreases the dependency on virgin materials, minimises carbon emissions from raw material extraction and processing, and generates economic benefits from the C&DW (Bao & Lu, 2020). Despite these benefits, SMs are less popular, especially in developing countries such as Sri Lanka, Bangladesh, and Nigeria, where weak regulatory frameworks, limited awareness, and lack of market infrastructure hinder their widespread adoption (Jin et al., 2019). Importantly, significant gaps exist between waste generation, recovery, and SM markets including the lack of proper waste segregation at source, limited reprocessing capacity, poor integration between waste collectors and reusers, and the absence of centralised platforms to connect recovered materials with potential users (Tennakoon et al., 2021). Having a rapidly expanding CI, growing C&DW generation, and the notable absence of a structured SM market despite increasing interest in circular economy practices exemplifies the need of practicaal and systematic solutions in construction and demolition waste management (C&DWM in the Sri Lanka. In response to this SM market development emerged as a pivotal area of focus in the CI (Shooshtarian et al., 2022). However, there is a lack of research, especially in the Sri Lankan context, that scrutinises the role of the SM market in C&DWM (Victar & Waidyasekara, 2023). Therefore, this study addresses the research question: "How can the gap in C&DWM in Sri Lanka be bridged through the development of a SM market?". The gap refers to the lack of a structured system that enables the recovery, reprocessing, and reuse of C&DW. Thus, the study aims to facilitate the widespread reuse of C&DW by reinforcing the SM market in Sri Lanka. Accordingly, the objectives of the study are: (1) to examine the current practices and challenges in managing the C&DW in Sri Lanka and (2) to explore the industrial need for a SM market in Sri Lanka.

2. LITERATURE REVIEW

2.1 CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT

C&DW can be categorised into two types: inert and non-inert (Caldera et al., 2020). Inert wastes are typically stable, non-hazardous, and suitable for repurposing in construction projects or disposal in public fills (Amararathne & Bandara, 2024). A significant portion of C&DW consists of inert waste, which is further divided into hard and soft inert waste. Hard inert waste includes materials such as rocks and shattered concrete, while soft inert waste includes soil, earth, silt, and slurry (Amararathne & Bandara, 2024). Contrariwise, non-inert waste may biodegrade, burn, or leak dangerous compounds, such as metals, glass, plastics, and wood (Ahmed & Zhang, 2021). Non-inert wastes are usually sent to landfills, considering handling and processing complexities, and negative environmental and health impacts. Therefore, waste segregation is essential for effective reprocessing and mitigating the associated risks (Ahmed & Zhang, 2021). This is further underpinned by the 3Rs: Reduce, Reuse, and Recycle that serve as the basis for C&DWM (Zhang et al., 2022). However, 3R strategy has now been shifted to 10R strategy: *R0-refuse, R1-rethink, R2-reduce, R3 reuse, R4-repair, R5-refurbish, R6-remanufacture, R7-repurpose, R8-recycle, R9-recover, and R10-regenerate* (Gherman et al., 2023).

Regulations have been implemented globally to reduce the negative impacts of C&DW and promote material recovery. For instance, the Waste Framework Directive (2008/98/EC) EU requires 70% of waste from C&DW to be recycled by 2020 (Shooshtarian et al., 2022). The law encourages resource efficiency and extended producer responsibility (EPR) by making stakeholders responsible for the whole lifecycle of materials. Similarly, in Japan, the Construction Engineering Materials Recycling Law mandates that wood, asphalt, and concrete materials be recycled, with the support of government incentives (Zhao, 2021). Although it is not exhaustive for all purposes, the Environment Conservation Act of 1995 in Bangladesh has a fair allowance for waste (Mustofa, 2020). Additionally, the Japanese government offers incentives for companies that utilise recycled materials, promoting a self-sustaining CE within the CI (Purchase et al., 2021). Similarly, in Korea, tightly regulated legislation on C&DWM has led to high reprocessing rates and reduced landfill dependency (Kim, 2021).

C&DW has become a major problem due to rapid urbanisation and accelerated infrastructure development in Sri Lanka (Liyanage et al., 2019). The lack of state mechanisms for collecting, sorting, and processing waste is one of the main obstacles to efficient C&DWM in Sri Lanka (Wijewansha et al., 2021). Though government initiatives encourage sustainability in the CI, they are constrained by inadequate policy enforcement, weak institutional frameworks, and limited stakeholder coordination (Weerakoon et al., 2023). As a result, significant gaps remain in Sri Lanka's approach compared to global best practices. However, the awareness of the economic and ecological benefits of sustainable C&DWM is gradually increasing, driving greater stakeholder involvement in C&DWM (Victar & Waidyasekara, 2023).

2.2 SECONDARY MATERIALS IN CONSTRUCTION

Wood, steel, and concrete are the most common C&DW that can be transformed into SM (Ginga et al., 2020). Reintroduction of waste into supply chains reduces reliance on virgin resources and makes a substantial contribution to resource efficiency (Liyanage et al., 2019). Additionally, permitting SM lessens the reliance on landfills, offers an economical

alternative by lowering the demand for virgin resources, reduces the related extraction expenses, and fosters economic resilience within the construction sector (Haider et al., 2019). Table 1 below depicts the properties of virgin material vs SM.

Table 1: Comparison of virgin material and SM

Property	Virgin Material	Secondary Materials	References
Mechanical Strength	Higher tensile and flexural strength.	Strength decreases with more reprocessing cycles due to polymer degradation. The 20% virgin material combination produced the best mechanical characteristics.	(Rahimi et al., 2014)
Thermal Stability	Higher stability due to intact polymer chains.	Reduced stability with reprocessing cycles; degradation occurs faster, particularly under thermal-oxidative conditions Compared to the virgin polypropylene (451.8 C), the recycled polypropylene had a higher maximum degradation rate temperature (457.1 C).	(Stoian et al., 2019)
Rheological Properties	Lower melt flow index (MFI), indicates higher viscosity and molecular weight.	Higher Melt Flow Index due to polymer chain scission and reduced molecular weight with each reprocessing cycle.	(Rahimi et al., 2014)
Impact Strength	Generally higher and more consistent across conditions.	Impact strength decreases significantly after the first few reprocessing cycles. The impact strength of a material subjected to 20 reprocessing cycles decreased significantly, from 87.7 J/m to 14.2 J/m, yet its functionality remained within a 15% deviation from that of the virgin material.	(Chiu et al., 2018)
Flexibility	Virgin materials maintain better flexibility and strain at break.	Reduced flexibility and elongation at the break due to molecular degradation over cycles.	(Traxler et al., 2023)
Additive Compatibility	Compatible with most standard industrial additives.	Requires higher concentrations of additives (e.g., chain extenders) to restore properties to near-virgin levels. recycled PET requires 15–20% higher additive content compared to virgin PET to achieve near-original tensile strength and thermal stability	(Chiu et al., 2018)

Difficulties in sorting and segregating C&DW due to technological constraints result in inferior quality SMs that might not satisfy industry standards. Additionally, high manufacturing costs related to quality control, advanced reprocessing technologies, and the unpredictable supply of C&DW impact the quality, availability, and price of SMs (Wijewickrama et al., 2021). Ultimately, these constraints lower the market value of SMs

and their ability to compete with virgin alternatives (Wijewickrama et al., 2021), resulting in less demand.

2.3 SECONDARY MATERIAL MARKETS

Establishing a SM market is identified as a sustainable solution to overcome the issues associated with SMs (Shooshtarian et al., 2020). Even though existing SM markets are not operating at the desired level (Jayasinghe, Chileshe & Rameezdeen 2019; Munaro & Tavares, 2023), several noteworthy efforts in establishing SM markets for C&DW can be identified globally. For example, Australia has three SM markets, namely, Buy Recycled, Business Recycling, and ASPIRE (Shooshtarian et al., 2020). Similarly, three SM markets can be identified in the US: 2Good2Waste, Materials Marketplace, and Austin Materials Marketplace. Further, Salza is an SM market operating in Switzerland, while France, Ireland, and India have Backacia, SMILE, and Mjunction, respectively (Shooshtarian et al., 2020).

Those global examples reveal that online platforms, together with digital techniques, thrive as effective SM markets due to their versatility and accessibility (Caldera et al., 2020; Shooshtarian et al., 2020). However, developing a SM market is challenging as it requires careful consideration of various interrelated aspects such as stakeholders' perceptions (Shooshtarian et al., 2020), material procurement, recycling process, plant management and market promotions (Caldera et al., 2020). Once established, SM markets can rapidly grow with the increasing supply of C&DW (Caldera et al., 2020). Moreover, they create numerous direct and indirect employment opportunities, thereby supporting the economy (Nadazdi et al., 2022). However, the absence of a proper SM market is a significant dearth in the Sri Lankan CI, which is mostly attributed to the less regulatory support for C&DW reprocessing (Victar & Waidyasekara, 2023). Therefore, it is essential to study the need for a SM market in Sri Lanka.

3. METHODOLOGY

The study was initiated by carrying out a background study to refine the research area. Next, the objectives of the research were established based on the research question. Research philosophy inspires the way of answering the research question (Saunders et al., 2009). Accordingly, this study adopted pragmatism research philosophy. Consequently, it adopted the ontological assumption that "reality is external and multiple at the same time and that a researcher chooses the view best serves his research purposes" (Saunders et al., 2009) and the epistemological assumption that "both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question" (Saunders et al., 2009). This research employed a mixed-methods approach, combining quantitative and qualitative methods. By conceptualising the ontological, epistemological and axiological stances, Maarouf (2019) concluded that pragmatism is the coherent and integrated paradigm for the mixed research approach. Furthermore, the study employed an 'explanatory sequential mixed methods' design, where the quantitative part was followed by the qualitative part to further explain the quantitative results (Maarouf, 2019).

Under the quantitative part of the study, a questionnaire survey was conducted by distributing the questionnaire via email among 175 construction professionals who were selected through purposive sampling. Accordingly, 92 responses were received, recording a response rate of 52.57%. The purpose of conducting the questionnaire survey

was to gather broad insights from industry practitioners on C&DWM and SM usage in Sri Lanka to identify prevailing trends and key issues. The collected data were analysed using descriptive statistics. Microsoft Excel was utilised for this purpose. Key measures such as weighted arithmetic mean (Equation 1), median, and mode were calculated. Subsequently, a qualitative survey was conducted with 13 experts selected through purposive sampling, as shown in Table 2, to explore the findings in depth and to capture nuanced perspectives on the structural and institutional gaps hindering SM market development in Sri Lanka. The data were collected through semi-structured interviews and analysed using content analysis. NVivo 12 was used in data organisation, coding, retrieval, and data exploration. This study followed the open, axial, and selective coding.

$$\bar{x} = \frac{\int(f \times x)}{\int f} \qquad Equation\ (1)$$

Where f = frequency and x = midpoint of each class.

Table 2: Interviewee profile

Interviewee	Profession	Criteria			
		CQ1	CQ2	AQ1	AQ2
E1	Quality Assurance Manager	√	√	√	
E2	Lecturer	√	√		√
E3	Project Manager	√	√	√	
E4	Project Quantity Surveyor	√	√	√	√
E5	PhD Scholar	√	√		√
E6	Quantity Surveyor	√	√	√	
E7	Engineer, CEO	√	√	√	
E8	Senior Lecturer	√	√		√
E9	Project Manager	√	√	√	
E10	Chartered Architect, Director	√	√	√	
E11	General Manager	√	√	√	
E12	Senior Lecturer	√	√	√	√
E13	PhD researcher	√	√	√	√

Compulsory Qualifications
CQ1 - Degree in construction related fields
CQ2 - Minimum 10 years working experience in construction projects
Additional qualifications (At least one should be fulfilled)
AQ1 - Involvement in Projects which use SMs
AQ2 - Research experience in C&DW management

4. FINDINGS AND ANALYSIS

4.1 METHODS OF MANAGING CONSTRUCTION AND DEMOLITION WASTE IN SRI LANKA

Survey findings revealed the levels of popularity of several C&DWM methods in Sri Lanka, as shown in Table 3.

Table 3: Level of popularity of C&DWM practices

Method	Frequency	Percentage (%)
Incineration	14	15.22
Landfilling	69	75
Let it subcontractor bring out of the project	01	1.08
Maintaining dumping yards	01	1.08
Offsite disposal	02	2.17
Handed over to a licensed waste disposer	01	1.08
On-site segregation of waste	60	65.22
Recycling materials	35	38.04
Reusing materials	38	41.30

Accordingly, landfilling (75%) is the most common method. On-site segregation of waste (65.2%) is also widely practised, indicating the tendency towards sustainable practices by separating reprocess able materials before disposal.

Subsequently, expert interviews explored the current C&DWM practices in depth. The findings showed the emergence of landfilling as the primary method. E2 stated, "*Landfilling is the most used method*," while E6 confirmed, "*the majority went to landfills*." Several respondents, including E5 and E13, emphasised the linear nature of current C&DWM practices. E7 described it as having "*no system in Sri Lanka*," highlighting the absence of organised C&DWM frameworks in many projects.

4.2 CONSTRUCTION AND DEMOLITION WASTE REPROCESSING IN SRI LANKA

Survey respondents were asked to identify the amount of C&DW typically directed for reprocessing from projects that they were involved in Figure 1.

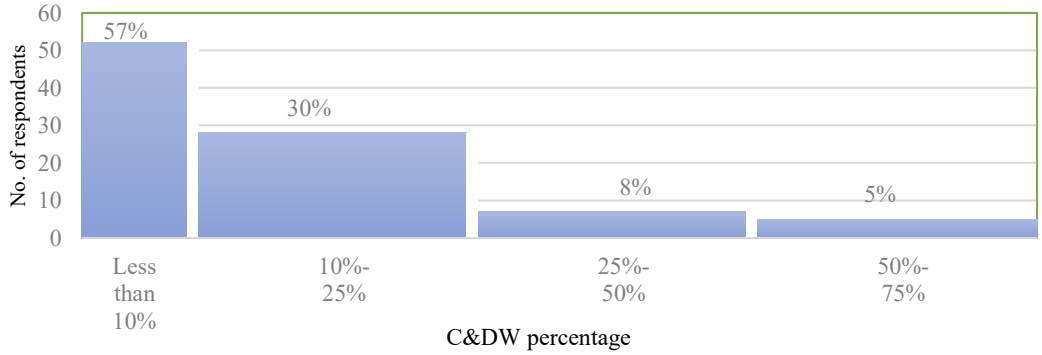


Figure 1 - Percentage of C&DW typically directed for reprocessing

According to Figure 1, occasions where at least one-fourth of the C&DW is directed for reprocessing are 13%. Moreover, as per Equation 1, the weighted arithmetic mean of the quantity of C&DW directed for reprocessing is 14.47%. Thus, despite the tendency towards segregation (as revealed in Section 4.1), only 14.47% of the C&DW is subjected to reprocessing, while the rest is discarded. Furthermore, limited public trust in the

durability of recycled materials and the absence of life-cycle data on SMs restrict their wider acceptance.

Elaborating on this further, the findings of the expert interviews revealed that reprocessing initiatives remain limited in scope and applications. E1 noted, "*it is developing but not up to the required scale*," indicating gradual but insufficient progress. However, E5's observation that recycling was "*rare*" and E6's comment about "*very few recycling approaches*" confirmed that these efforts are not yet mainstream.

4.3 USAGE OF SECONDARY MATERIALS IN SRI LANKA

Figure 2 demonstrates the survey respondents' opinions regarding the importance of using SMs in construction.

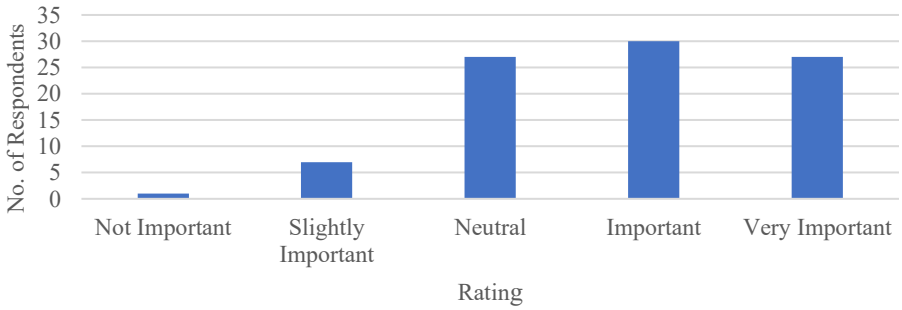


Figure 1: Importance of using SMs in construction

As per the findings, the mode of the data set is 'important', having 32.6% of the responses. Moreover, the 45.5th value holds the median position, which is 'important' as there are 34 responses up to 'neutral' and 64 responses up to 'important'. Accordingly, respondents held a positive attitude towards using SMs in construction. Additionally, 29.34% of the respondents remained neutral. However, despite the positive attitude, C&DW reprocessing is still nascent in Sri Lanka as discussed in section 4.2.

Intending an in-depth exploration of the survey results, the expert interviews focused on the different applications of SMs in the CI. The findings demonstrated varying levels of adoption across different material types. Concrete emerged as the most frequently recycled material, particularly in large-scale projects. E1 and E2 stated, "*in large-scale projects, it is concrete, concrete waste is the most reusable, recycled material*," with applications primarily in road construction as aggregate. E5 explained, "*demolished concrete waste was successfully used for low-volume roads via roller compacted concrete (RCC)*." Steel followed closely, with E12 noting its "*strong resale value*" and "*consistent recovery rates*". Timber reuse was widely reported (E3, E4, E8), though primarily limited to formwork and antique elements (E10). Furthermore, selective recovery of certain construction materials, though at limited scales, was reported. Bricks and roofing tiles showed partial reuse (E1, E7, E11), primarily in small-scale projects, while plastic recycling remained minimal due to technical constraints (E6). Materials such as gypsum are rarely recovered (E12), representing significant untapped potential. As E11 observed, "*we have reduced some of these things, but not for all*," highlighting the inconsistent adoption of material recovery practices across the industry.

Subsequently, the interviewees were questioned about the construction projects which used SMs in Sri Lanka. The responses revealed that while some projects demonstrated

innovation, widespread adoption remains limited. Post-tsunami reconstruction (2004) marked early examples of using SMs. E2 noted, "*in Galle, some projects used SMs after the tsunami*," while E10 added, "*post-tsunami reconstruction incorporated salvaged timber and roofing sheets into new buildings*." These efforts highlight crisis-driven sustainability practices.

Recycling and reusing were emerging, albeit selectively. E3 shared, "*in Kadirana, a converted office block reused 30% of materials, roof tiles and timber for new construction*." Similarly, E7 observed, "*green buildings such as MAS factories and Guga hotel utilised recycled material*s," E8 mentioned, "*a hotel in Dambulla reused C&DW, though I can't recall specifics*." Meanwhile, E9 stated, "*our organization produces paving blocks from plastic and soil-cement blocks for low-rise buildings*." Referring to the Colombo Port City project, E4 reported, "*we reused excavated materials for reclamation*," and E11 elaborated, "*We recycled debris for piling. Our workshop had a dedicated plant*." Additionally, E6 mentioned the Construction Waste Management project funded by the EU (2005–2009) as "*a pilot recycling plant in Galle that processed mixed waste into road aggregates*."

As per the findings, emerging practices reflect shifting norms. Herein, E4 emphasised, "*NSBM Green University mandates waste segregation and sustainability reporting*," while E12 noted, "*some high-rise projects in Colombo pilot on-site recycling, but structured systems are still nascent*." However, E1 admitted, "*I have seen no 100% C&DW reused projects*" and E7 conceded, "*except green-certified buildings, other buildings do not tend to use recycled materials in their projects"*. E11 added, "*recycling is still rare and people do not fully grasp its benefits*." According to E12 Sri Lanka's C&DWM landscape is dotted with '*successful pilots*' but lacks systemic uptake. As E11 summarised, "*using SM at scale is rare*," underscoring the need for policy incentives and industry-wide adoption.

4.4 SM MARKETS IN SRI LANKA

Several interviewees identified market immaturity as the key obstacle. E3 reported, "*people think they [SMs] are degraded and superstitious,"* while E10 observed, "p*eople are not aware of the possibility of using SMs. Herein, e*xperts consistently highlighted the requirement for market development. E13 emphasised that "*we do not have established second-hand market...people always follow clients' requirements for virgin materials.* E7 noted that current usage is "*based on architects' vision, not policy,"* while E9 called for "*a platform"* to facilitate transactions. The accessibility of SMs in Sri Lanka remains limited, with respondents highlighting fragmented supply chains and a lack of formal market infrastructure. E1 noted, "t*here are no very good refinery places,"* while E4 described reliance on informal networks: "*it mostly depends on connections or paper advertisements."* E6 and E12 emphasised the absence of centralised platforms, with E12 stating, "*we do not have a centralised system for trading SMs".* Most transactions occur through small-scale, informal vendors (E7, E9, E11), with E11 observed, "*You cannot buy 100 pieces of door frames".* While few markets exist (e.g., Bellanthota for old doors/windows, E9), broader accessibility is hindered by poor awareness (E10) and a lack of digital databases (E13). Importantly, E5 contended that "*SM markets face accessibility issues."* Without organised hubs or online marketplaces, sourcing remains difficult, particularly for large-scale projects.

The analysis revealed that Sri Lanka's SMs market remains underdeveloped with systemic gaps. While environmental and economic pressures are creating demand (E5, E8, E12), comprehensive solutions addressing market infrastructure and awareness (E4, E9, E10) are needed to accelerate the adoption.

5. DISCUSSION

Agreeing with Caldera et al. (2020), Lindhard et al. (2023), and Shooshtarian et al. (2022) empirical findings of this study confirm that landfilling, which is found to be 75%, is the most common destination of C&DW. On the other hand, the level of on-site segregation, which is discovered as 65.2%, and the positive attitude of the construction professionals towards using SMs, support the claim of Victar & Waidyasekara (2023) regarding the rising efforts and tendency in diverting C&DW from landfilling. Nonetheless, the average reprocessing rate, which is less than 15%, statistically proves the findings of Tennakoon et al. (2021), who highlighted the gaps in C&DW flow between the RLSC stages. Comparatively, in Australia C&DW reprocessing rate is 60%, which is lower compared to other developed countries (Kabirifar et al., 2021). In developing countries such as Bangladesh and Nigeria, weak regulatory enforcement and limited infrastructure hinder effective C&DW reprocessing and the growth of SM markets (Jin et al., 2019).

Additionally, the findings reveal the varying levels of SM usage across different material types. Agreeing with Ginga et al. (2020), concrete was found to be the most common C&DW type, which is used as a SM, followed by steel and timber. Moreover, results reveal that using SMs is not yet mainstreamed in the CI, and the scope is mostly limited to post-disaster reconstruction, green buildings, and a few signature projects. Resonating with the findings of this study, Caldera et al. (2020) highlighted the influence of post-disaster phases. Importantly, findings reveal that most of the signature projects which incorporate SMs have onsite reprocessing facilities or established mechanisms for the reuse of self-generated C&DW. On one hand, this is a noteworthy practice that heading towards a self-sustaining culture. However, on the other hand, SM usage being limited to such projects indicates the immaturity of the SM market.

Thus, this study emphasises the critical requirement of a centralised, established platform which interconnects different RLSC stages of C&DW and thereby ensures the accessibility and timely availability of SMs. Confirming the findings, Victar & Waidyasekara (2023) contended that the absence of an established market discourages potential clients and thereby decreases the demand. Further, the results validate the findings of Caldera et al. (2020), and Shooshtarian et al. (2022) regarding the web-based online SM market and highlight the lack of a digital database for C&DW in Sri Lanka. Material passports, building information modelling (BIM), and Internet of Things (IoT) devices are some commonly practised mechanisms globally to address this issue (Caldera et al., 2020).

Overall, in Sri Lanka, not only is the proportion of C&DW heading to reprocessing aiming to close the loop limited, but also the number of beneficiaries who have the opportunity to enjoy the benefits of SMs is restricted. Findings reveal the reason as the absence of an established SM market, which is backed by a digital database. Therefore, a systemic uptake is essential to outflow the environmental, economic, and social benefits of using SMs in CI beyond the successful pilots.

To the best of the authors' knowledge, this ground-breaking research is the first of that kind which sheds light on a research niche and scrutinises the SM markets in the CI in Sri Lanka. Accordingly, the outcomes of the research greatly contribute to both theoretical and practical bodies of knowledge. Theoretically, this study offers a sound understanding of the role of the SM market in realising the closed loop. Practically, it statistically proves the poor performance of C&DWM in Sri Lanka and establishes the ability to bridge the gap via a SM market.

6. CONCLUSIONS AND RECOMMNEDATIONS

Despite the growing interest towards closing the loop by reintroducing C&DW to the construction supply chains, the effectiveness and efficiency of the entire circular supply chain are affected by the SM market. Thus, this study examines the current status of the C&DW in Sri Lanka and the industrial need for a SM market by following the explanatory sequential mixed method. According to the findings, landfilling is the most common destination of C&DW in Sri Lanka, which is practised on 75% of the occasions. Out of the total C&DW generated, only 14.47% of C&DW is directed for reprocessing. Despite the positive attitude among construction professionals towards SMs, their usage is limited primarily to post-disaster reconstruction, green buildings, and a few signature projects. This is mostly attributed to the absence of a SM market, as the absence limits the accessibility to SMs, thereby resulting in decreased demand for SMs. Accordingly, it is crucial to overcome the limited scope and application of SMs and ensure widespread adoption across the CI by establishing a SM market. Therefore, it is recommended to establish a SM market that is characterised by a web-based digital database for the desired outcomes. Even though this research is conducted in the Sri Lankan context, other developing countries in the region can adopt the findings in their contexts. Further, data collection for the study was limited to construction professionals and industry experts. Thus, future researchers can expand the study focusing on the other stakeholders of the construction supply chains. Further, the next step of the research is to develop a framework for establishing a SM market.

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BUILDABILITY MOMENTUM ACROSS PROJECT STAGES: EMPIRICAL INSIGHTS FROM RIBA PLAN OF WORK TOWARDS SUSTAINABLE CONSTRUCTION

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ABSTRACT

Buildability deals with the optimal integration of construction knowledge at various project stages to achieve the overall project objectives. Incorporation of buildability improves the construction project performance in terms of its cost, quality, productivity, safety, and results in early completion. This study investigates how buildability considerations manifest throughout the RIBA Plan of Work stages, from Strategic Definition-Stage to In Use-Stage7. Using a qualitative methodology, this research draws on semi-structured interviews with a cross-section of industry stakeholders, including designers, contractors, project managers, consultants, and specialists, to uncover how knowledge, stakeholder input, and decision-making practices influence buildability at each stage. Thematic analysis embedded in phenomenological research philosophy was adopted as the data analysis method. The findings show that buildability is often underdeveloped in early design due to limited contractor involvement but becomes more prominent in Spatial Coordination and Technical Design stages through logistics, sequencing, and specialist input. Handover and Use Stages underscore the overlooked importance of commissioning, handover, and facilities management for ensuring project continuity and usability. The study introduces the Buildability Momentum Curve, a visual framework mapping the rising and falling influence of buildability insights across all RIBA stages. This curve underscores the importance of early integration and sustained knowledge flow to mitigate fragmentation and performance inefficiencies. The findings have practical implications for procurement strategies, project governance, and knowledge management systems. By conceptualising buildability as a dynamic and evolving construct, the paper advocates for a more integrated and anticipatory approach to design and delivery that spans the entirety of the project lifecycle.

Keywords: *Buildability; Constructability; Construction; RIBA Plan of Work.*

1. INTRODUCTION

The construction sector plays an essential role in the socio-economic development of a country (Rathnayake et al., 2022). Thus, success in the construction industry is undeniably vital for the growth of a nation (Osuizugbo, 2023). Lack of buildability was identified as a key factor that directly impacts the performance of a construction project

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(Samimpey & Saghatforoush, 2020). This is because the impact of buildability spans across construction projects, covering the entire procurement process and construction methods (Ansyorie, 2019; Samimpey & Saghatforoush, 2020). Buildability deals with the optimal integration of construction knowledge at various stages to achieve overall project objectives (Wimalaratne et al., 2021). There is a consensus that the design stage is critical for implementing buildability (Naoum & Egbu, 2016). Although some researchers established that buildability measures should be implemented through various stages of construction projects (Aina & Wahab, 2011; Osuizugbo & Oshodi, 2022), some researchers stated that buildability is a project management technique that runs throughout a construction project (Ding et al., 2019; Jadidoleslami et al., 2018; Kifokeris & Xenidis, 2017). Consequently, the existing body of knowledge does not explicitly articulate the presence or continuity of buildability momentum across the various stages of project development. Therefore, this study aims to explore buildability momentum across project stages by drawing on empirical insights from industry practitioners. In this study, "momentum" serves as a metaphor to describe how buildability can accelerate, stagnate, or regress depending on the application of knowledge across project stages. To systematically examine buildability momentum throughout a construction project, the RIBA Plan of Work 2020 was adopted as the structured framework for analysis.

2. LITERATURE REVIEW

2.1 CONCEPTUALISING BUILDABILITY

Buildability has emerged as a direct result of research and practical applications aimed at improving construction projects' efficiency, cost effectiveness, and quality (Griffith & Sidwell, 1997). It is a concept that deals with the optimal integration of construction knowledge and experience at various project stages to achieve the overall project goals (Osuizugbo et al., 2024; Wimalaratne et al., 2023). The Construction Industry Research and Information Association (CIRIA) in United Kingdom (UK) has published the first definition of buildability as, "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" (CIRIA, 1983).

Construction Industry Institute in United States (CII) defined Constructability, a similar term to buildability as, "The optimal use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII, 1986).

Later, the Building Construction Authority in Singapore (BCA) code of practice defined buildability as, "The extent to which the design of a building facilitates ease of construction as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building works" (Building Construction Authority, 2022).

The above definition of buildability varies slightly from territory to territory. Still, the common concept is to foster efficient decision making by fully reflecting construction knowledge and experience throughout the various stages of the project (Lee et al., 2018). Accordingly, the main components of buildability include knowledge sharing, throughout various project delivery phases, and improving construction project performance. As such the key construct of buildability includes knowledge sharing across the stages of a project.

Adding to this, Wimalaratne et al. (2023) identified knowledge sharing as the key driver of the buildability concept.

2.2 KNOWLEDGE SHARING IN CONSTRUCTION

As stated above, 'knowledge sharing' has been identified as the key driver within buildability concept. Knowledge is an exclusive concept. Tsoukas and Vladimirou (2002) described knowledge as, "the individual capability to draw distinctions, within a domain of action, based on an appreciation of context or theory, or both". There are two main types of knowledge: tacit knowledge and explicit/codified knowledge (Nishihara et al., 2017; Nonaka & Konno, 1998; Nonaka & von Krogh, 2009). Explicit/codified knowledge can be expressed in words and numbers and shared through data, scientific formulae, specifications, manuals, and the like (Hoe, 2006). Codified knowledge is generally stored mechanically or technologically in different media (Nonaka, 2007; Nonaka & Konno, 1998) and is readily transmittable between people through manuals and specifications.

Tacit knowledge, on the other hand, is not easily visible. Tacit knowledge is highly personal and hard to formalise, making it difficult to share with others (Hoe & McShane, 2010). Therefore, Tacit knowledge partly consists of hard to pin down technical skills (Nonaka, 2007). Subjective insights, intuitions, and hunches fall into this category of knowledge. Although some research suggests a third type of knowledge as 'implicit knowledge', which is the practical application of explicit, focusing on the two main types of knowledge is relevant in this study.

Knowledge transfer, exchange, or sharing does not have an agreed upon definition, and the terms are often used interchangeably with different connotations, such as information transfer. Nonaka (1994) stated that even though there is a difference, knowledge is formed due to information flows. In construction project delivery teams, knowledge gained through experience can be codified and shared as information; therefore, the terms are interrelated (Garcia & Mollaoglu, 2020). As such, Knowledge sharing involves deeper experiential understanding throughout the construction project delivery process.

2.3 THE CONCEPT OF "BUILDABILITY MOMENTUM"

Many research studies have triggered the emergence of the concepts of buildability carried out around professional fragmentation and poor construction performance in major construction capitals around the world (Wong et al., 2006). In the majority of the studies, there is a consensus that the design stage is critical for implementing buildability (Arditi et al., 2002; Lam & Wong, 2011; Naoum & Egbu, 2016). Adding to that, Low (2011) highlighted that the earlier the considerations towards buildability, the better the potential to influence the outcome. Owing to this, Samimpey and Saghatforoush (2020) emphasised that the presence of a proactive contractor at the pre-construction stage could remarkably enhance the project's buildability. However, the studies conducted by CIRIA, the first to coin the term 'buildability', found that buildability problems widely occur in the construction stages due to a lack of cooperation between designers and planners (Naoum & Egbu, 2015). In addition, CII (1987), in their "Constructability concept file", embraced all stages in building development, which had their respective impacts on achieving the overall project requirements for integrating construction knowledge. Agreeing with CIRIA and CII later studies, many researchers also criticised limiting buildability only to the design stage and argued that improvement measures are to be carried out throughout the whole building process (Griffith & Sidwell, 1997; Samimpey

& Saghatforoush, 2020). For instance, a recent study by Osuizugbo (2020) showed that buildability considerations should start at early project planning and designing stages and continue throughout all construction project stages.

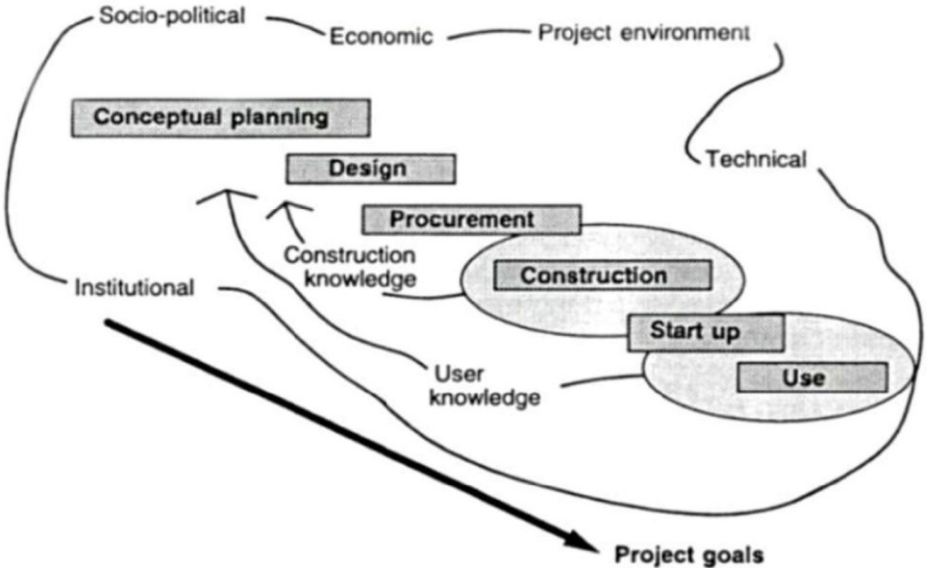


Figure 1: The wider framework of buildability
Source: (CIIA, 1993)

Figure 1 published by CIIA (1993), vividly shows the applicability of buildability in various stages of the construction project.

2.4 USING THE RIBA PLAN OF WORK 2020 AS THE FRAMEWORK

As outlined above, knowledge sharing is essential at every stage of the project delivery process to maximise buildability (Samimpey & Saghatforoush, 2020). Therefore, the selection of a suitable plan of work to capture the stages of the construction project delivery process is necessary. In this regard, several process maps, or plans of work, lay out the generic phases of a construction project. Table 1 below highlights the most prominent examples.

These frameworks and models have been helpful in developing a common language for construction sector activities. Amongst them, the Royal Institute of British Architects (RIBA) developed the most well-known plan of work. The RIBA Plan of Work outlines the activities involved in strategic planning, managing, designing, and administering building construction projects (Haylock, 2021). It organises these activities into several 'work stages'. Therefore, to capture the construction process comprehensively, the RIBA 2020 plan of work is selected as the key process for this study. Further, this plan of work is neutral to all the procurement methods.

Table 1: Comparison of plans of work
Source: (RIBA, 2020)

	Pre-Design		Design				Construction	Handover	In Use	End of Life
RIBA (UK)	0	1	2		3	4	5	6	7	
	Strategic Definition	Preparation and Brief	Concept Design	NOT USED	Developed Design	Technical Design	Construction	Handover & Close Out	In Use	NOT USED
ACE (Europe)	0	1	2.1	2.2	2.3	2.4	3		4	5
	Initiative	Initiation	Concept Design	Preliminary Design	Developed Design	Detailed Design	Construction	NOT USED	Building Use	End of Life
APM (Global)	0	1	2		3	4	5	6	7	
	Strategy	Outcome Definition	Feasibility	NOT USED	Concept Design	Detailed Design	Delivery	Project Close	Benefits Realisation	NOT USED
NATSPEC (Aus)		–	–	–	–	–	–		–	
	NOT USED	Establishment	Concept Design	Schematic Design	Design Development	Contract Documentation	Construction	NOT USED	Facility Management	NOT USED

Accordingly, the construction process development stages for this study are: Stage 0-Strategic Definition, Stage 1-Preparation and Briefing, Stage 2–Concept Design, Stage 3-Spatial Coordination, Stage 4–Technical Design, Stage 5-Manufacturing and Construction, Stage 6–Handover, and Stage 7–Use.

3. RESEARCH METHODOLOGY

Phenomenology is established as the philosophical stance for the study, and abductive reasoning is the research approach (Saunders et al., 2019). Data was collected using phenomenological interview techniques and the analysis was conducted using thematic analysis. Interviews were conducted following a semi-structured guide developed with the findings from the literature. The research strategy for this research is selected as exploratory survey (Saunders et al., 2019). The data analysis process was supported by a computer aided software program called NVivo 14. The study corroborated the findings through internal validation, thus increasing their acceptability. The following Table 2 presents the details of the respondents.

Table 2: Respondents' profile for data collection.

Ref:	Discipline of services	Years of experience
R1	Project Manager-Consultant	30
R2	Project Manager-Consultant	30
R3	Construction Manager-Contractor	28
R4	Construction Manager-Contractor	30
R5	Estimator/Tendering Manager-Contractor	16
R6	Commercial Manager (Post-Contract)-Contractor	16
R7	Estimator/Commercial Manager (Pre-Contract)-Consultant	28

Ref:	Discipline of services	Years of experience
R8	Schedulers/Programme Manager-Consultant	34
R9	Engineer-Consultant/Employer	20
R10	Engineer-Contractor	17
R11	Architect	34
R12	Estimator/Commercial Manager (Post-Contract)-Consultant	17

Professionals with over 15 years of experience with an understanding of buildability were recruited for the data collection through purposive sampling method. Participants were comprised with various stakeholders in the construction industry, such as designers, consultants, contractors, and specialists.

This study has obtained ethical approval from the University of Moratuwa Ethics Review Committee (Ethics Declaration Number: EDN/2022/013).

4. ANALYSIS AND DISCUSSION

This section presents the thematic findings from the qualitative interviews, structured according to the RIBA Plan of Work stages (0–7). Each stage reveals how buildability is understood, operationalised, and challenged throughout the life cycle of a construction project specifically in relation to its key driver, 'knowledge sharing'.

Literature synthesised that buildability discourse focused more on the early stages of construction projects (BCA, 2022; Moore, 1996). According to the research findings, buildability is ongoing throughout the work stages. Supporting this assertion, a recent study by Osuizugbo et al. (2024) introduced a conceptual framework for the execution of 'buildability assessment' during the construction management phase, diverging from the concept's traditional constraint. The literature review did not state a specific type of knowledge applicable to a particular stage of work. However, research findings acknowledged the presence of different knowledge requirements across various work stages of the construction project. Furthermore, literature shows that the stakeholder most responsible or capable of integrating buildability at a specific stage of the construction process varies (Ansyorie, 2019; CIIA, 1993). Agreeing with them, the findings found that the responsibility of buildability shifts among stakeholders throughout the different work stages. The following sub sections summarises the discussion under each work stage.

4.1 STAGE 0 – STRATEGIC DEFINITION

The findings indicated that tacit knowledge dominates at this stage, and early engagement with experienced professionals is critical. R3 stated, "*At the strategic definition stage, very defined, established data driven knowledge has to be there",* while highlighting the people's contribution. It was also noted that limited direct buildability input, but foundational understanding begins at this stage. R1 and R11 were the key contributors to sharing ideas. Key stakeholders involved in this stage include the client, risk managers, financial institutions, environmental consultants, and senior executives.

At this early stage, buildability is primarily framed through strategic foresight, client clarity, and stakeholder alignment. Several participants emphasised the value of engaging experienced consultants to advise clients on defining realistic project scopes and aligning them with future operational expectations. Interviewees highlighted the need to integrate

life cycle thinking from the outset to improve sustainability. Four key themes emerged as: client readiness, early expertise, feasibility thinking, and alignment with user needs.

4.2 STAGE 1 – PREPARATION AND BRIEFING

The respondents confirmed that codified knowledge becomes more relevant at this stage. Cost forecasting and early design estimation were found paramount to improve buildability. R1, R3, R10, R11, and R12 extensively shared their ideas under this theme. Key stakeholders involved include the architect (primary) and other professionals such as commercial managers, structural engineers, clients, project managers, consultants, and environmental experts. Merging the initial stages, R5 stated "So *in Strategic definition stage and preparation and briefing stage obviously clients knowledge and then the QSs and engineers and architects will be using their experience and high level type of knowledge to make decisions*".

At Stage 1, participants stressed the importance of brief robustness, including contributions from contractors and specialists where feasible to ensure sustainable construction outputs. Several interviewees flagged the risks of incomplete briefs, which often lead to later rework and coordination issues. Early contractor involvement (ECI) was advocated, where appropriate, to mitigate these risks and ensure buildability is embedded in early decisions. Key themes that emerged under this stage include early contractor input, stakeholder management, regulatory compliance, and multidisciplinary collaboration.

4.3 STAGE 2 – CONCEPT DESIGN

This stage is the peak point for initiating buildability momentum. Visualisation through modern technologies found enabling problem identification and solution generation. The respondents highlighted the importance of stakeholders' tacit knowledge. The respondents revealed that this stage provides the most conducive platform to convert initial intentions into practical and constructible designs.

The transition from strategic intent to technical resolution of form is where tacit and codified knowledge intersect with increasing complexity. A recurrent sentiment expressed across the respondents (R2, R5, R10, R11, R12) was that buildability concerns must be embedded early within the concept design, with one participant arguing it was "*the best place to integrate buildability or address the buildability issue*" (R10). Another participant elaborated that the integration of practical construction knowledge at this point can facilitate decisions such as the use of climbing scaffolding systems in high rise construction, reducing the need to adapt formwork or methods post design (R2), which influences the buildability of the project.

Interestingly, some respondents (R5, R6, R8) noted the fragmentation of design and construction knowledge, citing that contractor insights are often excluded from Stages 2 to 4. One remarked: "*In separate systems, 2–3 and 4 are completely separated. Contractor's knowledge is not coming in. We should value the knowledge of the contractor*" (R3). This omission presents a barrier to buildability, underscoring the need for procurement methods that foster ECI or frameworks for interdisciplinary knowledge exchange. Another contributor advocated for a knowledge sharing model that bridges expert silos and enables cross disciplinary communication (R6).

This stage highlights a transition from conceptual vision to tangible frameworks that support construction feasibility. Thematic findings show the importance of collaborative environments, particularly with contractor and specialist inputs. Participants noted that decisions regarding structure, materials, and spatial logistics made here are foundational to improving buildability towards sustainable construction delivery. Key themes emerged include specialist engagement, interdisciplinary knowledge exchange, and decision making on material and structural feasibility.

4.4 STAGE 3 – SPATIAL COORDINATION

R3, R4 and R12 extensively shared their view under this theme. Stage 3 of the RIBA Plan of Work represents a critical transition from concept to detailed articulation of the design. In this stage, the implications of design decisions on buildability become more tangible, and the collaborative input of stakeholders intensifies. Input from end-users and technical collaborators at this stage were found vital. Findings from interviews reinforce the imperative of integrating multidisciplinary expertise and recognising the contextual variability of projects, particularly with respect to practical constraints and construction feasibility. According to R2, R7, and R5, tacit and codified knowledge merge during this stage. The interviews revealed a growing emphasis on collaborative detailing through Building Information Modelling (BIM) and other digital platforms. Although not always explicitly mentioned, references to spatial and technical design refinements (e.g., according to R2, "*fine-tune the design*") imply the use of digital coordination tools that synchronise diverse inputs.

At this point, the integration of multiple design disciplines becomes paramount. Interviewees reported that coordination errors and poor technology utilisation at this stage significantly compromise buildability. There was consensus on the need for increased digital maturity and clear interface management across systems. Many participants highlighted the effective use of technologies such as BIM for sustainable construction deliveries. Three key themes emerged include multidisciplinary collaboration and stakeholder engagement, digital collaboration, practical integration of tacit and codified knowledge, and spatial coordination.

4.5 STAGE 4 – TECHNICAL DESIGN

During Stage 4, the translation of conceptual ideas into executable components intensifies. Respondents widely acknowledged this stage as a pivotal zone for integrating practical, codified, and experiential knowledge to ensure that design outcomes are both constructible and aligned with project goals. For instance, R5 highlighted the convergence of scientific rigour and real-world intuition, stating "*detailed calculations based on theoretical stuff*" and the "*need to have your experience and knowledge*" to explain this. This aligns with R4's assertion that this stage requires a blend of "*codified knowledge and tacit understanding*" to ensure that complex technical decisions reflect feasible on-site applications.

Further, R4 underscored the "*technology involvement*" as essential across Stages 3–5, with Stage 4 being particularly dependent on accurate digital detailing to translate the concept into a buildable reality. Hence, buildability at Stage 4 is best understood not as an isolated exercise in technical design but as a cumulative expression of upstream knowledge flows, collaborative engagement, and contextual responsiveness. Both R5 and

R7 agreed that codified knowledge leads in this stage, while tacit knowledge guides critical judgements.

Participants identified this stage as a critical buildability inflexion point. Key concerns included insufficient buildability reviews, unclear detailing, and the marginalisation of construction knowledge. Several interviewees advocated for structured reviews, involving both contractors and trade specialists, to test the buildability of drawings before final sign-off. Three key themes emerged under this stage, including convergence of practicality and precision, stakeholder expansion and technical interdependence, and interdisciplinary detailing and digital collaboration.

4.6 STAGE 5 – MANUFACTURING AND CONSTRUCTION

The findings from Stage 5 present a pivotal shift in the nature and dominance of knowledge contributions to buildability. Unlike the early design stages, which were heavily conceptual and reliant on collaborative insight, this stage embodies the tangible execution of design intent, where tacit knowledge and real time problem solving are paramount.

A consistent theme across multiple respondents' responses is the recognition of the 'contractor's central role' in shaping buildability during this stage. Contractor led knowledge, described as both superior and practical, was repeatedly highlighted as essential for effective execution. For instance, R9 asserted that "*contractor's know how is more prominent*" proposing that their practical grasp often outweighs that of design professionals when it comes to complicated construction challenges. This sentiment is echoed by R10, who emphasised the value of the "*project manager's integrative knowledge*" and the "*critical importance of logistics and construction sequencing*", both of which directly influence the buildability of construction on site.

Another emerging theme was the "dual reliance on tacit and codified knowledge". While some participants (e.g., R5, R12) stressed the enduring importance of building codes, standard documents, and theoretical frameworks, there was a clear consensus that "practical, experiential understanding" accumulated over time and contextualised to site-specific conditions becomes dominant at this stage. The interviews revealed that presence of external stakeholders such as regulatory bodies, utility providers, financial institutions, and safety officers adds another layer of complexity to buildability. These contributors not only verify compliance but also influence temporal and logistical dimensions, reinforcing the need for early coordination and robust communication pathways established throughout RIBA stages.

R4 emphasised that "knowledge pooling" and collaborative discussions at this stage are essential for a coherent execution strategy. Meanwhile, R1 and R10 outlined the necessity for "multi-disciplinary expertise" including sustainability consultants, procurement and contract specialists, and IT systems managers, reflecting the operational complexity of modern construction. In Stage 5, tacit knowledge was found prominent.

Stage 5 findings confirmed that buildability manifests most visibly during physical construction. Participants highlighted the importance of logistics planning, sequencing, and tacit knowledge transfer from experienced personnel. Specialist subcontractors were noted as critical actors in resolving on-site challenges. The success of this phase relies heavily on the robustness of earlier design decisions and collaboration among the key stakeholders. Three key themes emerged include contractor's central role, dual reliance

on tacit and codified knowledge, and knowledge pooling and collaborative discussions sharing tacit knowledge.

4.7 STAGE 6 – HANDOVER

Stage 6 marks the culmination of the construction process and the transition to operational occupancy. Although often perceived as a technical and procedural step, the findings reveal that this phase involves nuanced knowledge exchanges, significant specialist involvement, and a critical interface between design, construction, and end user operations. Respondents consistently referred to the need for dedicated professionals such as handover specialists, life safety consultants, MEP and low voltage engineers, and commissioning experts. For instance, R1 elaborated on the structured presence of "handing over specialists" whose expertise lies in ensuring functional integrity, testing, and life safety compliance of technical systems. Moreover, there is strong emphasis on the importance of codified and tacit knowledge working in combination. Certifications, compliance documentation, warranties, and standards based testing form the codified knowledge backbone of this stage. As R12 noted, municipal councils, regulatory bodies such as CIDA, and sustainability certification frameworks like LEED are all active participants in confirming the quality, safety, and sustainability of the final product. Yet, this technical closure is insufficient without practical orientation and user education, particularly when novel technologies are introduced into building systems. Participant R4 identified this educational role as crucial, stressing that the end users must be adequately informed and trained to operate the built facility efficiently.

Another key finding is the emergence of new stakeholders during this phase. For example, facility managers, asset managers, owner operators, and end users. These stakeholders were less visible in earlier stages but have now become central to the ongoing performance and maintainability of the building. Notably, some participants like R10 expressed a sense of limited agency at this stage, asserting that "*you're unable to do anything by the time the project reaches handover".*

This stage reveals the complexity of transferring the building from project teams to end users. Participants highlighted the role of handover specialists, particularly in commissioning safety systems and digital networks. Certification bodies and municipal councils' involvement in issuing final compliance documents was highlighted. Participants emphasised the importance of life safety consultants, knowledge transfer mechanisms, and client education, especially where novel technologies are introduced. Four key themes emerged under this stage as the specialist led nature of the handover process, documentation and compliance, the importance of codified and experiential knowledge working in tandem, and limited agency for knowledge sharing.

4.8 STAGE 7 – IN USE

Stage 7 shifts focus from construction to operational performance, user experience, and long term asset management. The findings reveal that buildability does not end at handover but continues through use based learning and operational feedback. End users and facilities managers take centre stage in this phase. R12 and R3 emphasised the involvement of these stakeholders in maintaining the design's performance intent. R1 noted that "*the specialist could even be the end user*!" highlighting how operational insights can reveal issues overlooked during earlier phases. Contractors may remain involved post handover through warranties and support services (R12). According to R4,

modern buildings often feature advanced technologies, but users may lack the digital skills to operate them fully. R4 and R12 recommended structured onboarding through user manuals, digital twins, and interactive training to bridge this gap. R3 added that involving facilities managers earlier in the process could reduce inefficiencies and improve lifecycle performance. R2 stressed the importance of lived experience and feedback stating, "*you might need to engage with the other stakeholders to fine tune the design*." R3 noted that architects and consultants often continue to assist post handover, indicating that professional responsibility extends beyond design and construction.

The final stage underscores buildability as a life cycle philosophy. Interviewees indicated that post-occupancy performance and usability are contingent on effective knowledge transfer, end user training, and responsive facility management. Further, in this stage, digital competency becomes more critical if the project comprises numerous innovative technologies. End users, facility managers, and maintenance teams emerge as new custodians of buildability. Key themes that emerged include harness specialist knowledge can reside with the end user, knowledge transfer and digital competency gaps, buildability as a life cycle philosophy, and feedback mechanisms.

5. BUILDABILITY MOMENTUM CURVE

The Figure 2 illustrates the momentum of buildability across the RIBA Plan of Work stages. It represents the intensity and nature of buildability contributions over time, integrating findings from Stages 0 through 7. Thematic analysis embedded in phenomenological research philosophy lead to creation of the buildability momentum curve. The curve shows that buildability is often underdeveloped in early design due to limited contractor involvement but becomes more prominent in stages 3–5.

Handover and Use Stages 6 and 7 underscore the overlooked importance of commissioning, handover, and facilities management for ensuring project continuity and usability.

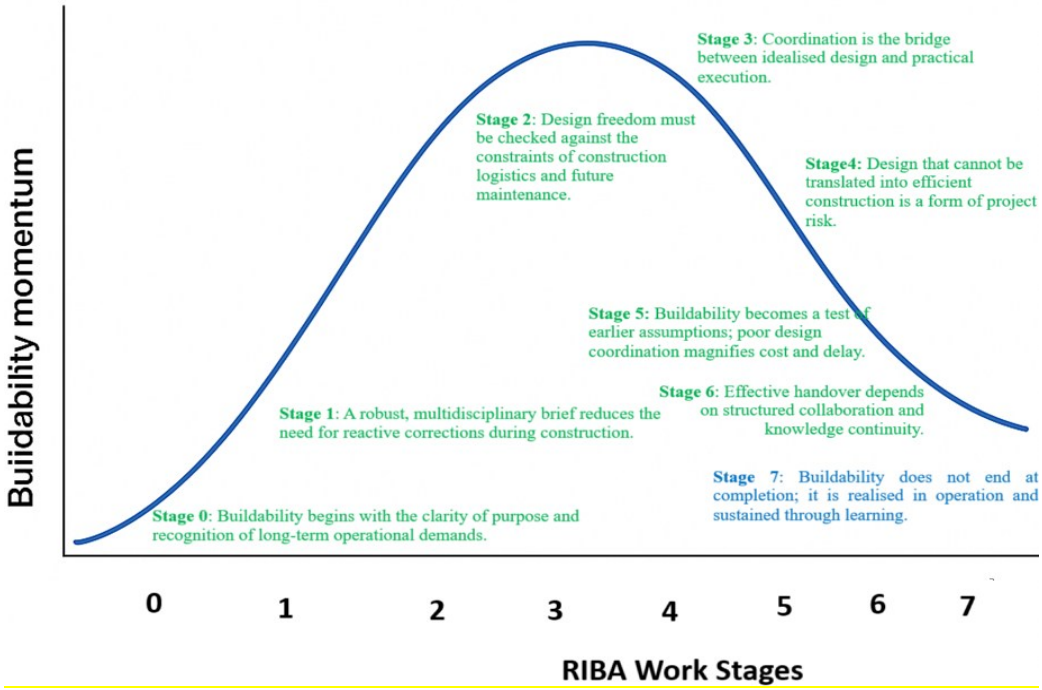


Figure 2: Diagram of the buildability momentum curve based on the RIBA Plan of Work stages

6. CONCLUSION

This research has provided a nuanced exploration into the dynamic integration of buildability across the RIBA Plan of Work 2020 stages, revealing a progressive accumulation of knowledge, collaboration, and decision-making that collectively fosters sustainable construction outcomes. By investigating stakeholder insights across all eight RIBA works stages, the study offers empirical evidence of the shifting nature and increasing significance of buildability considerations throughout a project's lifecycle. The findings indicate that while buildability begins conceptually in the early design stages, it gains substantial momentum in the technical design, manufacturing, and construction phases. These mid-stages are pivotal, acting as convergence points for tacit and codified knowledge from designers, contractors, and specialists, where theoretical planning transforms into practical execution. The contribution of the contractor and other implementation specialists becomes particularly critical from Stage 4 onwards, highlighting the importance of early contractor involvement and interdisciplinary collaboration. During later stages, particularly Stage 6 and Stage 7, the study finds that buildability evolves into maintainability and usability, necessitating structured knowledge transfer to facility managers, end users, and asset operators. Ultimately, this research positions buildability not as a static checklist, but as a momentum gathering complexity, insight, and impact across each stage of the RIBA framework. By capturing the voices and experiences of practitioners across disciplines, the study advocates for a more integrated, knowledge-driven, and strategically sustained approach to buildability that is essential for achieving resilient and sustainable construction outcomes in contemporary practice. The findings are limited to the ideas collected from the 12 professionals. The findings have practical implications for procurement strategies, project governance, and knowledge management systems within construction project teams. Additionally, the research bears the limitations arise from the specific data analysis methodology employed. Future research is encouraged to address these limitations by

developing stage specific buildability image models using AI and comprehensive buildability checklists to support implementation across all project stages.

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BUILDING ENERGY DATA MANAGEMENT SYSTEMS IN THE WORLD: A REVIEW

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ABSTRACT

Due to the growing number of buildings with higher population and urbanisation, tracking energy consumption in buildings is essential in reducing global energy demand and carbon emissions. For that, governments and energy-related international bodies have created many databases to collect data on building energy consumption and provide energy statistics based on that. This paper focuses on reviewing building energy databases in the world to study their policy implications and applicability in reducing building energy consumption. The qualitative approach was used in this study, and highly reputed and highly cited 09 databases were selected for the review. Among them, 04 databases provide energy benchmarks for buildings under different types of categories, while 05 databases provide energy statistics only. These databases allow government authorities to monitor the energy performance of buildings, determine tax credits and incentives for energy performance, rate the buildings and prioritise low-performing buildings for setting action plans. In addition, some of those have led to revisions of building codes and received the direct involvement of the relevant stakeholders through mandatory disclosure of energy data. Organisations also use these databases for marketing purposes, highlighting their high performance and allowing them to identify performance gaps. All the databases have been developed along with energy policies at the national and international levels. Compared to developed countries, energy databases are lacking in managing energy consumption in the national building stock. Especially, there is no energy database for the Sri Lankan building sector.

Keywords: *Building Energy Consumption; Building Energy Databases; Building Energy Data Management Systems; Building Performance Databases.*

1. INTRODUCTION

With the rapid population growth, building energy consumption has dramatically increased, contributing a significant portion of the global energy supply and demand over the past few years (Ali et al., 2020; Marinakis, 2020; Sun et al., 2020). An increase in energy demand directly affects the global Green House Gas (GHG) emissions, which has a significant impact on global climate change. Buildings contribute to 30% of global final energy consumption while accounting for 26% of global energy-related emissions by 2025 (Delmastro & Chen, 2023). However, numerous opportunities exist in buildings to

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reduce energy consumption in buildings promoting a sustainable built environment. According to the IEA, energy efficiency improvements of buildings can decrease up to 70% of the energy-related emissions by 2050, and buildings will be 40% more energy efficient by 2040 (Ali et al., 2020).

Currently, there is a global tendency for a shift towards global exchange of building energy data, energy performance analysis, and building energy efficiency policies (Ali et al., 2020). Due to the development of technology massive amount of energy data is being generated in every aspect of buildings, and building systems are being digitised rapidly (Marinakis et al., 2020). This accumulated data can be effectively utilised to optimize power generation, predict electricity demand, discover electricity consumption patterns, and develop dynamic pricing mechanisms (Li et al., 2023; Zhou et al., 2016). Thereby, the building sector can effectively manage energy consumption, and the government can regulate the energy supply and demand effectively because it integrates the demand side management and Demand Response (Kathirgamanathan et al., 2021).

Data-driven approaches in building energy management have gained higher popularity over the past few years (Ahmad et al., 2018; Amasyali & El-Gohary, 2018; Kathirgamanathan et al., 2021; Li et al., 2023; Marinakis et al., 2020; Sun et al., 2020; Wei et al., 2018; Zhou et al., 2016). Data-driven approaches enable the prediction of energy consumption, which is imperative for improved decision-making on reducing energy consumption and environmental emissions and estimating the economic feasibility of further energy conservation opportunities (Wei et al., 2018). In addition to that, according to Mathew et al. (2015), empirical energy data has a wide range of potential in energy efficiency, assessment of energy policies, energy management and energy planning. Further to the authors, comprehensive energy databases can consolidate data throughout the industry, reducing the data collection cost, creating new opportunities to analyse building energy data and accessing many stakeholders. Large-scale empirical building energy data provides benefits to the government, stakeholders in the energy industry, investors in energy efficiency and policymakers (Luo et al., 2021).

Therefore, empirical building energy databases play a key role in supporting national-level energy policy assessments. Some of the databases record asset data and in-depth energy use as a representative sample of different building stocks (Ye et al., 2019). Those databases aim to keep datasets for energy planning and forecasting purposes. However, they provide summary statistics of the national building stock. To reduce the energy consumption and environmental performance of the building stock, governments set energy and environmental policies (Shen et al., 2020). To make informed decisions in setting national building energy policies, some governments are monitoring the energy consumption of their building stock (Luo et al., 2021). It helps them to identify the effectiveness of the policies and initiatives to identify which policies provide more benefits, to invest wisely in implementing those policies and initiatives (Carnieletto et al., 2019).

However, there is a limitation in the literature focusing on the policy implications of building energy data management systems in the world. Therefore, this study focuses on reviewing existing building energy data management systems to assess how they have been used to achieve sustainable development goals and energy policies at the international level, regional level or country level. In this paper, existing energy databases are reviewed on the data collection methods, outcomes of the databases, applicable

policies and national-level initiatives, and how they support to achievement of the intended outcomes of the energy policies. In addition to that, this paper discusses the level of usage of energy databases in achieving energy management policies in different countries.

2. METHODOLOGY

A qualitative, descriptive review approach was used in this study to evaluate existing building energy data management systems that have been implemented in different countries and global level. The main objective of this research is to review the structure of the database, types of energy data provided by the database, functionality, insights they produce, and the role of these systems in supporting organisational and national-level energy policies. Mainly, two primary sources were used for the data collection for this study. Google Scholar was used to access scholarly literature such as journal articles and conference papers that address specific energy data platforms and the policy implications of those data platforms. In addition to that, up-to-date information regarding building energy data platforms was collected from the official websites of the respective organisations.

Both technical details and real-world examples of system applications were provided by these sources, allowing to conduct a comprehensive review of the purpose, design, and output of each platform. When considering the selection criteria, energy data platforms, databases or systems that are publicly available or well-documented were selected for this study. Even though more than 50 building energy databases are available in the world, globally and regionally highly recognized and highly cited databases were selected for this study due to limitations in time and publicly available data. Only 09 databases were examined for this study. All the databases or platforms were reviewed to identify the type of energy data collected and displayed, such as electricity consumption, air pollution, energy performance etc, data sources used for the data collection, types of analytics or findings presented, target users and role in supporting energy policies at the national and international level.

Since the data was collected through publicly available content from websites and scholarly literature accessible through Google Scholar, some systems with restricted access or limited documentation may not be represented in this study. This study is based on the sample of energy databases at the international level, regional level or country level.

3. REVIEW OF EXISTING BUILDING ENERGY DATABASES

Due to the climate change impacts, governments are struggling to improve the lives of people while improving energy efficiency to reduce fuel poverty and fight climate change (Shen et al., 2020). Different governments, professional bodies, international organizations and interest parties in the energy industry have introduced more policies, initiatives, technologies and methods to improve energy efficiency to combat the climate change impact (Ye et al., 2019). However, it is important to identify the best solution that works best for each consumer by monitoring their consumption patterns closely (Buchanan et al., 2014). For that, different governments and international organizations

have introduced databases to monitor the energy consumption of the building stock and provide benchmarks for energy performance in buildings.

Figure 1 shows the country-wise evolution of building energy databases. An upward trend can be identified in the building energy database development during the 2000-2025 period. In the early 2000s, a slow growth in energy database development in the building sector. At the initial stage required data for building energy policy formulation was collected through one-time national surveys and manual data collection methods due to limited digital integration. Energy performance certification mandates and energy performance benchmarking come into the picture slightly. However, there have been a few local pilot projects and academic databases. A significant policy-driven expansion can be identified during 2005-2010. Several government mandates were set with the requirement of standardisation and mandatory reporting. UK NEED (2006), Australia NABERS (2007) and ENERGY STAR Portfolio Manager (2009) are a few examples of databases that originated in this period. Web-based reporting was initially introduced in this period.

A digital and open data boom can be identified with the evolution of big data technology, system integration and research collaborations to enhance building energy performance to address climate change during 2010-2015. THE US BPD (2011), the EU Building Stock Observatory (2013), and China's National Monitoring System (2013) were developed in this period. In addition, a shift from surveys to real-time data can be identified during this period with the development of smart technologies and the Internet of Things (IoT). With the development of Artificial Intelligence (AI), Machine Learning (ML) and the concept of smart buildings, AI-driven analytics such as anomaly detection and load forecasting took place within the building sector during 2015-2020. Most advanced energy databases such as ASHRAE GEPIII (2019), Singapore Benchmarking Portal (2020) and Dubai DEWA (2020) were established in this period. Especially, private sector adaptation to use these databases for real estate ESG reporting has a positive impact of these data-driven approaches. With the real-time monitoring requirements and net-zero targets, more advanced data sharing platforms are being introduced after 2020. ISO 52120 was introduced in 2025 as the first global data exchange standard. Especially, real-time dashboards have replaced static reports.

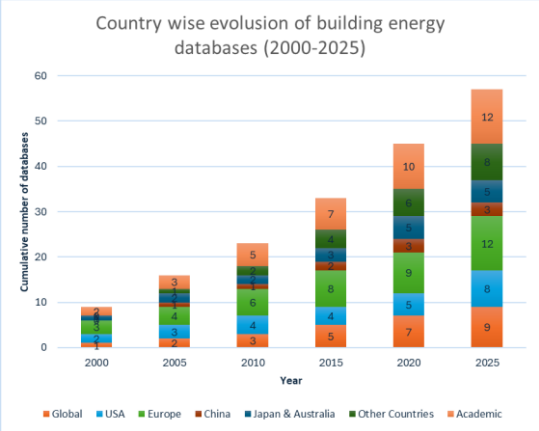


Figure 1: country wise evolution of building energy databases

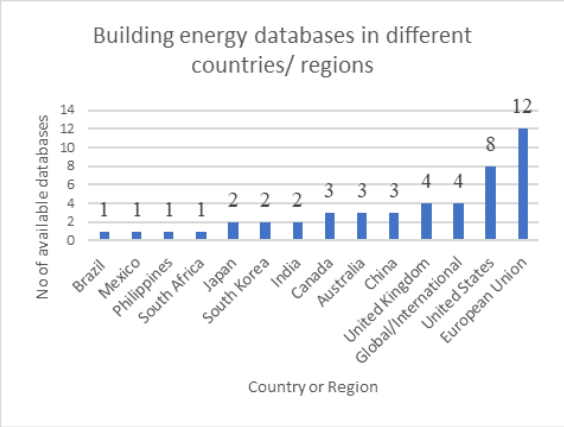


Figure 2: Building energy databases in different countries/ regions

Figure 2 shows the available building energy databases in different countries. According to Figure 2, the highest number of building energy databases is in the European Union, a result of the EU Energy Performance of Buildings Directive (EPBD) mandates and cross-border climate commitments, while the second heights number of databases is in the United States. The United Kingdom has 4 databases, and another 4 databases cover multiple countries in different regions. Canada, Australia, and China have 3 databases in each, while India, South Korea and Japan have 2 databases in each. According to Kumanayake and Luo (2018), the building sector contributes to 35% of the national energy consumption. However, in developing countries, there is a very small amount of energy databases covering their building stock due to limited funding for data infrastructure development, weak policy enforcement, and fragmented stakeholders lacking collaboration between governments, researchers, utility companies and building owners. Therefore, less popularity can be identified in building energy databases in developing countries.

Some of the leading and highly recognised energy databases are reviewed below.

- Energy in Buildings and Communities (EBC) Annex 70-International Energy Agency (IEA)

IEA has created a building energy database called Energy in Buildings and Communities (EBC) Annex 70, focusing on the analysis of energy use of buildings in 15 countries from 2017. It provides an international collaboration of governments, researchers and industry experts in the world working to develop methods to improve empirical data on the energy demand of the building stock. To study the energy demand of the building stock, Annex 70 collects data on features of buildings, energy consumption, characteristics of the occupancy, user behaviours, information on building systems and building morphology. The annex compares building energy data to address the energy performance gaps and assists businesses in the creation of low-energy and low-carbon solutions (Ruyssevelt & Hamilton, 2017).

- ENERGY STAR Portfolio Manager

ENERGY STAR Portfolio Manager collects benchmarking data in the United States and Canada buildings and assigns a rating for each building type. ENERGY STAR Portfolio Manager can be identified as a resource management tool which allows building users to benchmark the energy use of any type of building. Currently, more than 25% of US commercial buildings are being benchmarked in ENERGY STAR Portfolio Manager, which serves as the national benchmarking tool in Canada. Since every building type has been assigned a rating called the ENERGY STAR score, it compares the energy performance of the building with similar buildings nationwide, normalised for operating conditions and weather (Vaidya et al., 2009). To benchmark the buildings, only energy bills and basic information about the building are required. Apart from energy, ENERGY STAR Portfolio Manager allows benchmarking of water consumption, waste generation and GHG emissions.

- US Department of Energy-The Building Performance Database (BPD)

US BPD is one of the largest energy-related databases dedicated to commercial and residential buildings in the United States. It collects data from the government, energy efficiency programs, private companies and building owners. The collected energy data is available to the public (U. S. Department of Energy, 2025). It allows the users to

explore the data across different real estate sectors and regions and compare operational conditions and various physical characteristics to clearly understand the performance patterns and conditions in the energy market (Ye et al., 2019). Users can develop and save custom peer group datasets using different types of variables such as building types, locations, sizes, ages, equipment, operational characteristics and more. Furthermore, any two peer groups can be compared by users using statistical or actuarial methods (Tian et al., 2021).

- Commercial Buildings Energy Consumption Survey

The Commercial Buildings Energy Consumption Survey is managed by the US Energy Information Administration (EIA) (*Regional dashboards and data*, 2015). It serves as a sample survey in the US that collects data about US commercial building stock, including building characteristics that affect energy consumption, and energy usage data such as consumption rates and energy charges (Ye et al., 2019). It covers all the commercial buildings and schools, religious buildings, and hospitals, which might not be considered commercial buildings, with conventional commercial buildings such as shops, warehouses, restaurants and office buildings. It offers open data sets to manipulate energy data within the US energy industry, interactive dashboards to provide energy statistics and energy forecasting tools. EIA provides energy statistics for energy production, consumption, pricing, etc., related to building energy data. Stakeholders in the energy industry and policymakers are allowed to use this data to make informed and data-driven decisions (Department of Energy, 2025).

- EU Building Stock Observatory

The EU Building Stock Observatory is a comprehensive database on energy performance in buildings European Union. The main objective of this database is to provide reliable and transparent data and information on energy usage in buildings in European countries. It helps to monitor the current energy policies and measures in the European Union and helps future policymaking in building energy management. Building Stock Observatory covers a wide range of energy-related topics and provides building-related information such as building stock, energy usage, building elements and technical systems installed in buildings, certificates on energy performance, renovation rates and zero-energy buildings, energy poverty and investments in energy-saving buildings (Gevorgian et al., 2021). The EU Building Stock Observatory was introduced in 2016 along with the Clean Energy for All Europeans package. It is also aligned with the LIFE Clean Energy Transition subprogramme. In addition to that, the EU Building Stock Observatory is part of a broader policy strategy to support the implementation of the Energy Performance of Buildings Directive (EU/2024/1275) and the Energy Efficiency Directive (EU/2023/1791) (European Commission, 2025).

- National Energy Efficiency Data Framework (NEED) – United Kingdom

The National Energy Efficiency Data Framework (NEED) was established to gain a greater understanding of energy use and efficiency in both residential and non-domestic facilities in Great Britain. It provides gas and electricity consumption data in domestic and non-domestic buildings. The important thing is that the information related to energy efficiency measures installed in buildings is collected along with the energy consumption data. In addition to that, data related to characteristics of the property, such as floor area, property age, property type, occupancy data, geography, and socio-demographic data are

collected. Thereby, NEED evaluates the energy savings arising from the installation of energy-saving measures by comparing energy and gas consumption before and after the installation of the energy-saving measure. This database provides the largest available database to analyse gas and electricity consumption and the impacts of energy efficiency measures. After calculating the annual energy consumption, buildings are rated based on their efficiency of the buildings (Department for Energy Security and Net Zero, 2025).

- Australian NABERS (National Australian Built Environment Rating System)

NABERS is a voluntary performance-based rating system which evaluates the overall environmental performance during the operation of various types of buildings. This acts as a building rating and serves as the database in the building sector in Australia by storing data, providing valuable statistics from 1999. Further, it allows buildings to accurately measure, understand, and communicate the environmental performance of buildings while identifying areas for cost savings and future improvements. NABERS rates buildings from one to six stars for building efficiency categories such as energy, water, waste, and indoor environment. Building owners must submit their building data in an Excel spreadsheet provided on the NABERS website after creating a user account. NABERS provides a maximum amount of energy and water that buildings can use to achieve the desired rating. Benchmarks are updated every five years according to the updated data. Currently, this benchmarking tool and database have been launched in the United Kingdom and New Zealand as well (NABERS, 2025).

- India's Energy Efficiency Data Portal

The energy efficiency data portal of India was developed by the Bureau of Energy Efficiency under the aegis of the Ministry of Power in India to produce reliable energy data regarding the supply and demand of energy in different sectors within the country. Collected data is used to publish the National Energy Data Survey and Analysis report, covering both the supply and demand sides. In addition to that, it provides energy-saving and emission reduction statistics across the country by implementing energy-saving projects. There is a separate tab called BEEP stands for National Building Energy Efficiency Program. It provides a comprehensive database of the results of energy efficiency improvement projects across the country (Bureau of Energy Efficiency, 2023).

- TABULA and EPISCOPE

TABULA is a topology approach which has been created to assess the building stock energy, while EPISCOPE is an energy performance indicator tracking scheme for the continuation of the optimisation of the refurbishment process in the building stock in the European Union. Each topology consists of a classification scheme that groups the building stock according to their size, age and other parameters, and it gives a set of example buildings representing these building types. TABULA was funded by the European Commission's Intelligent Energy Europe (IEE) program, and EPISCOPE was established to follow up on the TABULA program to monitor renovation strategies. A reference building is created in TABULA for different building types in the participating countries. To create the reference building, construction characteristics, details related to geometry and layoutsand other related details of energy performance of retrofit scenarios are collected (Stein et al., 2016).

Table 1 shows the summary of the selected building energy databases.

Table 1: Summary of the building energy databases

Name of the Database	Aim of the database	Related policies and initiatives	Policy impact	Organizational impact
Energy in Buildings and Communities (EBC) Annex 70	Developing standardized methodologies to compare international building energy data to support evidence-based policymaking	EU Energy Performance of Buildings Directive (EPBD), Energy in Buildings and Communities Program	Supported energy-saving calculations for tax credits. Improved energy performance certification methodologies	Allows universities to harmonize global building energy datasets. Building automation service providers aligned their products with Annex 70's performance benchmarks.
ENERGY STAR Portfolio Manager	Enable benchmarking and tracking of energy/water use in buildings to drive market-based efficiency improvements.	Energy Policy Act of 2005 (EPAct 2005), Energy Independence and Security Act (EISA) of 2007	Used for mandatory energy benchmarking of buildings in 25 cities in the US. Became an industry standard for the real estate sector.	Some real estate companies used it for ESG reporting and lease agreements including clauses mandating ENERGY STAR scores. Some case studies show that Automated benchmarking reduced manual data entry by 40%.
Building Performance Database (BPD)	Collect performance data to identify retrofit opportunities and validate energy codes.	Energy Policy Act of 2005 (EPAct 2005), Energy Independence and Security Act (EISA) of 2007	Led to revisions of building codes. Adjusted tax credits for energy retrofits. Supported Chicago's Building Energy Use Reporting Ordinance.	Some companies use BPD to justify ROI calculations for clients. Sustainability authorities use BPD to audit compliance with Local regulations.
Commercial Buildings Energy Consumption Survey	Provide statistically representative data on US commercial building energy use for national policy and research.	Energy Policy Act of 2005 (EPAct 2005), Energy Independence and Security Act (EISA) of 2007	Started with the US Net-Zero Commercial Buildings goal and led to informed energy code updates. Supported design efficiency incentives for utilities.	Some architecture forms use this to validate energy models in the early design stage.
National Energy Efficiency Data	Link energy use data with socio-demographic factors to target fuel	Directly related to low-carbon policies in the UK	Identified households lack clean energy for subsidies. Targeted intervention using consumption patterns for smart meter installation.	Social Housing Providers used NEED to prioritize retrofits in residential buildings. Energy Suppliers developed targeted efficiency offers using poverty maps.

Name of the Database	Aim of the database	Related policies and initiatives	Policy impact	Organizational impact
Framework (NEED) – UK	poverty and efficiency programs.		Net-zero planning for 2050 decarbonization targets.	
EU Building Stock Observatory	Monitor the EU-wide building stock to track progress toward climate goals	Energy Performance of Buildings Directive (EU/2024/1275) and the Energy Efficiency Directive (EU/2023/1791)	Prioritized low-performing buildings for EU funding. Used to track progress towards 2030 energy targets. Used to map regional disparities in building energy efficiency.	Construction Companies have referenced it to market insulation products. City Governments used it to identify retrofit zones.
TABULA and EPISCOPE	Create standardized building typologies to simplify energy retrofit planning and cost-benefit analysis.	European Commission's Intelligent Energy Europe (IEE) program	Standardized building envelope design in EU buildings. Supported to establishment building energy roadmap policy in Germany and Vienna's 2040 Climate Roadmap.	Retrofit companies use TABULA archetypes for modular facade solutions. Some banks have introduced loan schemes which require TABULA-based energy audits.
Australian NABERS	Rate buildings based on actual operational performance to drive market competition for efficiency	Supports to achievement of the net-zero energy targets by 2050	It became a mandatory disclosure. Higher added value for high-rate buildings. Used for national climate policy implementation.	Some companies increased asset values via NABERS-driven upgrades. Some companies automate NABERS compliance for 80% of rated buildings.
India's Energy Efficiency Data Portal	Support compliance with India's Energy Conservation Building Code (ECBC) and PAT scheme for industries	National Building Energy Efficiency Program	Supported building code revisions. Used for retrofit targets in several estates. Became an industry benchmarking program.	Some companies use portal data to comply with national energy regulations. Some manufacturers reference portal data for HVAC sizing tools.

According to the analysis of the different building energy databases, Energy in Buildings and Communities (EBC) Annex 70 serves several countries in different regions, while other databases serve only a specific country. Some of the databases such as BPD, Commercial Buildings Energy Consumption Survey, EU Building Stock Observatory and India's Energy Efficiency Data Portal provide merely statistics related to building energy while some of the databases such as Energy in Buildings and Communities (EBC) Annex 70, ENERGY STAR Portfolio Manager, TABULA and EPISCOPE, and Australian NABERS act as an energy benchmarking tool for building while providing energy statistics for building stock. By providing benchmarks, buildings are given performance targets and are measured for the energy performance of each building compared to similar types of buildings.

When considering the data collection method, some databases collect data from surveys such as the Commercial Buildings Energy Consumption Survey while others collect data from other national-level or regional-level databases. Energy in Buildings and Communities (EBC) Annex 70 collects data from universities and national-level institutes by creating a collaboration with multiple organizations representing each country.

Currently, most of the databases cover the effectiveness of energy-saving initiatives and energy retrofitting, along with recording energy generation, consumption and pricing. Energy in Buildings and Communities (EBC) Annex 70, National Energy Efficiency Data Framework (NEED) – UK and India's Energy Efficiency Data Portal are examples of those types of databases. It helps to identify the effectiveness of energy-saving measures and building retrofits for different types of buildings (Carnieletto et al., 2019). To achieve sustainable development goals by easy access to information, some databases have provided free access and publicly available datasets for parties who are interested. India's Energy Efficiency Data Portal, EU Building Stock Observatory and Commercial Buildings Energy Consumption Survey are some examples of freely accessible databases. However, some databases still require paying to get energy data and have taken actions to restrict unauthorized access to maintain data confidentiality. ENERGY STAR Portfolio Manager and Energy in Buildings and Communities (EBC) Annex 70 require user accounts to get datasets from the database.

All the above building energy databases aim to compare the energy performance of different buildings and to support evidence-based policy making. Furthermore, some databases such as NEED and ENERGY STAR Portfolio Manager aim to identify energy-saving potentials and retrofitting opportunities in buildings. Moreover, NEED links energy use data with socio-demographic factors to identify target groups with fuel poverty. Meanwhile BPD and Commercial Buildings Energy Consumption Survey aims to validate existing building codes and revise existing policies and mandates based on the statistical conclusions of the collected data. According to Table 1, diversified stakeholders are considered by every database, such as national and local governments, national and international organizations, researchers, building owners, utility companies, architects, engineers, energy auditors, financial companies, real estate companies, retrofitting companies, and the community.

When considering the policy implications, all the above databases are governed by government bodies or international energy authorities. They directly aligned the outputs given by the databases to verify the benefits of the policies and to measure how well organizations adopt those policies. In addition to that, these energy databases enable

organizations to enhance their market value using benchmarks and comparing building energy data, such as ENERGY STAR Portfolio Manager and Building Performance Database. Some of the databases focus on the specific type of building stock, such as the National Energy Efficiency Data Framework (NEED) – UK, while other databases cover the entire building stock. However, they provide statistics for specific building types using collected data.

With the introduction of some of these databases, such as ENERGY STAR Portfolio Manager, Building Performance Database (BPD) and Australian NABERS, mandatory disclosure of energy data became an industry standard in the real estate sector. Energy in Buildings and Communities (EBC) Annex 70 and Building Performance Database (BPD) have been used to calculate the energy saving for tax credits. In addition to that, energy performance certification methodologies were improved with the use of collected data by Energy in Buildings and Communities (EBC) Annex 70. Building Performance Database (BPD), Commercial Buildings Energy Consumption Survey, India's Energy Efficiency Data Portal and Australian NABERS led to revisions of building codes. Specifically, NEED was used to identify the targeted groups with energy poverty to make required interventions and set decarbonization targets by 2050. Furthermore, the EU Building Stock Observatory identifies low-performing buildings for EU funding. It highlights the contribution of these databases in identifying energy performance gaps within the building industry. The EU Building Stock Observatory, TABULA and EPISCOPE, Australian NABERS, and India's Energy Efficiency Data Portal have directly supported to formulation of energy policies and climate policies. In addition to that, these databases have supported tracking the energy targets.

As a result of these databases, building service providers tend to align their products to meet industry benchmarks. Furthermore, real estate companies use these benchmarking and energy-related data for ESG reporting, and automated data platforms have reduced the manual paperwork in obtaining energy performance certification. Furthermore, utility providers have introduced efficiency offers for their customers based on reported data. In addition, these databases and mandatory reporting allow companies to identify performance gaps and retrofitting opportunities in their buildings to become more energy efficient.

Although the adaptability of building energy databases is becoming popular in developed countries, the usage of building energy databases is still fledgling in developing countries. Similarly, there is no dedicated energy database for buildings in Sri Lanka to monitor the building energy consumption to make informed decisions to create energy policies for buildings. Therefore, to achieve the intended outcomes of the national energy policy in Sri Lanka, a comprehensive building energy database is a key element that should be introduced to the building sector. Therefore, further research can be conducted on developing a building energy database in Sri Lanka.

4. CONCLUSION

Since buildings contribute a significant portion of total energy consumption, a higher consideration has been given to reducing building energy consumption by closely monitoring the adaptation of energy policies and initiatives by the governments. This study reviews the building energy databases in the world to identify their policy implications and applicability in reducing energy consumption in buildings. Nine

building energy databases were studied. Among them, Energy in Buildings and Communities (EBC) Annex 70 covers multiple countries acting as an international building energy database, while other databases cover only a specific country or region. Four databases act as benchmarking tools, while 5 databases provide only energy statistics. Surveys and other energy databases are used as the data collection methods. There is a tendency to evaluate the efficiency of energy retrofitting in buildings; while monitoring energy consumption, all the databases collect data on energy-saving mechanisms that buildings use to reduce energy consumption. Currently, most of the databases allow users to access energy data freely to assist them in informed decision-making in building energy management. All the databases have been established along with a specific energy policy or an energy management program to measure and validate the effectiveness of the introduced policies. Even though there is a growing tendency to manage building energy databases at the national level in developed countries, a limited approach can be seen in developing countries in this context. A building energy database is still lacking in the Sri Lankan context, even though a proportion of the national energy is consumed by the building sector. Therefore, future researchers can focus on developing an energy database for buildings in Sri Lanka.

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BUILDINGS DESIGNED FOR SYSTEMIC CIRCULARITY: A COMPREHENSIVE REVIEW OF METHODOLOGICAL TAXONOMIES

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ABSTRACT

Circular economy (CE) principles have been appraised as the requisite approach to enhance buildings and construction process to achieve sustainable development. Hence, architects and other construction professionals have been urged to adopt the CE principles in design thinking, supply chain systems, production, operation, and end-of-life activities of buildings. However, as much as CE principles could be seen subjectively to benefit the environment, it is incumbent to determine and document this empirically to propel its seamless adoption and enforcement. Therefore, extant studies have proposed several methods, metrics, and indicators to assess the environmental impact, recovery, technical, cost, systems, and recyclability potentials of buildings designed for total circularity. Nonetheless, the complexity of CE requires that such assessment should consider the integration of different methods that should be able to assess the different dimensions of the lifecycle of a circularly designed building. In this study, a thorough systematic review was conducted to explore the existing means of measurement and propose a comprehensive methodological approach for assessing buildings designed for systemic circularity. The proposed approach should enhance CE methodological development and guide construction professionals and building designers in the effective adoption of CE principles throughout building lifecycles to attain sustainable development.

Keywords: *Circular Economy; Design for Systemic Circularity; Indicators; Methods; Systematic Review.*

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1. INTRODUCTION

The fate of most existing building structures at their end-of-life have been predetermined for landfill due to adopted construction process. The traditional construction process follows a take-make-dispose design thinking approach whereby buildings are not designed with reusability of parts or materials in mind (Hossain et al., 2020). This approach has led to the exorbitant building and demolition waste which the construction industry is currently facing. To circumvent this approach and reduce the negative effects of building across its lifecycle, a new design thinking which embeds circularity and sustainable principles should be upheld (Ellen MacArthur Foundation, 2015; Antwi-Afari et al., 2023).

Extant studies have shaped the direction of contemporary building design thinking to incorporate key sustainable and circularity principles such as adaptability, manufacturability, assembly, reusability, systemic circularity, flexibility, and cost among others (c.f., Moraga et al., 2019; Attia & Al-Obaidy., 2021; De Silva et al., 2023). Hence, there has been an influx of new design strategies and models which helps construction stakeholders to target the sustainability agenda. However, how to evaluate the extent of systemic circularity of a building or component designed through these design thinking approaches needs to be identified. Systemic circularity encompasses the assessment of buildings entire production system and goes beyond the sustainable principles adopted within the design, manufacturing and construction process. Thus, it includes the adopted business models, system conditions and reverse cycles together with the key performance indicators under each of these building blocks (Antwi-Afari, 2023).

To assess buildings designed with sustainable or circular thinking, this study conducted a systematic review of extant literature to identify the existing methods, tools, metrics or indicators. The current study differs from existing review studies (c.f, Antwi-Afari et al., 2022; Oluleye et al., 2023) because of the broad perspective of not limiting the literature search to only one or few sustainability indicators, also, different methods and metrics as far as they fall within the scope of the study were considered in the study. To this end, this study was conducted to evaluate the intellectual core and key methods needed to evaluate buildings design for systemic circularity. The rest of the manuscript is as follows: the next section provides details on the methods adopted for reviewing extant literature. The key findings of the methods, metrics, indicators or tools for assessing buildings' systemic circularity is also presented. Then the discussion of these methods and conclusions and further research sections are also shown.

2. METHODOLOGY

This study adopted a critical review approach to carefully analyse all the extant literature. Based on different review methods in Grant and Booth (2009)'s studies, critical reviews help researchers to identify discrepancies in existing literature and resolve ideas by finding solution rather than merely highlighting gaps. A four-stage approach was used to conduct this critical review. To obtain the papers used for the study, a detailed advanced search was conducted in Scopus with relevant words such as methods, metrics, indicators and building construction and limited to the last decade.

The search string "circular metrics" OR "Circularity Indicator" OR "metric" OR "circular methods" OR "sustainable metrics" OR "Circularity Assessment" AND "building construction". Scopus was chosen as the preferred database because it has a wide range

of reach and a powerful data control and quality analytical tools (Oteng et al., 2021). A total of 143 documents were retrieved from the advanced search. Further analysis of the abstract, keywords and the title of the documents led to 99 obtained papers used in the critical review analysis. A thorough content review was done to cut down the papers even further for the content analysis. This led to the use of 17 articles which were considered as appropriate and detailed enough for such purposes. The overall 99 retrieved papers were also classified across predefined criteria such as scope, document type, year, materials used, citation count, and methods adopted.

The 17 articles selected for content analysis were then reviewed and their key findings concerning methods, metrics, indicators and tools for assessing buildings design for systemic circularity were identified and presented. Based on the in-depth content analysis, the key methods, tools, metrics, and indicators for evaluating buildings systemic circularity were discussed and a comprehensive methodological approach which could be adopted to enhance buildings systemic circularity were formulated based on extant literature.

3. FINDINGS

The year trends of the selected documents revealed that majority of the articles on methods for assessing the circularity of buildings were published in 2023 with more than two-thirds published after 2020 (Fig. 1). This matches the influx and popularity which circular economy (CE) was obtaining during and after the Covid-19 era. The need to rethink existing systems, achieve resilience and enhance innovation in the construction industry (CI) post-pandemic era increases the attention of researchers considering how to measure the improvements made to the circularity of buildings along its lifecycles.

The cited sources citation shows that of the selected documents, at least 23 received 0-20 number of citations on average. While more than 50 articles received more thana 20 citations but less than 41 citations. Hence on average, we can infer from the analysis that at least more than half of CE metrics, methods or measurement studies in the last decade had at least receive 40 citations. This shows the influence, relevance and impact of this research to the built environment and the scientific community. Hence, a more important reason to continue to research in this area to push the frontiers of knowledge in the key methods for assessing building circularity to reduce poor measurement and gauge the improvement done in building circularity correctly.

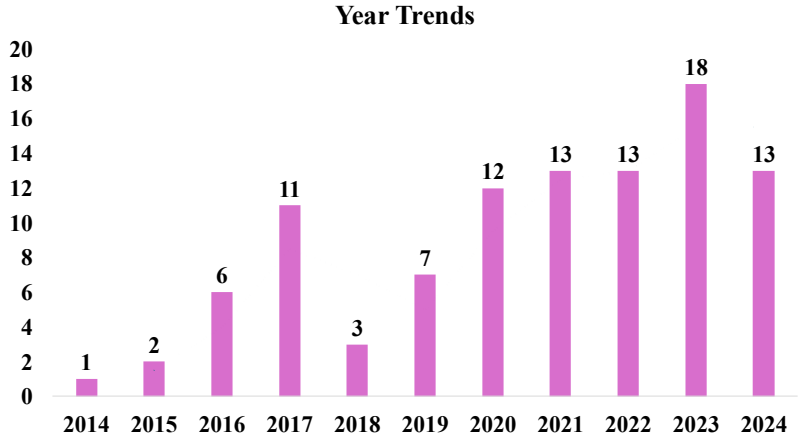


Figure 1: Year trends of CE methods for assessing buildings circularity

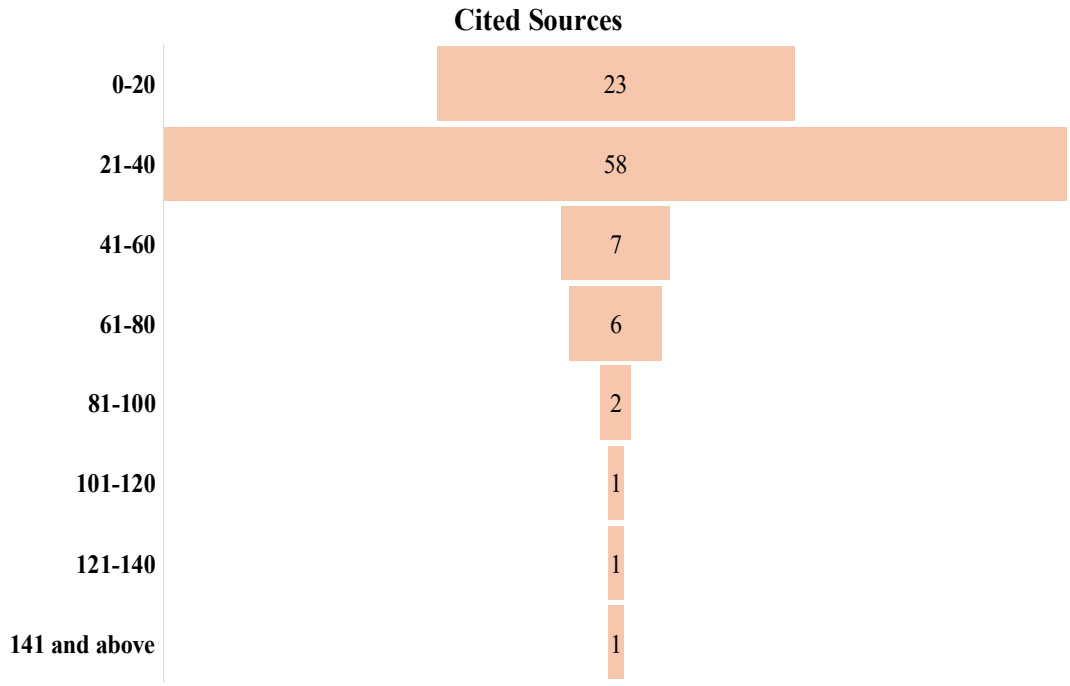


Figure 2: Cited source co-citation of selected articles

The selected documents used for the study were mainly peer-reviewed published journal articles from Scopus. This formed about 77% of the total number of articles with about 14% being peer-reviewed conferences. Since this study was looking at methods used for assessing building circularity, the key focus was on analytical articles with few very good review articles considered which formed about 6% of the selected articles. Book chapters were only 3% of the selected articles for this study.

The scope of selected articles helped to identify the focus of these articles. It was seen that most of the articles on CE measurement for building circularity looked at the materials level. Thus, concrete, steel, plastics etc. which formed 28.28% of all the selected articles. Case-specific articles were mainly studies which looked at different case scenarios of materials, buildings or projects. This formed 21.21% of all the selected articles. Component level such as slabs, floors, roofs etc. formed 13.13% of all the articles used in the critical review while 7.07% and 5.05% of the articles were focused on national or corporate level looking at circularity of buildings from business models and policies impact on decision making.

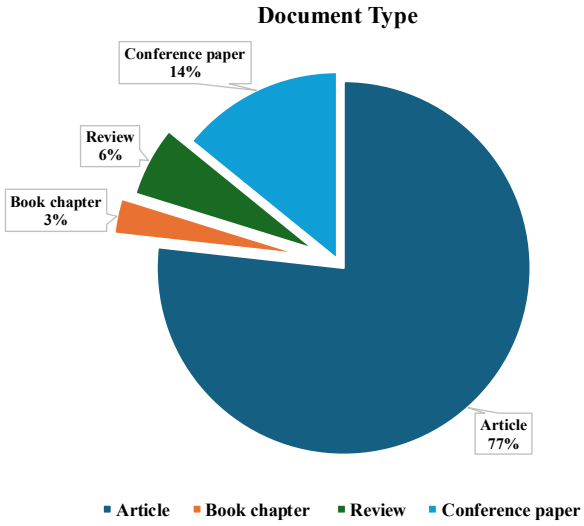


Figure 3: Document types of selected articles

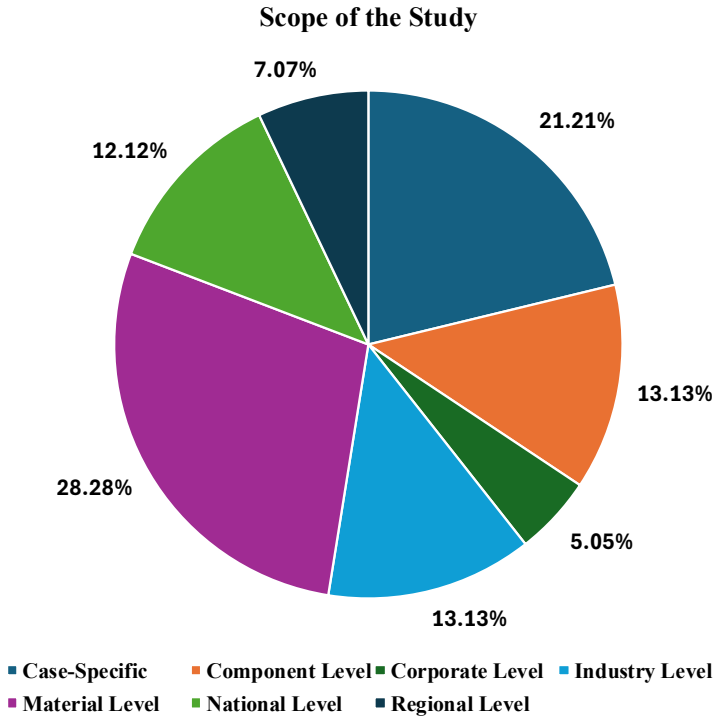


Figure 4: Scope of selected articles

The next analysis of the review was to consider the materials used for the analysis. About nine of the studies did not specify any kind of materials or did not provide any material usage details at all. These were mainly corporate or policy related studies which focused on improving existing building business models to be circular. Eight of the articles focused on wood and its derivates such as cross laminated timber, sawn timber, glue laminated timber and their usage for kitchen modules or other parts of buildings. Different kinds of materials were all considered in the extant literature. For example, steel (nine studies), concrete (nine studies), Paper (three studies), composite materials which encompass a reinforced concrete, engineered wood products and fibre-reinforced

polymers among others formed about 12 of the selected articles. Also, about nine of the studies looked at waste during construction and demolition of circular buildings and how the circularity at that phase is measured.

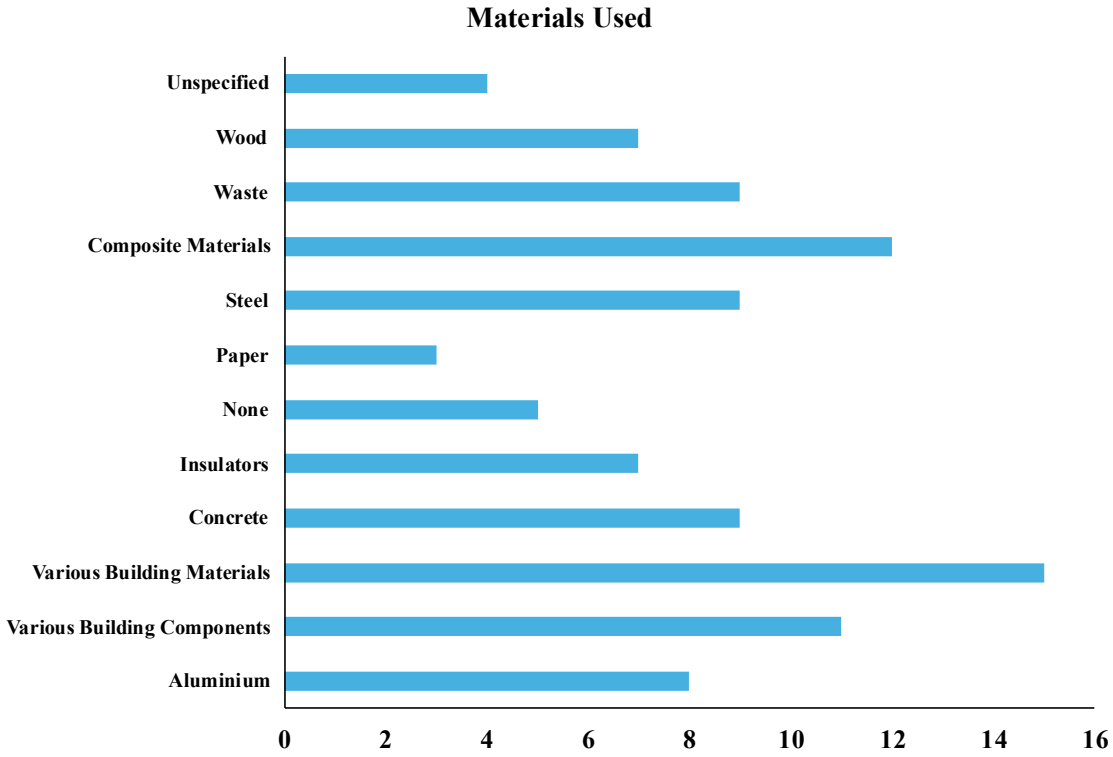


Figure 5: Materials assessed in the methods of selected articles

The last analysis in this section was to evaluate the methods adopted in extant literature for measuring the circularity of buildings. Aside from review articles which used document analysis (about five studies), the rest of the articles used some kind of method to assess the impact of materials along the environment, social, economic, technical, and systems dimensions. Most studies used only one type of method for analysis. For instance, lifecycle assessment (LCA) only was used to determine the embodied carbon impacts of materials, while building information modelling (BIM), LCA and multi-criteria decision-making methods (MCDM) were used to assess the decision-making models of circular designed buildings among others. The use of different methods enabled extant studies to evaluate the sustainability and circularity of different materials, decisions, processes and strategies of circularly designed buildings, materials, components and design guidelines for CE attainment in buildings.

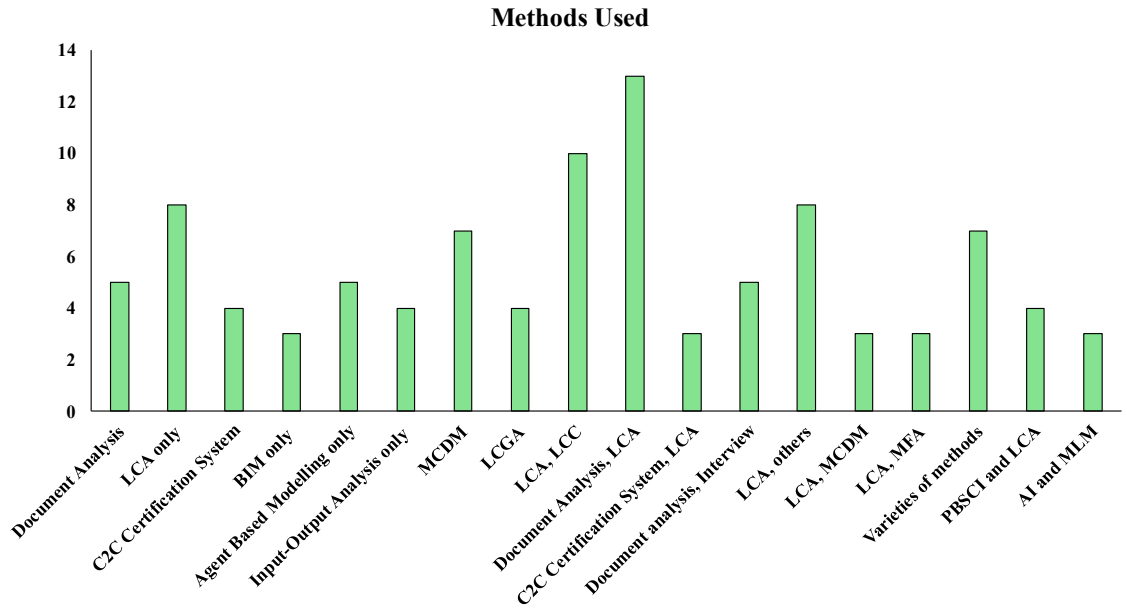


Figure 6: Methods used in the selected articles

4. DISCUSSIONS AND IMPLICATIONS

Different methods, metrics, and indicators have been adopted in extant literature to assess the circularity potentials of activities involved the in the lifecycle of building construction or circularly designed buildings. In this study, the key 17 articles used for content analysis were evaluated and the adopted methods, metrics and indicators used classified across the environmental, social, economic, technical, business and legislative dimensions.

4.1 ENVIRONMENTAL DIMENSIONS

To assess the environmental impacts of materials, processes or buildings designed to attain circularity, extant literatures have used indicators such as waste intensity indicators, longevity indicators, water intensity indicators, embodied carbon, embodied energy, resource output rate and resource duration indicators for environmental impact assessments (Franklin-Johnson et al., 2016; Romnee et al., 2019). Other methods such as LCA which look at assessing the environmental impact of materials across different midpoint and endpoint categories have been used to evaluate the environmental impact of plastic waste and end-of-life waste management (Hossain et al., 2021). To make decisions concerning circular buildings, Carvalho et al. (2021) used LCA and other methods to quantify the highest environmental impact performance among several different scenarios. LCA was also used together with input-output analysis to assess the cradle to grave embodied carbon and embodied energy of residential buildings designed to attain sustainability. The adoption of a hybrid form of LCA provided an improved means of quantifying buildings' material emissions (Zhan et al., 2018).

4.2 ECONOMIC DIMENSIONS

To assess the economic impact of buildings or materials designed for circularity, extant studies such as Magrini et al. (2021) and Malabi et al. (2021) adopted life cycle costing, material flow cost accounting, net present value, cost benefit analysis and life cycle sustainability assessment to assess circular waste and circular building components.

Indicators mostly used in examining the economic impacts of circularly designed buildings or materials includes investment cost indicator, cost of energy consumption, cost substitutive goods, sustainability financial incentives, transportation cost among others. Braakman (2019) adopted lifecycle cost (LCC) to assess the building circularity levels of a standard one-family house using design-oriented scenarios. The usage of LCC showed that increasing circularity of these buildings may not have substantial effect on its lifecycle cost, but as circularity increases, the LCC increases to almost double the initial cost. This provided an array to gauge circularity improvements to cost-effects of attaining circularity in buildings. Jansen et al. (2020) also proposed a circular economy LCC model for building components which helped to provide decisions on the most economic, but circular kitchen module to adopt taking into consideration product lifespan, interest rates and expected value retention percentages of the module.

4.3 SOCIAL DIMENSIONS

To evaluate the social dimensions of buildings designed for circularity, extant studies have used several indicators such as social fairness of building designs, health and safety during construction and stakeholder awareness among others as some of the key indicators. (c.f., Braungart et al., 2007; Toxopeus et al., 2015). Key methods or metrics adopted to measure the social aspects of circularity measurements include managerial indicators, organizational indicators, social circularity indicators, social life cycle assessment and cradle to cradle (C2C) assessment (c.f., Niero et al., 2017; Antwi-Afari et al., 2022). Fatourehchi & Zarghami (2020) adopted a social sustainability assessment framework to include social indicators in the measurement of sustainable residential buildings in Iran. The study identified that some key determinants of meeting the social aspects of a sustainable or circular building includes workplace health and safety, performance and flexibility at the workplace.

4.4 TECHNICAL DIMENSIONS

When assessing the technical dimensions of products designed for circularity, extant studies such as Geldermans (2016) Adams et al. (2017) and Alamarew et al. (2020) have proposed or used indicators such as material separability rate, usage level of recycled products, viable take back schemes, technological indicators and technical feasibility for examining the technical aspects of circularly designed materials or buildings. For metrics or methods, disassembly time and cost, end-of-life indices and predictive building circularity indicator (PBCI) have been used. For instance, Geldermans (2016) argued that to embrace full circularity measurement, technical, temporal, and social implications need to be calculated together with the economic and social impacts in formulating decisions.

4.5 BUSINESS DIMENSIONS

Circularity measurement encompasses consideration of the requisite business model enacted to enhance the reusability of building's materials or components across several lifecycles. Hence, measuring the circularity potentials of a product should include the business dimensions as well. Thus, whether the product (materials or building) has a reusability/recyclability plan and a circular business model to enhance its usage during the first cycle and reusability in subsequent lifecycles. Indicators such as supply chain indicators, and methods such as Agent Based modelling, system dynamics, multi-criteria decision-making methods among others have been proposed in extant literature to be

considering some of the business dimensions of CE measurement (c.f., Adams et al., 2017; Alamerew et al., 2020; Rossi et al., 2020).

4.6 LEGISLATIVE DIMENSIONS

To achieve systemic (total) circularity, a circularly designed product should also exhibit some key legislative dimensions such as responsible communication, meeting the required standards and performance solutions/minimum criteria of quality. Indicators such as strategy and policy indicators and methods such system dynamics, multi-criteria decision-making methods among others have been identified in extant literature to help in the evaluation of the legislative dimension of circularity (Magrini et al., 2021).

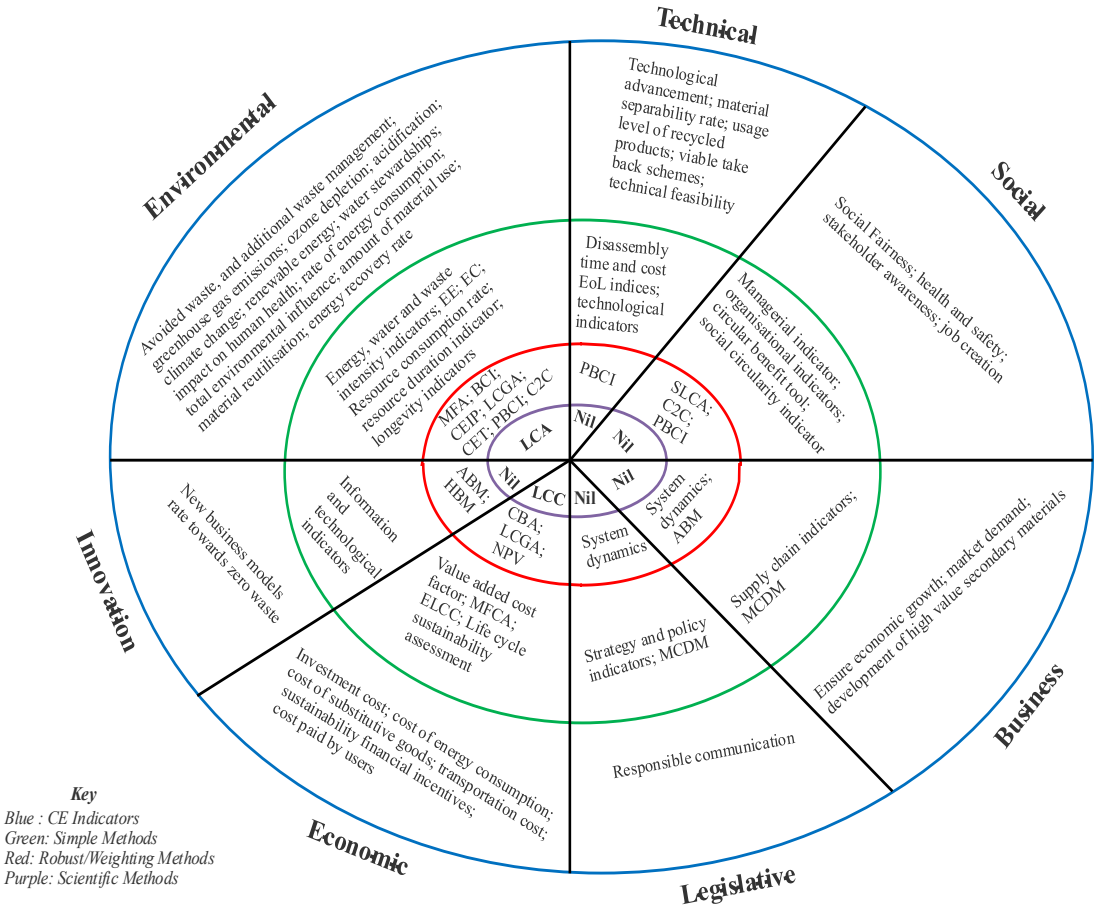


Fig. 7. Indicators, methods and metrics for circularity assessment. Adapted from Antwi-Afari et al. (2022)

4.7 AN INTEGRATED METHOD FOR ASSESSING BUILDING'S CIRCULARITY

To assess that a building or material has attain a total/systemic circularity, different impact dimensions should be evaluated such as the building's environmental, social, economic, business, technical, innovation and legislative dimensions. However, deducing from existing methods (Fig. 7) shows that none of the methods alone would be enough to assess the key dimensions of building's circularity. For example, LCA can give a clear indication of the building's environmental impact but its usage for assessing technical, cost and social dimensions is limited. LCC can also help in the economic quantification of different materials but its usage for environmental impact and social impact is

constrained. Multi-Criteria Decision-making methods could be used to evaluate some business and legislative aspects of product lifecycle systems, but its usage for environmental or economic impact assessment is inadequate.

Since total circularity of buildings will not only consider its environmental, economic or social impacts, but also its technical, systems and legislative considerations of the product lifecycle, there is the need to develop a robust assessment tool which will consider the requisite dimensions for a detailed assessment of the building's circularity. However, there is a problem with methods compatibility when integrating them as such some must still be assessed separately and infused into the integrated method calculation along the process or considered during the final decision-making process. This study proposes that, LCA, C2C and PBCI should be integrated into a methodological framework by combining their system boundaries, strength and indicators to assess the environmental, social, technical, business and legislative dimensions of circularly designed buildings.

To propose this integrated framework, LCA midpoint and endpoint indicators should be merged with that of C2C indicators and strengthened with an improved PBCI calculation to reduce the limitations of circularity assessments. Therefore, with LCA-C2C-PBSCI method, assessing the systemic circularity of buildings would consider the environmental, technical, social, business, legislation and innovation dimensions. Economic impacts could be added to the decision-making process using LCC or other economic impact indicators/methods and MCDM could also be used to help in the selection of the optimal circular scenario based on the assessed examples.

5. CONCLUSIONS

Assessing systemic circularity in building construction is critical for advancing sustainable practices and effectively integrating circular economy principles into the construction sector. Although numerous methods exist to evaluate circularity, a comprehensive, integrated approach that addresses multiple dimensions simultaneously remains underexplored. Existing research primarily focuses on isolated dimensions such as environmental impacts or economic assessments, neglecting a holistic view necessary for systemic circularity. Addressing this gap, the current study systematically reviewed existing methods, metrics, indicators, and tools utilized across environmental, economic, social, technical, business, and legislative dimensions.

A critical review methodology was adopted, analysing selected literature from the Scopus database. After rigorous screening, 17 relevant studies were subjected to detailed content analysis to identify prevalent methods and indicators. Key findings reveal that predominant methodologies employed include LCA, LCC, MCDM, C2C, and PBCI. Indicators commonly applied include embodied carbon, resource efficiency, cost-benefit analyses, social fairness, material separability, supply chain considerations, and policy compliance.

These findings highlight the fragmented but complementary nature of current approaches. To overcome the identified fragmentation and enhance practical circularity assessments, this study proposes an integrated methodological framework combining LCA, C2C, and PBCI (LCA-C2C-PBSCI). This framework merges environmental, technical, social, business, and legislative dimensions, enabling stakeholders to make informed, multidimensional decisions regarding building circularity. Practically, adopting this integrated approach can significantly streamline evaluations, promote consistent

practices, and facilitate broader implementation of circular principles in the construction industry.

Nevertheless, this study has limitations. The restriction of the literature search to the Scopus database potentially excludes relevant research indexed elsewhere. Additionally, the relatively small sample size may limit generalizability, and the broad scope adopted could overlook detailed nuances within specific dimensions. Future research directions should address these limitations by expanding database searches and validating the proposed integrated framework through empirical studies and practical case applications across various contexts. Developing standardized sets of indicators and tools is also recommended to facilitate comparability and consistency. Further exploration of underrepresented dimensions such as social and legislative aspects will enhance the holistic understanding and effectiveness of systemic circularity assessments.

6. ACKNOWLEDGEMENTS

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CARBON FINANCING IN CONSTRUCTION: REVIEW OF BENEFITS AND BARRIERS

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ABSTRACT

The buildings and construction sector is responsible for 37% of global GHG emissions. Given the inefficacy of traditional methods in reducing GHG emissions, the adoption of sustainable strategies including low-carbon materials, energy-efficient practices, and the integration of renewable energy has become essential. Among these, Carbon Financing (CF) stands out as a mechanism that not only reduces emissions but also provides economic opportunities, making it highly attractive to investors. CF enables stakeholders to earn and trade carbon credits by reducing emissions allowing construction firms to monetise their environmental efforts. Hence this study aims to systematically review the benefits and barriers of CF for sustainable construction. The study conducted a systematic literature review on Carbon Financing (CF) in construction utilising the PRISMA framework. From an initial 126 articles, 91 articles were shortlisted for detailed analysis. Findings reveal a range of CF instruments categorised as primary products and derivatives, to manage carbon emissions and enhance market liquidity. Additionally, the study highlighted both the economic and environmental benefits of CF, including promoting green job creation, attracting investments in sustainable energy, and supporting biodiversity conservation. However, factors including lack of understanding, limited policy support, and a need for innovative CF products have been discovered as challenges faced in CF adoption. The study concluded that CF holds significant potential for transforming the construction sector into a more sustainable industry. This research contributes to the existing body of knowledge by providing a blueprint for integrating CF into construction practices while setting the stage for further research and practical application towards global sustainability goals.

Keywords: *Carbon Finance (CF); Carbon Market; Carbon Trading; Construction Industry.*

1. INTRODUCTION

Being the most resource-consuming industry (Feng et al., 2022), the construction industry is responsible for more than 40% of raw material consumption (Dixit et al., 2022) and over 30% of the world's energy consumption (Banawi & Bilec, 2014). This has led to the emission of significant amounts of harmful greenhouse gases (GHGs) into the environment. GHGs absorb and re-emit thermal radiation, thereby contributing to the warming of the planet's atmosphere. The principal GHGs include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (Brander & Davis, 2012;

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Shirinbakhsh & Harvey, 2021). GHG emissions significantly contribute to climate change, threatening ecosystems, human health, and economic stability (Ling, 2021). To mitigate carbon emissions from the construction industry, various sustainable strategies can be employed. The adoption of low-carbon materials and energy-efficient practices (Zhang et al., 2024), integration of life cycle assessment (LCA), green supply chain management (GSCM), and the utilisation of renewable materials have emerged as viable approaches to address these issues. Among all these viable approaches carbon financing stands at the forefront of the global battle against carbon emissions. (Chien, 2024). CF, a branch of environmental finance, focuses on creating financial tools to achieve environmental goals and manage environmental risks (Li & Liu, 2011), and solve climate issues (Liu et al., 2015). It involves investment and financing activities within the low-carbon economy, aligned with the Kyoto Protocol of 1997 (Li & Liu, 2011) and the Paris Agreement of 2015 (Delbeke et al., 2019). One notable real-world example of carbon finance in practice is the Clean Development Mechanism (CDM) projects. CDM projects are sustaible initaitives focused on emission reduction (Mok et al., 2014). Later, the volume of emissions reduced is quantified and converted into Certified Emission Reductions (CERs), which can be traded on carbon markets to generate financial returns, becoming the (carbon) financing of the project. CF can influence carbon trading, enhance research and development efforts (Zhu et al., 2019), and encourage innovation of new materials with lower embodied carbon (Bamgbade et al., 2019).

CF can encourage industries to create green jobs (Wang et al., 2024) and it stimulates local economies to perform well (Chen & Wu, 2023). Additionally, due to CF's ability to influence low-carbon construction, it can reduce long-term operational costs of building making it a financially attractive sustainable practice (Topak et al., 2019). Carbon financial instruments can be effective in the construction industry, particularly when the upfront costs of adopting sustainable practices are significant (Liu et al., 2019). Despite its benefits, the adoption of CF face numerous challenges in construction industry (Wu et al., 2022). Lack of understanding on CF, insufficient knowledge about CF systems and shortage of experts in CF has made it less popular among the public (Liu et al., 2015). Additionally, existing policies, regulations, and legal frameworks not being robust enough to support CF, and lack of innovation in CF products (Parenteau & Cao, 2016) are two noteworthy challenges. The absence of a nationally unified carbon trading platform also poses problems in many countries (Wu et al., 2022). These obstacles highlight the complexity of implementing and adopting CF effectively in the construction industry.

Despite carbon financing's ability to empower sustainable construction, the integration of these financial mechanisms into the construction sector remains fragmented and underexplored. The existing literature offers a limited comprehensive analysis on the effectiveness of carbon financing in promoting sustainable construction practices. Recent literature, including Murali et al. (2024), investigates key enablers for integrating deconstruction and CF to enhance sustainable and resilient construction in the Industry 5.0 era. This complements Zhou and Li (2019), who explored the challenges and progress in implementing CF in construction, providing a foundation for understanding the obstacles faced. Oke et al. (2024) further contribute by identifying barriers to CF adoption and proposing practical solutions. Jiang et al. (2020) analyse the interplay between carbon trading, financing costs, and emission reduction strategies within the construction supply chain, shedding light on the financial mechanisms that influence emission reductions.

Even though there are studies on enablers, challenges, barriers, and solutions regarding the financial dynamics of carbon trading, there is a lack of an integrated framework that synthesises these various aspects. Each study, though valuable, tends to focus on specific dimensions without holistically addressing how these elements interact. For instance, studies such as Li (2020), Jiang et al. (2017), and Zhou and Li (2019) focuses on the Chinese construction industry, while research by Woo et al. (2020) and Eicker et al. (2020) primarily examine the US market. This regional focus creates a fragmented understanding, leaving a significant gap in understanding how carbon financing can be systematically applied to drive sustainability across the global construction industry. Therefore, this research aims to investigate the integration of CF into sustainable construction practices, with a specific focus on identifying the key benefits and barriers to its implementation within the construction industry. The systematic review will offer insights into the current state of knowledge, identify best practices, and propose recommendations for integrating carbon financing more effectively into the construction industry's sustainability strategies.

This paper is structured to provide a comprehensive exploration of the research topic. It begins with an introduction that outlines the background, significance, and aim of the study. The methodology section details the systematic approach employed to collect and analyse CF data. This is followed by a thorough systematic literature review, the paper reveals the CF instruments, key challenges, and benefits associated with the application of CF in the construction industry. Finally, the paper concludes with a summary of key findings, along with practical recommendations for future research and industry application.

2. RESEARCH METHODOLOGY

A literature review is a widely used technique in construction-related research to expand the body of knowledge on specific topics (Chen et al., 2022). To identify and select a relevant topic in academia, a systematic review of previous research is essential (Ayat et al.,2021). In this study, a scholarly journal article on CF in the construction sector was located using the Scopus search engine. Scopus was chosen for three main reasons: (1) it has been extensively used in construction review research (Osei-Kyei & Chan, 2015); (2) it is an effective tool for conducting literature reviews (Ghaleb et al., 2022); and (3) it is more accurate and reliable compared to other search engines like PubMed, Google Scholar, and Web of Science (Ahmad et al., 2021). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was selected as the optimal methodology for this study after considering various systematic literature review methods. According to Shahruddin and Zairul (2020), PRISMA enhances the quality of evidence-based results and ensures transparency in the literature selection process. Moher et al. (2015) highlight that PRISMA's analytical and methodological approach is clear and straightforward. Further, Karunarathna et al. (2024) emphasise that a well-defined research topic is for a successful systematic review. The PRISMA framework explicitly incorporates the PICO (Populations, Interventions, Comparator, and Outcome) method for developing research questions of the study, as it facilitates literature reviews that address specific queries (Hosseini et al., 2024). Following Figure 1 presents the PRISMA flow diagram used for the study.

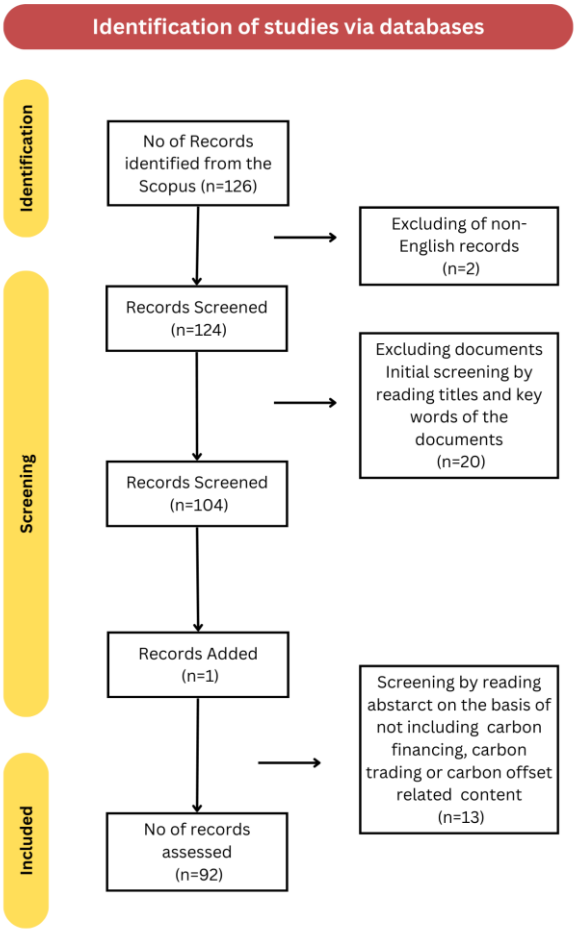


Figure 1: PRISMA flow diagram used for the study

The main search string used to retrieve bibliometric data related to the research area of concern was: ("carbon finance" OR "carbon financing" OR "carbon credit" OR "carbon trading" OR "carbon trade" OR "carbon offsetting" OR "carbon offset" OR "carbon accounting") AND ("construction industry" OR "building sector" OR "construction projects" OR "construction management"). Furthermore, more keywords and exclusion criteria have been used in the Scopus database to select relevant literature. Next, the screening process was performed by including journals, conference papers, and unpublished theses. Accordingly, 126 articles were selected from the search protocol. Due to language barriers, 2 non-English articles were excluded. Due to time and resource limitations, the search criteria were restricted to 'Article title, Abstract, Keywords.' From the remaining 124 papers, inclusion and exclusion criteria were applied to identify the most relevant papers and conduct a qualitative content analysis. The product-related papers, non-construction related papers, and papers that did not focus mainly on CF were excluded. As illustrated in Figure 1, 91 papers out of 124 were shortlisted. Papers have been reviewed using both content analysis and descriptive analysis. The content analysis was used to review the paper's contents thoroughly in broader themes such as (1) benefits of CF; (2) CF instruments; (3) challenges in CF; and (4) strategies to overcome the challenges. The research findings are presented in the two sections of the 'Findings and Discussion' section.

3. FINDINGS AND DISCUSSIONS

As GHG emissions continue to rise at alarming rates, the need for sustainable measures, including CF, is more critical than ever. Liu et al. (2019) explained that CF explores the financial implications of living in an environment where emissions of carbon dioxide and other GHGs carry a cost. Borghesi et al. (2015) describe carbon finance as encompassing activities that promote carbon emission reductions, such as investing in certified emission reductions (CERs) and carbon emissions trading. Liu et al. (2015) assert that carbon finance serves as an economic measure aimed at effectively addressing the climate problem. As noted by Su et al. (2023), CF includes cash flows from the sale of carbon credits, which represent the right to emit a certain amount of carbon dioxide. The UNHCR notes that CF is an innovative funding tool that places a financial value on carbon emissions, allowing companies to offset their emissions by purchasing credits from sustainable projects. Hence, CF is mostly integrated with trading carbon credits (Li & Liu, 2011; Zhou & Li, 2019).

Building upon this foundation, the ability to trade carbon credits and earn profits has become one of the main reasons for the popularity of CF as a business opportunity and investment among investors and businessmen (Su et al., 2023). The CF business primarily consists of two types. The first is the credit business, which focuses on the transformation of traditional industries through low-carbon upgrades, including CDM project investment and financing. The second is the intermediary business, which involves designing and developing carbon financial derivatives (Zhang & An, 2014). According to Labatt and White (2011), CF involves financial instruments and approaches that address climate issues through market-based solutions in a carbon-constrained world. Hence, these has become indispensable trading products in the CF market (Zhu et al., 2022). CF derivatives also known as CF instruments mainly include carbon futures, carbon options, and carbon swaps (Zhang & An, 2014; Sandor & Diperna, 2023; Liu & Li, 2024). Trading of CF derivatives occurs either on exchanges or over-the-counter (OTC) (Spilker & Nugent, 2022; Xu & Liu, 2023). These derivatives serve purposes such as hedging, carbon credit trading, and value discovery.

In light of these developments in the CF context, placing a monetary value on carbon emissions offers significant incentives and encouragement for construction firms to lower their emissions. Hence, CF has become an emerging area of focus within the construction industry. To further explore the role of CF in the construction industry, both content analysis and descriptive analysis were conducted to examine relevant literature and publication trends.

3.1 DESCRIPTIVE ANALYSIS

The publication trend of empirical studies conducted through the past years and the geographical distribution of related studies are insights through descriptive analysis.

3.1.1 Geographical Analysis

Understanding the geographical origins of research on CF within the construction industry offers valuable insights into global scholarly engagement and regional focus areas. As illustrated in Figure 2, the geographical distribution of CF-related publications demonstrates a growing global academic interest in applying CF principles to the built environment, underlining its rising relevance in achieving sector-wide sustainability goals.

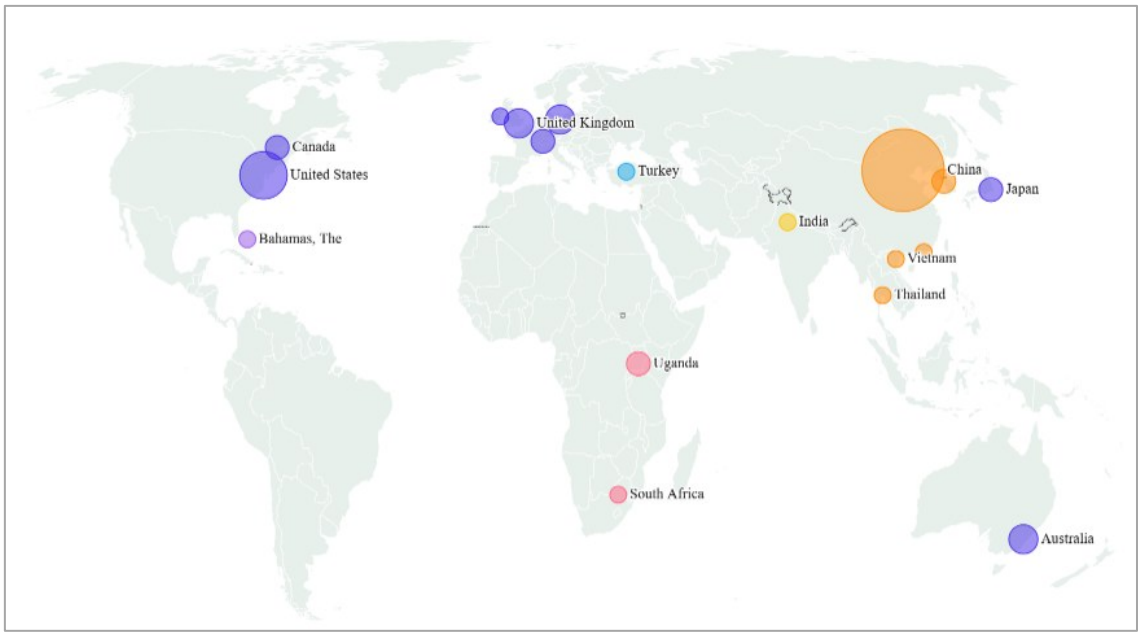


Figure 2: Geographical distribution of publications for CF of construction industry

The geographical distribution of publications illustrated in Figure 2 reveals significant disparities in research output on Carbon Financing (CF) within the construction industry across different regions. Countries like China and the United States emerge as leading contributors, reflecting their advanced commitments to climate action, regulatory frameworks supporting carbon markets, and institutional capacity to conduct large-scale research. China, in particular, dominates with 24 publications, likely driven by its national emissions trading scheme and increasing focus on green finance. In contrast, regions such as the EU and Europe, despite their progressive climate policies, show surprisingly lower publication counts, possibly due to data aggregation under broader European initiatives or journal indexing practices. Developed countries like Australia, Germany, the UK, and Canada exhibit moderate contributions, indicating a steady interest in integrating CF into sustainable construction practices. Meanwhile, developing nations including Uganda, India, South Africa, Vietnam, and Thailand demonstrate minimal scholarly activity. This limited engagement can be attributed to constraints such as resource scarcity, limited research infrastructure, and the prioritisation of socio-economic development over academic inquiry.

3.2 CONTENT ANALYSIS

The benefits and challenges associated with the implementation of carbon financing are thoroughly examined through the content analysis.

3.2.1 Benefits of CF

CF offers numerous benefits that significantly contribute to sustainable development and environmental protection. Table 1 presents the benefits of utilising CF.

Table 1: Benefits of utilising CF

Benefits	Sources
Global (Carbon) Emission Reductions	[1], [2], [3], [4], [5], [6],
Creation of Green Jobs	[4], [5]
Sustainable Energy Initiatives	[1], [2], [3], [4], [5], [6]
Biodiversity Protection	[7]
Climate Resilience	[1], [6]
Influence water quality trading	[8]
Cleaner Air and Health Benefits	[3]
Combatting Greenwashing	[9], [10]
Attract New Investments	[1]
Diversified Income for Communities	[1]
Economic Development for countries	[1]
Environmental Protection	[1], [5], [6]
Banks can enhance their capacity	[1]
International Cooperation	[1]

(1-Zhou & Li, 2019); (2- Yang & Luo, 2020); (3- Cai et al.,2016); (4- Wang et al., 2024); (5- Yu et al., 2021); (6- Firdaus & Arkananta, 2024); (7- Essl et al., 2018)

CF offers numerous benefits that significantly contribute to sustainable development and environmental protection. Among its primary advantages is the reduction of global carbon emissions, a critical step in combating climate change (Zhou & Li, 2019; Wang, 2021). The Olkaria II Unit 3 Geothermal Expansion Project in Kenya, the country's first CDM project to issue CERs, can be highlighted as a strong example of effective carbon financing (World Bank, n.d.). The project adds 276 gigawatts to the national grid while reducing 149,632 tonnes of carbon dioxide per year, making it a profitable project for both humans and the environment. In terms of climate resilience, CF plays a pivotal role by enhancing the capacity of communities to withstand environmental challenges such as floods and cyclones, thereby reducing vulnerability to climate-related disasters (Firdaus & Arkananta, 2024). Additionally, it creates green jobs, which are essential for promoting sustainable economic growth and providing employment opportunities within local communities (Yu et al., 2021). Moreover, CF supports sustainable energy initiatives, which not only reduce carbon footprints but also enhance energy security and resilience (Wang et al., 2024). Another key benefit is the enhancement of biodiversity protection, as CF backs projects that restore ecosystems and safeguard habitats for native species, addressing critical conservation needs (Essl et al., 2018). The majority of the benefits of CF also perform as a way to mitigate some of the environmental harms caused by the construction industry.

3.2.2 Challenges in CF

Despite the benefits the challenges faced while applying and utilising CF in the construction industry are also significant. Table 2 presents such challenges.

Table 2: Challenges encountered in utilising CF

Challenges	Sources
Global (Carbon) Emission Reductions	[1], [2], [3], [4], [5], [6],
Lack of understanding of CF	[1], [2]
Lack of knowledge on CF systems	[1], [5]
Lack of experts	[1], [5]
Lack of Transparency	[2], [3], [5]
Lack of innovation in carbon financial products.	[1], [2], [4], [5]
Lack of Universally recognised carbon market	[1], [3], [4], [5]
Lack of robustness in the existing policies and regulations,	[1], [5]
Lack of legal frameworks.	[1], [5]
Inaccuracies in Carbon Accounting	[2], [3], [5]
Difficulties in integration with Other Policies	[2], [3], [5]
Sectoral Fragmentation	[2], [4]
Price volatility	[2], [5]

(1-Liu et al., 2015; 2- Parenteau & Cao, 2016; 3- Wu et al., 2022; 4-Wang et al., 2019; 5- Lo, 2016)

A significant issue is the lack of understanding of CF (Liu et al., 2015), coupled with insufficient knowledge about CF systems and their operations (Lo, 2016). This knowledge gap extends to both financial institutions and enterprises, limiting their ability to fully engage in carbon financing initiatives (Liu et al., 2015). Despite the significant knowledge on CF in many Western countries, some nations, including China, have a more limited understanding of establishing and developing a comprehensive carbon financial system even by 2019 (Zhou & Li, 2019). Furthermore, the shortage of experts in CF (Lo, 2016), has reduced its popularity among the public and within industries. The inadequacy of existing policies, regulations, and legal frameworks further exacerbates the challenges faced by CF, as these frameworks are often not robust enough to support CF adequately (Zhou & Li, 2019). Chinese literature including Zhou and Li (2019) highlighted the absence of a nationally unified carbon trading platform as another significant hurdle. For the construction sector, a unified platform could streamline the process of acquiring carbon credits, making it easier for companies to offset emissions and invest in greener technologies.

3.2.3 Final Framework

Based on the findings of the study, a comprehensive final framework has been developed, encapsulating the key insights and outcomes derived from the research. This framework serves as a visual synthesis integrating the major findings, highlighting both the benefits and challenges of carbon financing, along with the classification of its financial instruments. As illustrated in Figure 3 the framework provides a structured representation of how carbon finance operates, offering a clear and concise overview of its benefits, limitations, and strategic mechanisms.

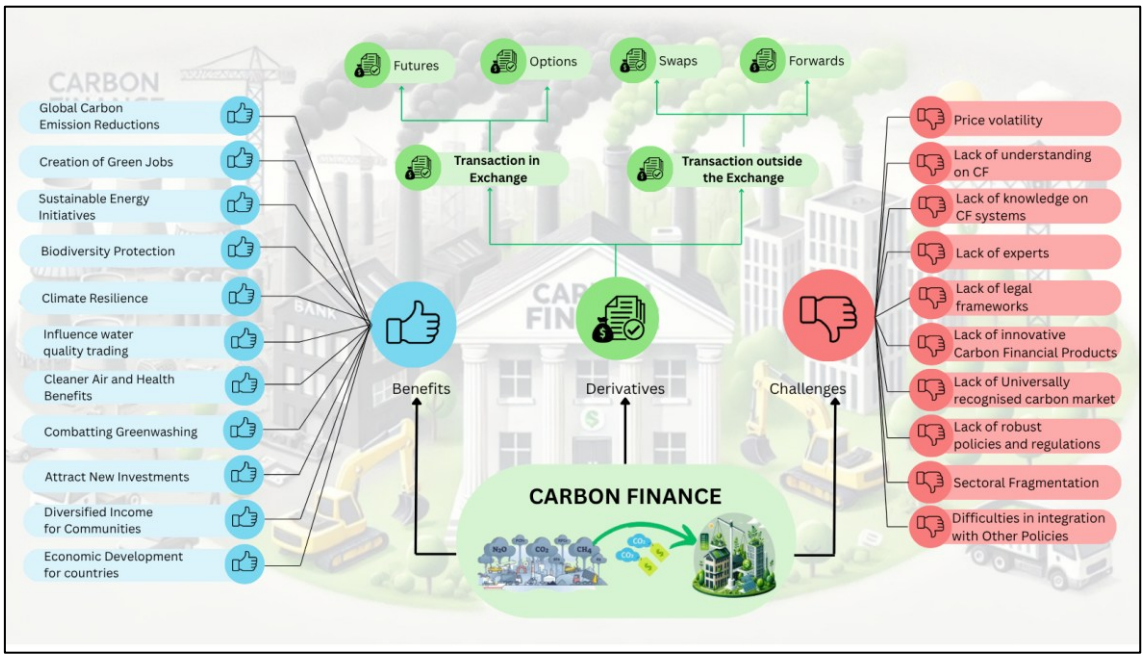


Figure 3: Final framework

Figure 3 presents a comprehensive visual framework of Carbon Finance, organising its key components into three interconnected segments: derivatives, benefits, and challenges. At the centre lies the core concept of "Carbon Finance," symbolised by a gradient illustration that contrasts pollution from industrial. Furthermore, the top section categorises carbon finance derivatives into two transaction types: those occurring outside the exchange (swaps and forwards) and those within exchange markets (options and futures), clearly showing the structural division in financial instruments. On the right, the benefits of carbon finance are listed within a green bubble, emphasising environmental, economic, and institutional gains such as emission reductions, creation of green jobs, sustainable energy initiatives, and enhanced international cooperation. Opposite this, the left section highlights the challenges, including a lack of expertise, transparency, legal frameworks, and policy integration, as well as issues like price volatility and sectoral fragmentation. Together, the image effectively illustrates how carbon finance operates at the intersection of environmental goals, market mechanisms, and systemic barriers, offering a clear and structured understanding of its multifaceted impact.

4. CONCLUSION AND RECOMMENDATIONS

CF is an emerging and largely underexplored area within the context of sustainable construction, offering innovative financial mechanisms that could significantly reduce the environmental footprint of the construction industry. Despite its immense promise, CF remains a hardly touched concept in the construction sector. Hence, this study has explored the critical role of CF in sustainable construction by introducing financial solutions to reduce GHG emissions. This paper contributes to the body of knowledge by providing an in-depth exploration of CF within the construction industry. It offers a comprehensive definition of CF specific to construction while emphasising the CF instruments that can be utilised. The paper also examines the geographical distribution of CF research, revealing the disparity between developed and developing countries.

Additionally, the paper discusses the challenges and benefits of CF, while highlighting its potential to drive sustainable construction practices when applied effectively.

Building on these insights, this study serves as a blueprint for integrating CF into construction practices. By addressing the current challenges and implementing the presented recommendations, the construction industry can move towards a more sustainable future where CF becomes an essential component of its sustainability strategy. This groundwork sets the stage for CF to be a cornerstone of sustainable construction. To achieve this, the study recommends that industry practitioners take several key actions. First, stakeholders, including policymakers, construction firms, and financial institutions should be educated about the benefits, markets, and systems of CF through targeted training programs and workshops. Second, robust policies and regulations must be developed to support CF initiatives, including a clear and universal set of guidelines. Third, utilisation of CF instruments should be encouraged, and new derivatives should be developed to cater to the evolving needs of the construction market. Finally, the creation of a nationally or regionally unified and recognised carbon trading platform is essential to streamline processes and enhance transparency.

Future research could focus on developing sector-specific carbon finance models tailored to the construction industry's unique emissions profile. Additionally, exploring digital tools, including blockchain to enhance transparency and accuracy in carbon accounting is vital. Finally, studies should assess stakeholder knowledge gaps and propose targeted capacity-building initiatives to support the adoption of carbon finance within the sector. Research should continue to explore the interplay between CF and other sustainability initiatives to create a holistic approach to reducing the environmental impact of the construction industry.

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CAUSES, DETECTION AND REMEDIATION OF WATER-INDUCED BUILDING DEFECTS: A SYSTEMATIC REVIEW

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ABSTRACT

Water ingress in buildings can considerably impact the building and its occupants by compromising structural integrity, health, safety, and financial stability. While existing research has identified common defects associated with water seepage, a comprehensive framework for systematically documenting these issues and their corresponding solutions is currently needed. This study aims to comprehensively review the means of water ingress, its root causes, associated defects, detection methods, and remediation techniques, using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines. A comprehensive search was conducted on articles related to water ingress-related building defects in the Scopus and Web of Science databases. Content and thematic analysis methods were applied to analyze 66 publications. The study identified seven vulnerable building components: exterior and interior walls, facades, roofs, basements, wet areas, and plumbing systems. It was found that cracks, faulty joints, defective fittings, and inadequate waterproofing lead to water ingress, causing structural, aesthetic, and functional damage. Further, detection methods ranging from visual inspections to advanced technologies like thermography and unmanned aerial vehicles (UAVs) were explored and various remedial actions including repairing, replacing, or reconstructing affected elements were suggested. The framework presented in this study provides design and construction professionals with proactive strategies for detecting and remedying water-related defects, offering practical guidelines for informed decision-making to effectively manage building defects linked to water ingress.

Keywords: *Building Defects; Causes, Diagnosis; Maintenance; Systematic Review; Water Ingress.*

1. INTRODUCTION

In the construction industry, one of the main concerns post-constructions is the manifestation of building defects. This issue carries economic implications (Talib & Sulieman, 2020), affects the builders' reputation (Gurmu et al., 2021) and compromises building quality (Jonsson & Gunnelin, 2019). In Australia, building defects cost around $2.5 billion annually with rectification accounting for 75% of the total cost (The Centre for International Economics, 2021). Defects occur due to poor workmanship, non-

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adherence to building design and standards, low-quality materials, and inadequate maintenance (Chong & Low, 2006). Notably, water-related defects are the most prevalent (Chew & De Silva, 2003b). In Australia, 42% of defects are related to water leaks with exterior water penetration and plumbing faults accounting for 40% and 22%, respectively (PICA, 2021).

Water ingress continues to pose significant structural and economic risks (Chew & De Silva, 2002), and contributes to energy loss (Kirimtat & Krejcar, 2018). Rectification costs for water-related defects are 42% in residential buildings and 31% in commercial buildings (The Centre for International Economics, 2021). Additionally, moisture intrusion promotes mould growth, creating unhealthy living spaces (Coulburn & Miller, 2022). Often latent in nature, these defects appear over time and may be overlooked (Chong & Low, 2006), highlighting the need for better understanding and prevention of water ingress.

The existing literature on building defects and water ingress tends to focus broadly on building defects, with limited emphasis on water or plumbing-related issues (Gurmu & Mudiyanselage, 2023). While previous studies have explored the causes and manifestations of this phenomenon in different building areas (Chew & De Silva, 2003a) as well as methods for detecting water or moisture ingress (De Filippo et al., 2023), the literature remains fragmented. Additionally, existing remediation discussions predominantly address defects in a general context (Sandanayake et al., 2022), lacking a comprehensive framework that integrates the causes, resulting defects and remedial strategies for water ingress. Thus, the research gap identified here is twofold: first, there is a need for focused studies on water and plumbing defects; second, a holistic framework linking water ingress causes with defects and remediation strategies is missing. Addressing these gaps will enhance understanding and inform practical strategies for addressing water-related defects. This study will investigate water ingress and develop a framework linking causes, defects, identification techniques, and remediation strategies.

2. LITERATURE REVIEW

Several studies have explored building defects and their causes. Sandanayake et al. (2022) reviewed residential building defects in Victoria, Australia, and found that poor workmanship was the leading cause, responsible for 90% of rectification costs, with waterproofing and water penetration defects having the highest cost implications. However, their study was limited to residential buildings. Talib and Suleiman (2020) categorized defects into latent and non-latent types, noting that dampness from water ingress was the most common latent defect, also contributing to other non-latent defects.

Recognizing water ingress as a major contributor to building defects, several studies have examined water-related issues. Chew et. al (2004) analyzed defects in wet areas in 56 non-residential high-rise buildings in Singapore, identifying 14 common defects, nine of which were linked to water penetration or moisture. These included water leakage, staining, paint defects, concrete spalling, tile debonding, water ponding, and corrosion, with construction deficiencies being the primary cause (43%). Similarly, Chew & De Silva (2003b) found that ceiling leaks accounted for 36% of defects in residential high-rise buildings, leading to fungi growth and paint deterioration. However, these studies predominantly focus only on wet areas of a building. Later research also highlights

internal and ceiling leakages as major defects caused mainly by construction issues (Gurmu et. al., 2025).

Studies on basement water seepage have identified plumbing leaks, poor waterproofing, and groundwater changes as key contributors to below-ground defects, which can compromise structural integrity (Chew & De Silva, 2003a). Gurmu and Mudiyanselage (2023) reviewed residential plumbing system anomalies, identifying leakage, clogging, corrosion, damaged pipes, faulty equipment, and poor installation as common causes, along with diagnostic methods for defect identification. However, these studies focus on specific areas - wet zones, basements, or plumbing - rather than providing a comprehensive review of water-related defects across an entire building.

Studies on inspection methods include Kot et al. (2016), who applied electromagnetic waves to detect water infiltration in concrete flat roofs, enabling early identification of moisture content to prevent critical defects. De Filippo et al. (2023) explored the use of UAVs with AI algorithms for defect detection, although their research focused only on identification without addressing causes or remediation. Chong and Low (2006) examined design-related defects in 74 buildings, attributing failures like plaster cracks, staining, and paint peeling to weather, occupant impacts, load, and moisture from wet areas. They offered strategies on material use and water leakage prevention. Ghani et al. (2023) emphasized the importance of planned maintenance and regular visual inspections to reduce the occurrence and impacts of building defects, including water ingress. Accordingly, the existing literature highlights the significant impact of water ingress-related defects in buildings. However, a comprehensive analysis of their causes, implications, and remediation has not been thoroughly explored. Therefore, further research is necessary to gain a holistic understanding of these defects.

3. RESEARCH METHODOLOGY

This study aimed to comprehensively review existing literature on water ingress in buildings, focusing on the causes and associated defects. A stand-alone review approach was adopted, which is effective for summarizing prior research and providing valuable insights (Templier & Paré, 2015). The research utilized a systematic literature review (SLR), a structured and transparent method that enhances the quality, replicability, reliability, and validity of findings (Xiao & Watson, 2019). Following the SLR guidelines outlined in Xiao and Watson (2019), the study defined its scope, searched and screened relevant literature, extracted and analyzed data, and reported the findings. It focused on building defects and water ingress, using Scopus and Web of Science (WoS) databases, which are widely recognized for comprehensive coverage (Sandanayake et al., 2022). A rigorous review protocol was established, following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework as shown in Figure 1.

The literature search keywords were based on research themes and included commonly used synonyms. The search string for Scopus was TITLE-ABS-KEY ("building*") AND TITLE-ABS-KEY ("defect*") AND TITLE-ABS-KEY ("water") OR TITLE-ABS-KEY ("moisture") AND TITLE-ABS-KEY ("ingress") OR TITLE-ABS-KEY ("leak*") while a similar string was used for WoS as ("building*" AND "defect*" AND ("water" OR "moisture") AND ("ingress" OR "leak*")). The asterisk was used to include all possible variations of relevant search terms.

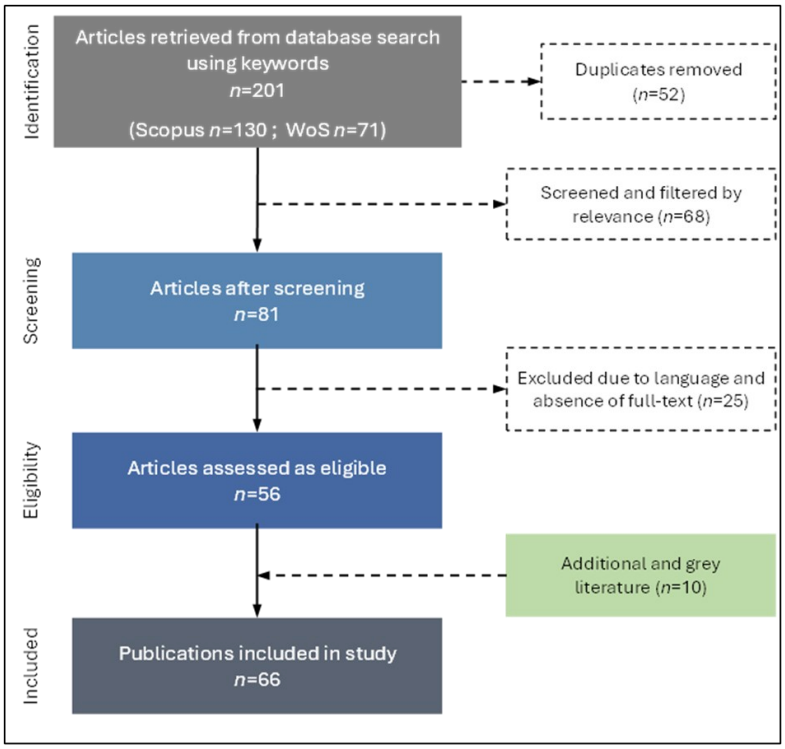


Figure 1: Article screening and eligibility assessment protocol – PRISMA Flowchart

The search focused on scientific publications, including journal papers, conference papers, books, and book chapters. Scopus yielded 130 records, and Web of Science (WoS) provided 71, totalling 201 records as of October 2023. After removing 52 duplicates, titles and abstracts were screened, excluding 68 irrelevant publications. Further, 25 non-English or unavailable full-text papers were removed, leaving 56 eligible for analysis. Additionally, 10 grey literature sources from government and private organizations were included. Ultimately, 66 publications were reviewed, comprising 42 journal articles, 18 conference papers, 1 book section, and 5 reports. The research used content analysis to organize and categorize articles, identifying patterns related to building defects caused by water ingress (Bengtsson, 2016). The literature findings were categorized into five main areas: (1) means of water ingress into buildings, (2) causes of water ingress and associated defects, (3) defects caused by water ingress, (4) methods of detecting water ingress, and (5) remediation techniques.

The research employed thematic analysis to synthesize the data and identify emerging themes (Clarke & Braun, 2017). A defect and cause table was created in Microsoft Excel to analyze the causes, related defects, and remediation for each component, while detection methods were analyzed separately.

4. RESULTS AND DISCUSSIONS

The review of articles identified key themes related to water ingress in buildings, including the most vulnerable building components, associated defects, detection methods, and remediation techniques. The findings highlight the vulnerabilities of these components and discuss the multifaceted nature of water ingress, offering potential remediation strategies for the construction industry. Figure 2 presents the framework

developed based on the SLR of existing literature. Detailed discussions of the framework are provided in the subsequent sub-sections.



Figure 2: Framework for water ingress into buildings

4.1 Means of Water Ingress

Water ingress in buildings manifests in different forms, affecting structural integrity and indoor air quality. Sahi et al. (2022) categorize water ingress into three types: water penetration/leakage, moisture/dampness, and airborne particles (aerosol). The causes and defects related to these types vary depending on the building component. Studies have identified seven key vulnerable areas where water ingress occurs, including exterior and interior walls, basements, wet areas (ceilings and floors), roofs, building façades, and plumbing systems.

Exterior walls act as a barrier between indoor and outdoor environments, making them vulnerable to water infiltration, especially when construction deficiencies and deteriorating materials create pathways for moisture to enter (Talib & Sulieman, 2021). Similarly, building façades, which include cladding, windows, doors, and balconies, are crucial in preventing water ingress. Inadequate weatherproofing and faulty installation of façade components can lead to water infiltration and allow moisture and airborne particles

to enter (Jonsson & Gunnelin, 2019). Interior walls, designed as partitions, can retain moisture if leaks or cracks compromise the building envelope (Yu et al., 2023).

The most common areas in which water ingress in buildings are wet areas, including bathroom, kitchen, and utility room floors and ceilings, due to their frequent exposure to moisture (Chew, 2005). Water penetration in these areas is often linked to structural damage and mould growth (Chong & Low, 2006). Roofs, another key defence against environmental elements, are also prone to water infiltration, leading to leaks and moisture issues (Kot et al., 2016). Basements are at high risk due to groundwater seepage and construction defects, which can severely affect structural integrity (Chew & De Silva, 2003a). The plumbing system, including water supply, drainage, and water tanks, is a major source of water ingress, with leaking pipes and poor drainage contributing to water damage and indoor air quality problems (Gurmu & Mudiyanselage, 2023). The next section will explore the defects and causes linked to these building components.

4.2 DEFECTS THAT CAUSE WATER INGRESS INTO BUILDINGS

Exterior walls often give way to water penetration due to structural defects such as cracks or gaps, faulty building joints, and porosity in the materials used for construction. These defects are commonly induced by structural movements, poor construction practices and material use, while inadequate waterproofing further encourages greater water absorption (Talib & Sulieman, 2021). Defects identified in building facades include anomalies in balconies, windows and door seals which create air and moisture gaps (Crean, 2017). These defects are often attributed to environmental exposure such as high winds, UV radiation and rain, and defective installation and materials (Cladding Safety Victoria, 2023). Similar to exterior walls, interior walls are also susceptible to cracks resulting from structural and construction deficiencies. Additionally, improperly sealed gaps where the wall is penetrated by plumbing or other fixtures highlight the need for meticulous installation practices (Singh et al., 2011). Furthermore, high humidity and condensation due to restricted airflow contribute to moisture retention in indoor spaces which have been linked to the deterioration of wall finishes (Felipo & Charpin, 2022).

While its characterisation implies the presence of water, anomalies such as water leakage from faulty pipes and cracks in the floor or wall joints due to poor workmanship and excessive moisture absorption pose added risks in wet areas (Sahi et al., 2022). Additionally, design defects leading to water ponding, along with inadequate drainage and waterproofing issues, highlight the importance of thorough inspection and repair protocols (Chew & De Silva, 2003b).

The roof presents susceptibility to water ingress through the manifestation of cracks and material deterioration due to high exposure to environmental conditions and construction deficiencies. Inadequate attention to specifications also causes defects in construction joints and drainage resulting in water penetration into the building (Pamera & Gurmu, 2020).

Cracks in the foundation often induced by structural movements or poor construction practices and faulty joints serve as conduits for water and moisture penetration in basements. Additionally, the lack of good airflow in these spaces intensifies moisture retention (Chew & De Silva, 2003a). Similarly, there are several common defects associated with water ingress within the plumbing system. The defects associated with water supply are water leakage due to faulty pipes or fixtures, corrosion of pipes and

overflowing tanks (Gurmu & Mudiyanselage, 2023). Pipe leakage was identified as the most commonly occurring defect. The defects related to sanitary drainage include defective water trap seals and sewer backflow resulting from defective installation, which has been linked to the dispersion of contaminated aerosolized particles and the transmission of pathogens, with severe health implications (VBA, 2023). Additionally, the incorrect discharge of stormwater from the roof and defects in swimming pool structures caused by defective design and installation are also identified as contributing to water ingress.

The defects that encourage water ingress in buildings are often physically evident; however, they may not always be visually distinct. Overall, the defects discussed above were identified as commonly associated with issues relating to inadequate design, low-quality material use, poor workmanship and lack of regular maintenance of buildings. The origin of these defects could further be linked to the designers, contractors, material suppliers and maintenance contractors (Chong & Low, 2006). However, similar to the findings by Chew (2005) and Chew and de Silva (2002), most causes were attributed to the construction stage, particularly deficiencies or non-adherence to construction standards and attention to detail. Nevertheless, understanding the root causes of these defects is necessary for implementing effective remediation strategies.

4.3 DEFECTS CAUSED BY WATER INGRESS

Water ingress, caused by defects in building structures, leads to additional issues such as structural, aesthetic, and functional defects. Structural defects are defined as issues that compromise the structural integrity and stability of a building. Water and moisture in buildings have been identified as causing deterioration of building materials and corrosion of structural components leading to the weakening of the overall structure (Singh et al., 2010). Aesthetic defects refer to damages primarily affecting the appearance of the building. Water ingress not immediately visible to the occupants is often first visible through defects in the paint/plaster such as peeling, blistering or flaking on walls and ceilings, discolouration of surfaces and increasing efflorescence. These defects occur as a result of water seepage and excessive moisture absorption on surfaces (particularly those in proximity to wet areas), which also lack sufficient waterproofing (Chew & De Silva, 2002). While they may not directly compromise the structural integrity of a building, they significantly impact its visual appeal and are typically common visual indicators of water damage.

Functional defects impact the usability of the building, affecting the comfort, convenience as well as health and wellbeing of its occupants. Water ingress has been associated with electrical system malfunctions and plumbing defects caused by corroding pipes which are both functional and safety hazards (Law et al., 2021). However, it is more commonly associated with the growth of toxic mould and algae on surfaces exposed to moisture and dampness which is a significant health hazard in most affected buildings (Felipo & Charpin, 2022). Water ingress in indoor spaces, combined with low ventilation can create a suitable environment for fungal growth and once established, could affect material with low moisture content (Talib & Sulieman, 2020). This has been linked to respiratory issues and allergies among exposure to other health risks, leading to ‘sick buildings’ (Singh et al., 2010). Additionally, the presence of water could also encourage insect infestations and the breeding of mosquitos (Singh et al., 2010). These defects highlight the significance of this issue and the immediate need to address them. Thus, it is important

to identify these defects such that the root cause or origin can be addressed to ensure the functionality and structural integrity of the building. The following section discussed methods of detecting water ingress and associated defects.

4.4 DETECTION METHODS

The literature identifies various methods for detecting water ingress or damage, with a focus on non-destructive techniques. These methods differ in the technology used but all aim to identify affected areas and determine the underlying causes of water-related issues. The most traditional method to detect water ingress is through regular visual inspection (Bortolini & Forcada, 2018). This refers to visually examining different components of a building for signs of water leaks, staining, dampness, condensation, mould or algae growth and corrosion (Wahab & Hamid, 2011). It also serves as the initial step in diagnosing potential defects, to guide further investigation or testing, if needed. However, effective inspection and results rely on the expertise and experience of the inspector (Gurmu & Mudiyanselage, 2023). Other traditional testing methods include the use of moisture meters and electrical resistance or conductivity tests, which are both low-cost strategies for measuring moisture in building materials (Phillipson et al., 2007).

Thermography and microwave technology are non-destructive methods that can be used to detect water ingress and related defects that are not visually evident. Thermography detects variations in surface temperature based on thermal properties, which can reveal underlying dampness or water within the structure (Pamera & Gurmu, 2020). Similarly, microwave technology allows areas of leakage due to cracks in concrete structures (Kot et al., 2016). This could be a more effective method if used together with thermography, where the water-ingress areas can be more easily detected due to the specific temperature distribution caused by microwave heating (Barreira et al., 2013). However, the level of moisture content cannot be evaluated with these methods (Phillipson et al., 2007). More recent innovations include the use of UAVs and robotic technology to diagnose defects, particularly on building facades. These methods can provide 3D visual and thermal data and locate points of air or moisture leakage more accurately, thereby, reducing operational costs and safety risks (De Filippo et al., 2023). These methods are most suitable for inspection of high-rise buildings.

In addition to visual inspection, defects in the plumbing system can be diagnosed using specialized equipment and testing methods. Water leaks and faulty pipes could be identified using hydrostatic pressure tests. Additionally, infrared cameras combined with listening devices such as leak detectors and leak loggers can be used to isolate points of ingress, particularly in inaccessible areas, such as underground piping and within walls and slabs (Gurmu & Mudiyanselage, 2023). Water trap seals within the sanitary drainage system have been previously tested using air pressure transient simulation in building drainage and vent systems. This operates similarly to a sonar system, reflecting air pressure waves off drainage boundaries, and revealing defective seals (Swaffield, 2005). The detection of defective water trap seals can be significant in preventing cross-contamination and the spread of infectious diseases.

4.5 REMEDIATION OF WATER-RELATED DEFECTS

The above sections discussed the causes and defects of water ingress in buildings, along with methods for detecting and addressing them. The required remedial actions such as repair, replacement, or management depend on the stage at which the defects are

diagnosed. Nevertheless, the foremost step would be to control water ingress at the source or remove the source (Singh et al., 2011). To do this, the results suggest that the most common method is to seal sites of infiltration or repair defects that could lead to water ingress in the future. This includes repair or replacement of defective elements and substandard material (Chong & Low, 2006) and appropriate application of waterproof coatings or sealant. Waterproofing is a key step in the construction process which limits moisture levels on building surfaces, preventing water-related aesthetic and structural damage. It also protects against the growth of toxic moulds. However, if there is existing evidence of dampness or mould, immediate remediation is necessary to minimize health risks to the occupants. The most effective strategy in this instance is cleaning or treating affected surfaces by chemical means and improving ventilation and airflow (Singh et al., 2010). Humidity control and maintenance of HVAC systems could further address issues and defects associated with condensation and moisture retention (Wang & Yin, 2019).

The defects previously discussed also revealed design and construction-related causes due to possible non-compliance with standards and guidelines. Some of these defects may require design improvements or reconstruction of the related elements to rectify the damages. This highlights that many building defects are not merely symptoms of isolated workmanship issues but are indicative of more systemic shortcomings in design decision-making, quality assurance practices, and regulatory enforcement. The identified defects, such as water ingress, concrete cracking, and joint failures, signal a disconnect between design intentions and construction execution. These issues may also reflect a lack of robust feedback mechanisms from post-construction performance data into future design and specification standards. Thus, the findings from this SLR could inform a design-feedback framework, where recurrent defects become catalysts for revising design protocols, detailing practices, and material selections, thereby preventing recurrence in future projects.

Additionally, remediation must be undertaken following the appropriate design and construction specifications (Chong & Low, 2006). Furthermore, building defect investigations often take place following signs of damage that might hinder the functionality of the building, requiring extensive repair which is both time-consuming and costly. This can be avoided by regular inspection and appropriate maintenance of the building (Talib & Sulieman, 2021). Maintenance that is unplanned and occurs following defect diagnosis to rectify the defect and its causes is referred to as corrective maintenance. Conversely, preventive maintenance involves planned strategies to minimize the materialisation of such defects. Of these, preventive maintenance is identified as the most suitable and effective strategy to ensure the long-term structural and functional integrity of the building (Ghani et al., 2023). Thus, it can be noted that preventive maintenance of buildings together with good construction practices could limit water-related defects and the need for defect remediation.

4.6 IMPLICATIONS OF THE STUDY

This research enhances the theoretical understanding of water ingress in buildings by systematically examining its causes, related defects, identification methods, and remediation strategies. It proposes a comprehensive framework that connects these elements, offering a theoretical model for addressing this complex issue and forming a foundation for future research in building maintenance and pathology. By integrating

knowledge from engineering, construction management, and materials science, the study strengthens the interdisciplinary foundation related to building defects and water ingress.

The research also offers valuable insights for architects, engineers, and construction professionals by identifying common causes and defects associated with water ingress. The findings support improvements in building design, material selection, and construction techniques to mitigate water intrusion risks. The framework can improve maintenance and inspection processes, enabling early detection and resolution of water ingress issues, thereby extending the building's lifespan. By linking specific causes to effective remediation strategies, the study provides practical guidance for developing cost-effective repair plans to prevent structural and aesthetic damage.

5. CONCLUSION

Water ingress in buildings poses significant challenges to the construction industry, impacting structural integrity, indoor environmental quality, and occupant well-being. This review comprehensively analyzed defects linked to water ingress, highlighting causes, resultant defects, and remediation strategies. Key vulnerable components identified include exterior and interior walls, façades, roofs, basements, wet areas, and plumbing systems. Defects such as cracks, faulty joints, material deterioration, and inadequate waterproofing contribute to water penetration and typically arise from issues in design, workmanship, materials and maintenance. Water ingress leads to structural, aesthetic, and functional problems, affecting building stability and appearance. Detection methods range from visual inspections to technologies like thermography and UAVs. Remediation involves sealing, repairing, replacing, or redesigning affected elements, with preventive maintenance being essential to prevent future defects and maintain a healthy environment. The study emphasizes the need for better design and construction practices and greater awareness of the impacts of poor workmanship and maintenance. Findings can guide contractors, architects, and engineers to prevent water ingress and support building owners and managers in developing proactive maintenance strategies to reduce costs and minimize occupant disruption. Although the study offers a framework for understanding water ingress causes, defects, and remediation, it relies on existing research and may not capture all defects or regional variations. Future research could examine specific building components in greater depth and contribute to improved construction standards and diagnostic tools.

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CLIENT SATISFACTION MODEL FOR LEAN IMPLEMENTED CONSTRUCTION SMES: A REVIEW

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ABSTRACT

Client satisfaction is a critical determinant of success in the construction industry, particularly for small and medium-sized enterprises (SMEs) that have implemented lean principles. Despite the recognised benefits of lean construction, many SMEs continue to struggle with achieving high levels of client satisfaction. While existing studies primarily explore the advantages and challenges of Lean implementation, there is a lack of research that specifically investigates the underlying causes of less client satisfaction in Lean implemented construction SMEs. Therefore, this study aims to bridge this gap by developing a conceptual framework for a client satisfaction model tailored to lean implemented construction SMEs. A literature review was conducted to examine the key factors affecting client satisfaction in lean implemented construction SMEs. The review analysed existing studies on lean construction, client satisfaction, and SME-specific challenges to identify critical themes. The data was synthesised to develop a framework that integrates lean principles, benefits, barriers, factors influencing client satisfaction, and reasons for failing to meet client expectations. The findings highlight that perceived quality, customer satisfaction, and customer loyalty are interrelated, with higher satisfaction leading to increased client retention and improved financial performance. Additionally, the study identifies key barriers that hinder client satisfaction in lean implemented SMEs, including ineffective communication, resistance to change, and inadequate understanding of lean principles. This study contributes to both theory and practice by offering a structured framework to enhance client satisfaction in lean implemented SMEs. It provides SMEs with strategic insights to improve lean adoption while recommending future research directions to empirically validate the proposed framework through case studies and stakeholder engagement.

Keywords: *Client Satisfaction; Construction; Lean; SMEs.*

1. INTRODUCTION

Construction SMEs play a vital role in the economy by creating jobs, contributing to economic growth and stability, and remaining one step below large construction companies (Ranadewa et al., 2018; Palacios-Manzano et al., 2024). Globally, SMEs are contributing significantly to innovation, economic growth, poverty reduction and supporting job opportunities and large-scale enterprises (Ismail et al., 2023). Often

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construction SMEs are responsible for residential, commercial and infrastructure developments due to the rising demand (Motsetse, 2015). As demand for affordable housing increases, while raw materials become scarcer, medium construction firms need to adopt creative circular economy practices (Zuofa et al., 2023). These practices will help them build sustainably and grow their businesses, providing a strong reason to embrace circular economy principles in their construction processes (John et al., 2023).

Even though SMEs were able to gain more benefits than micro-sized firms due to the availability of required basic capacities, most SMEs are still unfamiliar with the lean concept (Ranadewa et al., 2015). According to Balkhy et al. (2021), the performance and productivity of a company can be achieved through a lean implementation to SMEs in the construction sector. Lean offers several intrinsic direct advantages that improve an organization's capacity to compete successfully by increasing operational effectiveness and efficiency. Worldwide construction industries have adopted lean construction and have reaped its benefits (Dehdasht et al., 2020).

According to Demirkesen and Bayhan, (2022), the most important benefit from LC (lean construction) will be client satisfaction when implementing lean construction under customer focus. Lean principles in the construction industry can minimize and eliminate non-value adding activities, increasing value for the client (Maradzano et al., 2019). Even though many construction companies across the globe have embraced lean principles, the achievement of client satisfaction for many of the construction firms is still a dream (Bayhan et al., 2019). Therefore, construction industry needs to understand the essential factors for enhancing lean implementation that would eventually improve client satisfaction. However, due to the fact that lean principles have not been implemented to the fullest, some of the SMEs have failed to achieve their objectives (Yusup et al., 2015) and could not achieve the expected client satisfaction level.

Most studies have been done to address the barriers to lean implementation and have developed models for those causes. Durdyev et al. (2018) have developed a client satisfaction model: a PLS-SEM approach to investigate the service quality on construction client satisfaction. In the local context, De Silva et al. (2023) have done a fuzzy TOPSIS analysis for implementing Lean Six Sigma in SMEs in the construction industry.

Despite that, there is lack of studies that specifically address the causes for lack of client satisfaction in lean implemented construction SMEs, as the problem remains the same. Therefore, this research aims to develop a framework for a client satisfaction model in lean implemented construction SMEs. The structure of the paper is as follows: It begins with an outline of the methodological approach. This is followed by the presentation of research findings, derived from an extensive literature review. Finally, the paper concludes with a summary and suggestions for future research.

2. METHODOLOGY

The method adopted is a literature review of the LC at SMEs in the construction industry. The literature review is a comprehensive and reproducible method for identifying, evaluating, and synthesising the existing body of recorded knowledge produced by researchers, scholars, and practitioners (Chen, 2017; Pollock & Berge, 2018). Literature reviews are essential in generating evidence from existing studies and for their ability to

create new knowledge by compiling the existing works, which is essential for directing new research (Cobo et al., 2011).

The review covers the literature published in the last 15 years between 2010 and 2025 (March), a period in which both the lean and SMEs research domains have visibly matured and attracted significant attention from researchers and practitioners. Figure 1 describes the research process of this study.

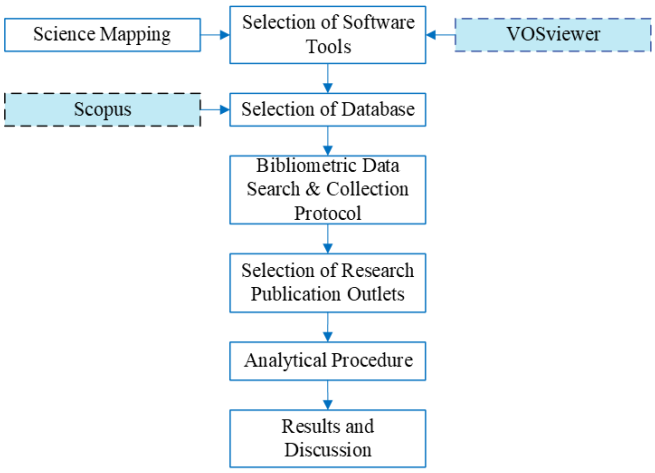


Figure 1: Research Methodology

In the first step of the literature review, the following main keywords were searched in the titles, abstracts and (or) keywords of publications in three search rounds: {("Lean" OR "Lean construction" OR "Lean principles" OR "Lean management" OR "Lean implementation" OR "Lean tools") AND ("small and medium-sized enterprises" OR "SMEs" OR "Construction SMEs") AND ("construction industry" OR "construction sector" OR "building industry" OR "construction projects" OR "construction" OR "building sector")}. Articles were identified after the exclusion of non-peer reviewed publications, articles out of the construction research domain, and articles that do not actually discuss or do not mainly focus on Lean and construction at SMEs in the construction industry even though they contain those keywords in their titles, abstracts, and (or) keywords.

3. FINDINGS

3.1 LEAN IMPLEMENTED CONSTRUCTION SMES

Lean construction is an approach to managing the performance of construction activities where maximum value is achieved with reduced wastage and lean construction draws principles of Lean manufacturing, which originated from the Toyota Production System (Salem et al., 2006). Lean practices are used as an approach to develop and continuously improve production efficiency and to enhance the effectiveness of a business by reducing wasteful practices and improving efficiency (Majava & Ojanperä, 2017). Furthermore, lean practices enable firms to satisfy customer expectations while reducing cost and wastage at the same time (Bhamu & Sangwan, 2014). Lean Construction (LC) has been widely used in several industries, including building, road infrastructure, sanitation, mining, industrial facilities, and energy and oil projects (Erazo-Rondinel & Huaman-Orosco, 2021).

In many countries, the construction industry will be categorized into a few numbers of large companies and a very large number of SMEs (Tezel et al., 2020). Globally, SMEs represent 90% of businesses and contribute to economic growth, job creation and support for larger companies in the construction industry (Ranadewa et al., 2015; Tezel et al., 2020). The definition of SMEs varies across countries due to factors like the economic conditions of the country, population, and government policies. According to Tezel et al. (2020), an organization which has fewer than 50 employees is a small company, and one that has between 50 and 249 employees it is considered a medium-sized company. SMEs are considered the backbone of many economies, as they are instrumental in promoting economic growth, reducing poverty, and fostering sustainable development (Erhan & Gaugas, 2022). SMEs in the construction industry face a variety of challenges, including limited access to financial resources, technological barriers, and the ability to adapt to rapidly changing market conditions. Implementing lean construction principles has emerged as a potential solution to mitigate these issues by minimizing various forms of waste (Islam et al., 2019).

LC at SMEs has also attracted little attention from researchers, evidenced by the limited number of publications that directly reference the use of LC within SMEs (Tezel at al., 2020). The application of lean principles in construction SMEs involves tailoring lean tools to the specific characteristics of these enterprises, considering factors such as size, financial capabilities, organizational culture, and human resource capacity (Ayarkwa & Agyekum, 2017).

3.2 BENEFITS OF LEAN IMPLEMENTED CONSTRUCTION SMES

Lean Construction methods can improve performance in the construction sector by addressing project-related issues and focusing on stakeholders and management to add value (Nwaki & Eze, 2020). Many countries see Lean Construction as an appropriate method that can save resources, decrease costs, speed up activities, and improve control (Ivina & Olsson, 2020). Lean construction methods, techniques, tools, and concepts could face value challenges in construction and offer a solution for the efficiency-based problem in the construction industry (Shaqour, 2022). Many project-related items could be enhanced after implementing Lean Construction tools, such as time saving, material waste reduction, labor waste reduction, and space-cost saving (Reinbold et al., 2018). Many studies have discussed the benefits of lean construction, and Table 1 will summarize them.

Table 1: Benefits of Lean Construction in SMEs

Benefits Group	Benefit	Reference
Environmental benefits	Safety control improvements	[1]
	Time, cost, and material waste reduction	[2], [3]
	Material waste reduction	[3], [4]
	Improve the quality of the environment	[5]
	Preventing pollution and emissions	[6]
	Material storage control (access and inventor)	[1]
	Reduction of energy consumption	[5]
	Water conservation	[4]
	Enhancing work environment	[7]

Benefits Group	Benefit	Reference
Economic benefits	Time reduction	[1], [8]
	Cost reduction	[1], [3], [8]
	Improve quality	[4], [8]
	Increase productivity	[1]
	Rework minimization	[7]
	Improve prediction of risks	[7], [9]
	Improving safety	[7]
	Improved planning	[9]
	Improve process control	[9]
	Labor cost reduction	[9]
	Value achievement	[9]
	improving life-cycle cost	[9]
	Reduction of rework	[9]
Social benefits	Customer satisfaction	[1]
	Employee satisfaction	[1]
	Minimization of conflicts	[1], [3]
	Improve communication between project stakeholders	[3]
	Enhancing transparency	[4]
	Improving decision making	[3]
	Continues improvements	[3]
	Enhancing teamwork	[3]
	Valuing relationships	[9]

[1] - (Sarhan et al., 2017), [2] - (Ghosh & Bhattacharjee, 2014), [3] - (Silvius et al., 2017), [4] - (Ogunbiyi et al., 2014), [5] - (Saieg et al., 2018), [6] - (Salem et al., 2014), [7] - (Maradzano et al., 2019), [8] - (Ansah & Sorooshian, 2017), [9] - (Ivina & Olsson, 2020)

Table 1 highlights the key benefits of Lean implementation in construction, categorized into environmental, economic, and social benefits. Environmentally, Lean techniques contribute to waste reduction, pollution prevention, energy conservation, and improved safety and material management. Economically, they enhance efficiency by reducing time, costs, rework, and labour expenses while improving productivity, quality, and risk management. Socially, Lean fosters better communication, transparency, teamwork, and overall stakeholder satisfaction, minimizing conflicts and enhancing decision-making. Collectively, these benefits emphasize Lean's role in promoting sustainability, efficiency, and collaboration within the construction industry.

3.3 CHALLENGES OF LEAN IMPLEMENTED CONSTRUCTION SMES

The adoption of Lean principles within SMEs in the construction sector is fraught with numerous challenges, many of which stem from resource constraints, organisational limitations, and a lack of strategic integration. One significant challenge is the lack of time to implement Lean in ongoing projects, as SMEs often operate under tight schedules and financial constraints that prioritise immediate project deliverables over process improvements (Salvatierra et al., 2015). Further, client satisfaction in construction SMEs is a crucial issue in lean implemented construction SMEs. The real need of the clients is not being fulfilled as the lean implementation is not customized to the specific needs of the clients (Sergeeva, 2022). Another critical challenge is the inability to measure

performance and team progress, which hampers the ability of SMEs to assess the effectiveness of Lean implementation (Koohestani et al., 2020). Performance metrics are essential for continuous improvement, yet many SMEs lack the necessary tools and frameworks to systematically evaluate their Lean initiatives (Aslam et al., 2020). The absence of clear performance indicators not only diminishes accountability but also makes it difficult to justify further investments in Lean practices. This issue is closely linked to the low ability of personnel to recognise waste, as employees may lack the training to identify inefficiencies within workflows (Cerveró-Romero et al., 2013; Bashir et al., 2015). Without this fundamental awareness, Lean strategies risk becoming ineffective, as inefficiencies remain embedded within existing processes. Furthermore, low levels of Lean knowledge among university graduates present a systemic challenge. Many construction professionals enter the workforce with limited exposure to Lean principles, resulting in a workforce that is ill-equipped to drive Lean implementation (Murguia, 2019; Thomas et al., 2015). This knowledge gap necessitates extensive in-house training, which SMEs may struggle to provide due to resource constraints.

Compounding these difficulties is the tendency of some SMEs to replicate another organisation's Lean strategy without tailoring it to their specific needs. While benchmarking against successful Lean adopters can provide insights, blindly imitating methodologies without considering organisational context can lead to inefficiencies and misalignment with business objectives (Almanei et al., 2017; Kawish, 2017). Similarly, the lack of leadership and empowerment of personnel presents a substantial barrier, as effective Lean implementation requires strong managerial support and a participatory work culture (Huaman-Orosco & Erazo-Rondinel, 2021). In SMEs, where leadership structures are often less formalised, decision-making tends to be concentrated at the top, limiting employees' ability to contribute to Lean initiatives. This hierarchical approach can stifle innovation and reduce engagement with Lean principles at the operational level.

Moreover, Lean adoption in SMEs is often hindered by local rather than global flow optimisation, where firms focus on improving isolated processes rather than considering the broader supply chain and project-wide coordination (Bashir et al., 2015; Wandahl, 2014). This narrow focus prevents Lean from delivering its full benefits, as bottlenecks persist in areas that are not addressed holistically. Additionally, the lack of collaboration among project stakeholders exacerbates inefficiencies, as fragmented communication and misaligned objectives hinder the seamless integration of Lean processes (Gomez et al., 2018). Without early-stage collaboration involving all stakeholders including suppliers, subcontractors, and designers' lean efforts may be undermined by conflicting priorities and inadequate information sharing.

3.4 FACTORS AFFECTING CLIENT SATISFACTION IN LEAN IMPLEMENTED CONSTRUCTION SMES

Even though there are so many studies that have proved the benefits of lean implementation to the construction SMEs due to poor service design and an over focus on efficiency, lean implementation can fail (Radnor & Osborne, 2013). The adoption of lean manufacturing techniques has garnered substantial interest in recent years, especially within the construction sector, as a strategy to improve efficiency and minimize waste (Demirkesen & Bayhan, 2022). Nevertheless, the success rate of lean implementation has been quite unsatisfactory, with studies indicating that up to 90% of lean initiatives fail to be sustained beyond the first three years of their introduction (Xing et al., 2021).

One of the primary problems that has not been addressed is client satisfaction in construction SMEs. The real needs of the clients are not being fulfilled, as the lean implementation is not customized to the specific needs of the clients (Sergeeva, 2022). The construction industry is inherently complex and dynamic, with projects often facing a myriad of uncertainties, complex supply chains, and varying site conditions (Bayhan et al., 2019). This complexity and varying conditions can pose significant challenges to the effective implementation of lean principles, which are often more easily applied in a manufacturing setting. Furthermore, the lack of knowledge and expertise in lean methodologies among construction professionals exacerbates the challenge, further impeding successful implementation (Bayhan et al., 2019).

To overcome these obstacles, construction companies need to take a more comprehensive approach to lean implementation, focusing not just on process-level adjustments but also on cultivating a culture that encourages continuous improvement and the elimination of waste.

3.5 CLIENT SATISFACTION MODELS

The client is the owner of a construction project or the buyer/seller of goods or services (Challender & Whitaker, 2019). Client satisfaction refers to meeting or exceeding their expectations with services or products (Riak & Bill, 2022). Accordingly, client satisfaction is based on recognizing and addressing their requirements (Durdyev et al., 2018; Rahman & Alzubi, 2015). Customer satisfaction is often associated with performance in the construction sector and companies with high client satisfaction ratings get a competitive advantage (Alshihre et al., 2020). Moreover, failure to communicate effectively and meet deadlines may result in dissatisfaction on both sides of a construction contract (Obonadhuze et al., 2021). Client satisfaction is an emotional response when realizations exceed expectations (Sulistyawati & Listiyanti, 2024). Client satisfaction models have evolved significantly over the years, reflecting a diverse range of approaches and methodologies tailored to various sectors and contexts. These models are crucial for understanding the factors that contribute to client satisfaction and for improving service delivery across industries.

One foundational model is the Kano model, introduced by Noriaki Kano, further enriches the discourse on client satisfaction by categorizing customer needs into five distinct types: basic, performance, excitement, indifferent, and reverse qualities. This classification helps organizations prioritize features and services that enhance customer satisfaction (Wang et al., 2019; Rahaju & Dewi, 2014). The applicability of the Kano model extends beyond product development to service industries, where understanding the nuances of customer expectations can lead to improved satisfaction outcomes.

Moreover, the SERVQUAL framework, which assesses service quality through dimensions such as reliability, assurance, tangibles, empathy, and responsiveness, has been widely utilized to evaluate client satisfaction in various sectors, including healthcare and retail (Luruli et al., 2016) This framework allows organizations to identify gaps between customer expectations and actual service delivery, thereby facilitating targeted improvements.

American Customer Satisfaction Index (ACSI) serves as a benchmark for measuring customer satisfaction across various sectors. It emphasizes the relationship between perceived quality, customer satisfaction, and customer loyalty, suggesting that higher

satisfaction leads to increased loyalty and, consequently, better financial performance for firms (Liu et al., 2020; Wang et al., 2021). The ACSI methodology captures the nuances of customer expectations, perceived quality, and perceived value, all of which contribute to the overall satisfaction score. The resulting data enables businesses to identify areas for improvement, refine their strategies, and benchmark their performance against competitors, enhancing their competitiveness and fostering sustainable growth (Wang et al., 2021; Sha et al., 2022). This insight is invaluable for prioritizing investments in product development, service enhancements, and customer relationship management (Liu et al., 2020). Figure 2 illustrates the ACSI model.

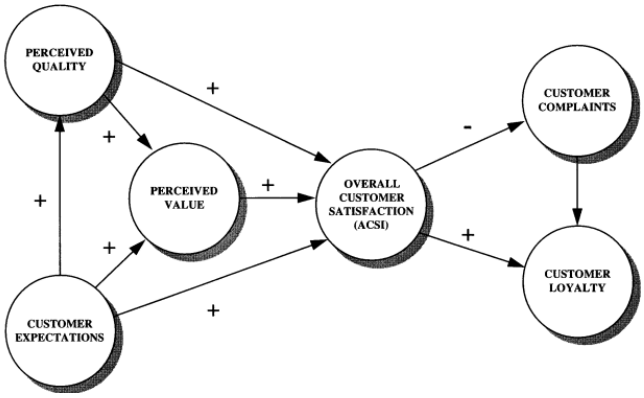


Figure 2: ACSI model (Source: Fornell et al., 1996)

Furthermore, the ACSI model's proven track record in various sectors underscores its robustness and reliability as a tool for measuring customer satisfaction (Sha et al., 2022). Therefore, by integrating the ACSI framework in lean implemented construction SMEs can gain actionable insights into client satisfaction, enabling them to refine their processes, enhance service quality, and achieve a competitive edge in the market.

3.6 CONCEPTUAL FRAMEWORK

The literature review revealed a clear need to establish a client satisfaction model specifically for construction SMEs that have adopted lean principles. Accordingly, the conceptual framework presented in Figure 3 was developed based on the insights gained from the literature review.

This framework offers a structured approach to identifying and understanding the factors that influence client satisfaction in construction SMEs that have implemented lean principles. It outlines key elements, including lean principles, the benefits of lean implementation in SMEs, barriers to adoption, factors affecting client satisfaction, and reasons for failing to achieve client satisfaction. Furthermore, the framework proposes a model for identifying these influencing factors and enhancing client satisfaction in construction projects.

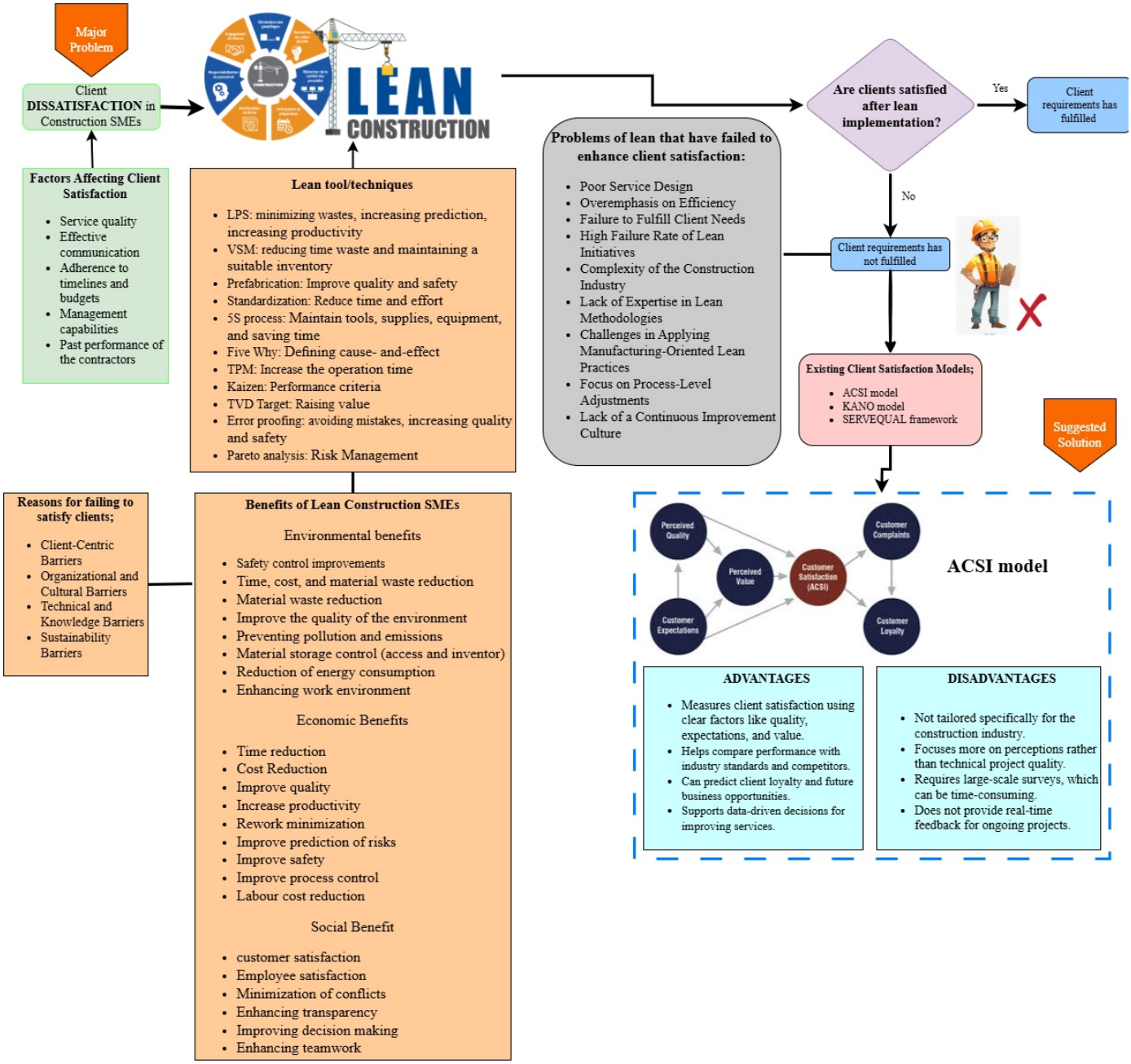


Figure 3: Framework for client satisfaction model in lean implemented construction SMEs

ACSI model is selected over other client satisfaction models due to its comprehensive, adaptable, and empirically validated structure, which makes it particularly suitable for application in lean implemented construction SMEs. Unlike generic satisfaction models, the ACSI model provides a robust, cause and effect framework that links client expectations, perceived quality, and value to satisfaction, and subsequently to client loyalty and complaint behaviour. This alignment is especially beneficial for construction SMEs adopting lean principles, as it enables the evaluation of how lean strategies directly influence client satisfaction outcomes. The model's flexibility allows for the integration of lean-specific factors such as process efficiency, waste minimisation, and continuous improvement. Through this framework, construction SMEs can not only assess the current level of client satisfaction but also identify specific lean-related practices that

enhance value delivery, thereby fostering long-term relationships and competitive advantage in the industry.

4. CONCLUSIONS

Despite the increasing adoption of lean principles in construction SMEs, there remains a significant gap in research addressing the causes of low client satisfaction in these organisations. This study aimed to bridge this gap by developing a framework for a client satisfaction model tailored to lean implemented construction SMEs. Through a literature review, key factors influencing client satisfaction were identified, along with the benefits, barriers, and challenges associated with lean implementation in SMEs. The study proposes the adoption of the ACSI as the basis for the client satisfaction model, emphasising the relationship between perceived quality, customer satisfaction, and customer loyalty. The model suggests that higher client satisfaction leads to increased loyalty, which in turn enhances financial performance, making it a valuable approach for improving business sustainability in lean implemented construction SMEs.

This study contributes to both academic knowledge and industry practice by offering a conceptual framework that can serve as a foundation for improving client satisfaction in lean implemented construction SMEs. From a theoretical perspective, it enriches the existing literature by identifying critical factors affecting client satisfaction within the lean construction context. In practice, the proposed framework, grounded in the ACSI model, provides SMEs with strategic insights to enhance their lean implementation processes and client engagement strategies. Future research should focus on empirically validating the framework through case studies and stakeholder interviews to refine its applicability and effectiveness in real-world construction projects.

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COMMUNITY BENEFIT AND ENGAGEMENT FRAMEWORKS IN AUSTRALIAN RENEWABLE ENERGY TRANSITION: A THEMATIC ANALYSIS

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ABSTRACT

The renewable energy transition has become a core priority in Australia over the past few decades, with a target to achieve 82% renewable energy in the country's electricity grids by 2030. The social dimension, along with community acceptance of renewable infrastructure developments, is essential. Several publicly accessible documents guide decision-making at the Federal and State levels, as well as the roles of key stakeholders involved in the energy transition. However, obtaining the social license to operate remains a significant challenge, as it is hindered by the gap between strategic suggestions and actual implementation in practice. Therefore, this study employed the Thematic Analysis approach inductively, using NVivo, to collect textual data from documents and frameworks published by state governments and reputable non-governmental bodies in Australia since 2020. The thematic analysis of paragraphs was conducted under four categories (parent nodes): benefits sharing mechanisms, equity and inclusion, transparency and accountability, and monitoring and evaluation mechanisms. Thereafter, maps were generated to illustrate sub-themes (child nodes) along with referenced documents. In practice, the results underscore the need for more integrated strategies that align with timelines and involve stakeholders, including developers, policymakers, and communities, in future guidelines. Furthermore, the thematic analysis approach adopted in this study provides a proven methodology for analysing differently organised frameworks and reports. As analysis in academic research using industry frameworks is rare in the renewable energy sector from a social perspective, this provides a basis for future research. The created maps could be beneficially used and generalised for future frameworks.

Keywords: *Community Benefits; Community Engagement; Renewable Energy Transition; Thematic Analysis.*

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1. INTRODUCTION

Recently, the Australian government enacted laws in 2022 to reduce carbon emissions by 43% compared to 2005 levels by 2030, aiming to achieve net zero by 2050 (Australian Trade and Investment Commission, 2023). The redesigned safety mechanism is a tool designed to facilitate the execution of this objective by directing Australia's top greenhouse gas emitters to keep their net emissions at or below a set baseline. This baseline is reduced annually, and those that exceed it must manage their excess emissions, including by purchasing and surrendering Australian carbon credit units (Wells et al., 2018). The Australian Government aims for 82% renewable energy in the nation's electricity systems by 2030 (Department of Climate Change, Environment and Climate Action, 2022). Under the leadership of the recently elected Australian government, which has pledged to a more ambitious target of lowering national greenhouse gas (GHG) emissions by 43% by 2030, relative to 2005 levels, this transition to clean energy is anticipated to accelerate (Koskinen et al., 2023). The rapid transition has presented numerous challenges for grid and market operations; for instance, market estimates by the Australian Energy Market Operator have consistently underestimated the pace of the transition to clean energy (Funder et al., 2021).

Subsequently, renewable energy sources are revolutionising the production, distribution, and use of energy (Clean Energy Council, 2019). These systems have the capacity to overturn the current economic and social structure of energy delivery since they provide heat and power in different capacities (Bauwens et al., 2016). It has been suggested that shifting to decentralised and renewable energy generation is a way to address climate change and boost energy supply self-sufficiency (Rae & Bradley, 2012). Several studies disclose that the social dimension is important as the technology component to stress the need for community responses that are more predisposed to successful transition (Lennon et al., 2019; Soltani et al., 2021). Significantly, creating and sustaining a social licence and providing social value to communities are crucial prerequisites for the success of the renewable energy transition from an infrastructure perspective (Kola-Bezka, 2023, Lennon et al., 2019, Miller et al., 2015). As a result, several stakeholders involved in energy research and policy concur that transdisciplinary consortia must lead energy transitions under the direction of social science concerns about the human dimensions of energy transition (Chodkowska-Miszczuk et al., 2021; Lennon et al., 2019; Stephanides et al., 2019). These methods are crucial for achieving community acceptance of green energy solutions among members of a social unit. There are several publicly accessible documents that guide decision-making at the Federal and state levels, as well as the roles of key stakeholders involved in the energy transition. Nevertheless, the content of the documents tends to focus predominantly on a single area (e.g., benefit sharing), or exhibits repetitiveness, overlapping subject areas, and multiple facts that lack practical applicability (Hicks & Mallee, 2023; NSW Department of Planning and Environment, 2023). Therefore, this paper aims to answer the research question, "How *have community benefit and engagement frameworks published after 2020 addressed key aspects of community engagement in the Australian renewable energy transition?*" through a qualitative research approach. Consequently, it highlights the need to identify these overlaps and gaps, particularly in relation to the practical implementation of community benefit and engagement frameworks, in order to guide future research in addressing key concepts within these frameworks and to stimulate meaningful community engagement.

Section 2 presents an overview of the selected documents on community benefits and engagement in Australia after 2020. The adopted methodology for identifying the key themes via NVivo is discussed in Section 3. Analysis and discussion of the findings are presented in Section 4, where the identified key themes (codes) are discussed under four main categories (see Sections 4.1, 4.2, 4.3, and 4.4). The conclusion, along with its limitations and the way forward, is presented in Section 5. Finally, Sections 6 and 7 are allocated for acknowledgements and references used in this paper.

2. COMMUNITY BENEFITS AND ENGAGEMENT FRAMEWORKS

In the past few decades, the Australian Government has considered various policies to mitigate the consequences of climate change, including the emissions trading system, the carbon pollution reduction scheme, and the carbon tax, among others. According to records, all of these have different successive levels and were never implemented. Accordingly, the federal and state governments, as well as various reputable non-governmental organisations (such as the Clean Energy Council and RE-Alliance), have published strategies to guide all aspects of the renewable energy transition. As this paper focuses on the communities and their engagement in the energy transition, seven recently published documents (publicly available) were selected, particularly due to their emphasis on heightened climate action goals, post-COVID recovery plans, and shifts in political will. Considering public accessibility, trustworthiness, and the reputation of the publishing organisations (both state governments and non-governmental organisations), the analysis was limited to seven documents. Table 1 presents the details of the selected seven documents for this analysis, along with their publishing organisations, year of publication, and an overview of the content.

Table 1: Overview for community benefits and engagement frameworks (after 2020)

No	Document	Organisation and Source	Year	Overview
A.	Community Benefits Handbook	RE-Alliance (Re-Alliance, 2024)	August 2024	Emphasises the importance of local engagement in decision-making processes, offers insights into community enhancement funds that can support local initiatives, and highlights opportunities for co-investment and ownership in renewable projects. It also highlights the significance of including First Nations' perspectives to ensure that their rights and knowledge are respected, ultimately aiming for a collaborative approach.
B.	Community Benefits Framework	Queensland Hydro (Queensland Hydro, 2024)	August 2024	Presents sustainable relationships with local communities by prioritising engagement, transparency, and collaboration, while addressing the environmental, economic, and social needs through initiatives that benefit individuals and regional development.

No	Document	Organisation and Source	Year	Overview
C.	Energy and Jobs Plan: Local Energy Partnerships	Queensland Department of Energy and Climate (Queensland Government, 2024)	May 2024	Outlines Queensland's commitment to engaging regional communities in the energy transformation by prioritising local voices, choices, and benefits through a framework that encourages collaboration, resource allocation, and the improvement of renewable energy practices, with a focus on supporting First Nations and local councils.
D.	Renewable Energy Development in Tasmania: Guideline for Community Engagement, Benefit Sharing and Local Procurement	Tasmania Department of State Growth (Tasmania Department of State Growth, 2024)	May 2024	Presents best practices for renewable energy development in Tasmania, emphasising effective community involvement, the importance of understanding social contexts, and mechanisms for sharing benefits. It aims to empower Tasmanian communities to participate actively in the renewable energy sector while ensuring that local businesses and residents gain tangible advantages.
E.	Draft Benefits Sharing Guideline: Energy Policy Framework	NSW Department of Planning and Environment (NSW Department of Planning and Environment, 2023)	November 2023	Provides a comprehensive policy framework aimed at ensuring equitable distribution of benefits from large-scale renewable energy projects in NSW, emphasising community involvement, particularly that of Aboriginal communities, and promoting mechanisms for sharing economic and social benefits to enhance local resilience and support.
F.	Regional Benefit Sharing Discussion Paper	Community Power Agency (Hicks & Mallee, 2023)	October 2023	Explores strategic frameworks for community benefit sharing in regions hosting multiple renewable energy projects, emphasising the need for coordinated approaches to enhance local engagement and maximise positive impacts while minimising community disempowerment and engagement fatigue.
G.	Community Engagement and Benefits Sharing in Renewable Energy Development in Victoria	Victoria Department of Energy, Environment and Climate Change (Department of Energy Environment and Climate Change, 2021)	July 2021	Presents a comprehensive framework for renewable energy developers, emphasising the necessity of active community engagement and benefit-sharing strategies to obtain social license to operate. It outlines best practices for social impact assessments and encourages innovative approaches

These documents frequently refer to case studies, best practice frameworks, and empirical findings to strengthen their recommendations. For example, "Community Engagement and Benefits Sharing in Renewable Energy Development in Victoria" and "A Guide to Benefit Sharing Options for Renewable Energy Projects" include case studies that illustrate successful benefit-sharing mechanisms and community engagement strategies. Moreover, many documents adopt a principle-based approach to maintain the core values of social science content, including benefits sharing mechanisms, equity and inclusion, transparency, accountability, and monitoring and evaluation. Batidzirai et al.(2021) evidence that principle-based approaches protect community rights, especially when working with marginalised groups, ensuring that content does not cause harm or exploitation. Moreover, that consistency facilitates comparison, replication and validation of findings (Walker et al., 2010).

3. METHODOLOGY

Thematic analysis was used to identify, analyse and interpret patterns (themes) within the textual data in the selected seven documents. Mainly, thematic analysis can be conducted inductively (letting themes emerge from the data) or deductively (following existing theory or frameworks) (Rosenthal, 2016). As this paper intends to collect textual data from existing documents, thematic analysis was conducted inductively. Moreover, NVivo 15 software was used to analyse the data as it enables easier extraction and categorisation of key themes with reference to the relevant document (via each code connected to the relevant document) (Krishnan et al., 2025). Figure 1 illustrates the flowchart of the executed methodology.

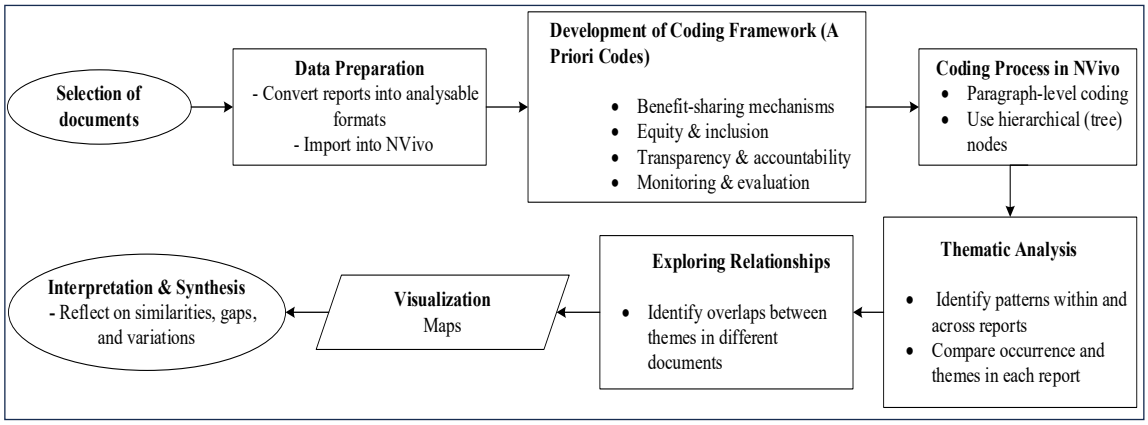


Figure 1: Methodology flowchart

Firstly, the seven documents were selected based on the main criteria of public accessibility, trustworthiness, the reputation of the publishing organisations (as state governments and non-government bodies), and publication after 2020. Then the files were imported into the NVivo software with their analysable formats. As per the third step in the flowchart (refer to Figure 1), coding framework was developed. The coding process was based on hierarchical nodes; it refers to the way nodes are organised into a parent-child structure. For example, parent nodes represent broader themes, such as benefits-sharing mechanisms, and child nodes fall under these parent nodes, representing more specific sub-themes, as seen in section 4.2. The four parent nodes were selected based on their prominence in both the reviewed documents and the broader literature on community engagement (Victoria Department of Energy Environment and Climate

Change, 2021; NSW Department of Planning and Environment, 2023; Tasmania Department of State Growth, 2024). Benefit-sharing mechanisms have emerged as a central theme, as ensuring the fair distribution of all aspects. Equity and inclusion were prioritised to reflect the importance of involving First Nations peoples, landowners, and other marginalised groups, ensuring that engagement processes are fair and inclusive. Transparency and accountability were identified as essential characteristics of good governance, as policy-supporting frameworks must demonstrate openness. Finally, monitoring and evaluation mechanisms were included as effective frameworks require systematic processes to track progress, assess outcomes, and enable continuous improvement after implementation. Other topics that emerged during analysis, such as technical considerations or project financing, were treated as sub-themes or supporting elements under these primary categories, where appropriate. The findings were visualised via "Maps" in the NVivo software, as it offers more visual clarity than presenting numerical values alone. Figures 2, 3, 4, and 5 illustrate the thematic coding structure derived from the data. To enhance visual clarity, parent nodes are consistently coloured in red, while child nodes are presented in various colours to aid in the quick identification and differentiation of categories.

4. ANALYSIS AND DISCUSSION

This section presents the findings generated after thematic analysis, with a discussion of the obtained data. By critically analysing the structure according to a principles-based approach (under four parent codes) and strategic priorities, this section reveals the extent to which communities are positioned as active and/or passive beneficiaries in the transition process.

4.1 DEFINITIONS OF "COMMUNITY"

The concept of community and its related forms of engagement have multiple meanings. The community is not a place, a building, an organisation, or an exchange of information (Koirala et al., 2016; Rogers et al., 2008). In the renewable energy transition, communities consist of groups of citizens, social entrepreneurs, public authorities, and community organisations that are actively involved in the energy transition by jointly investing in, producing, selling, and distributing renewable energy (Boulogiorgou & Ktenidis, 2020). Table 2 presents the definitions of community provided in seven documents as they change according to the underlying assumptions and priorities when presenting strategies, i.e. "community", whether geographically surrounded residents or marginalised groups, First Nations peoples or whose voices are heard (Pons-Seres de Brauwer & Cohen, 2020; McMillan & Chavis, 1986).

Table 2: Definitions of "community"

A	"a group of individuals living in close proximity to renewable energy projects, who may share common interests, aspirations, or issues related to the projects."
B	"All individuals residing in the geographic area surrounding the proposed renewable energy project, including various interest groups and cultural demographics."
C	"The collective of stakeholders impacted by renewable energy projects, emphasising the importance of engaging these stakeholders to ensure."
D	"Residents, local businesses, and organisations are involved in renewable energy projects"

E "a geographic and social entity, highlighting the need for definitions to be site-specific, based on local demographics and relationships to renewable energy developments."

F "Various groups that reside in or are affected by renewable energy projects, stressing the importance of understanding local dynamics in benefit-sharing discussions."

G "Individuals and organisations within defined geographic areas, stressing the significance of diverse representation in engagement processes."

The "community" has been defined in consideration of three key aspects: the local population living near or affected by renewable energy infrastructure developments, diverse groups based on geographical areas, marginalised and First Nation peoples, and social and cultural perspectives that consider landscape value and heritage. Therefore, people who live in or are connected through shared interests, culture, or location affected by renewable energy infrastructure developments are recognised as a "community" in the context of community engagement and community benefits sharing. The following subsections present the method of aligning the selected documents with these aspects.

4.2 BENEFITS SHARING MECHANISMS

The concept, 'benefit sharing', concerns sharing the rewards of renewable energy developments with communities (NSW Department of Planning and Environment, 2023). This concept is based on a desire to establish and maintain positive long-term connections with the area and to be a stimulator of positive perception among the communities (Tasmania Department of State Growth, 2024). Figure 2 presents the codes (documents), and child nodes (sub-themes) associated with the benefits-sharing mechanism (parent node).

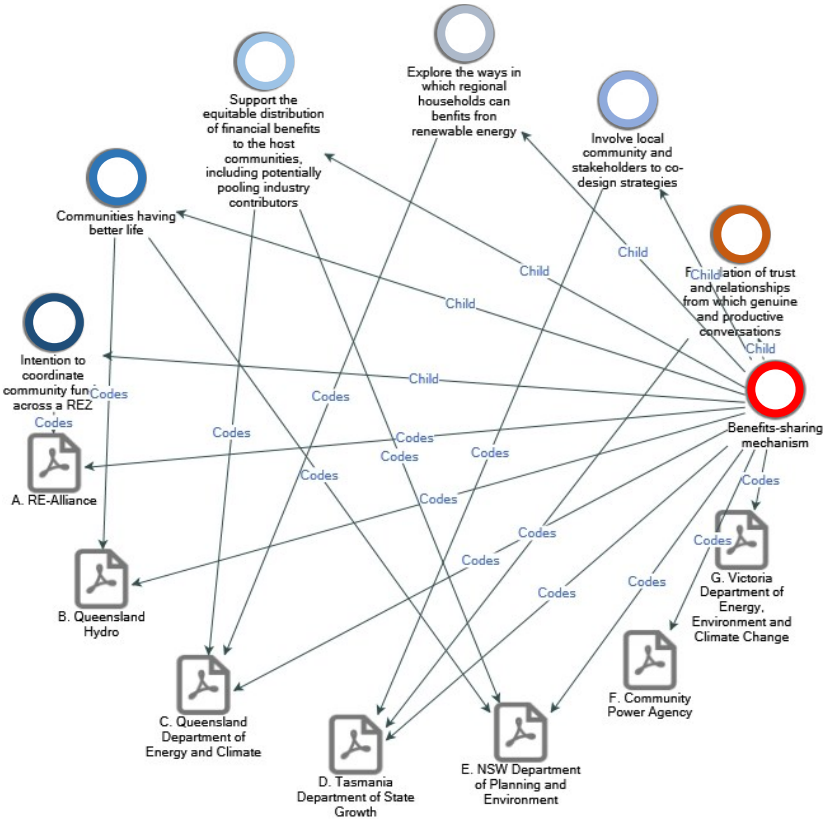


Figure 2: Benefits sharing mechanisms – nodes

The NSW benefits sharing guidelines specify that sharing initiatives offer a means of enhancing benefits for the community in the vicinity of and affected by renewable energy developments. This includes communities that may be affected by projects nearby, as well as members of the broader local community that host the development. All seven documents mentioned 'benefits sharing' as a key concept, along with strategies for implementing it. For instance, building community solar projects for local businesses, developing micro grids for the community, allocating some portion of the project's profit for a revolving fund that can operate in perpetuity, tourism and education programmes, and adding optical fibres to transmission towers are a few strategies to provide a better life for communities.

Ultimately, developers/government expect to create a foundation from genuine contributions and productive conversations (Tasmania Department of State Growth, 2024; Hicks & Mallee, 2023). Furthermore, equitably distributing and coordinating community funds across Renewable Energy Zones (REZs) is also a key consideration in benefits sharing (NSW Department of Planning and Environment, 2023). Nevertheless, power imbalances between stakeholders are a noticeable loophole that critically reflects from the analysed frameworks, i.e. who decides on benefits distribution?

4.3 EQUITY AND INCLUSION

A wind farm project-based research paper found that the "local host community perceived there to be 'winners and losers' from the project, with the 'winners' being host landholders who would receive an annual income and the 'losers' being neighbouring landholders who would be impacted but receive no direct benefits" (Re-Alliance, 2024). In recent years, this perceived inequity has been a cause for increasingly shared agreements between energy project proponents and neighbouring landholders. This theme mainly implies equitable access to opportunities for all communities (Queensland Hydro, 2024).

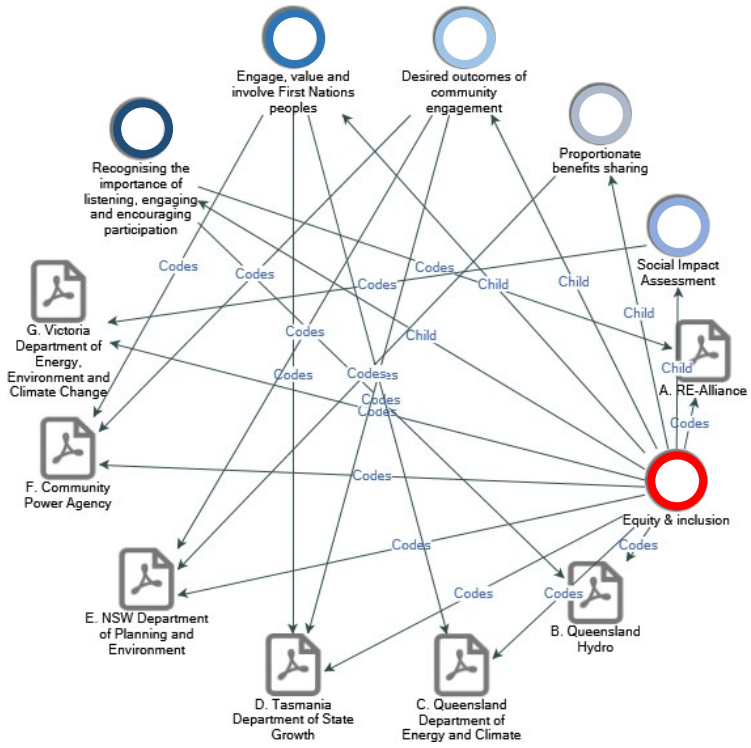


Figure 3: Equity and inclusion - nodes

Figure 3 presents the codes (documents) and child nodes (sub-themes) connected to the equity and inclusion (parent node). Equity and inclusion have sometimes been treated as overlapping, while in other instances as a combined theme. Nevertheless, both aspects are consistently addressed in all the selected documents. For instance, equity and inclusiveness of Aboriginal (First Nations people) through engagement and policy initiatives is a positive approach identified by the Tasmanian government (Tasmania Department of State Growth, 2024).

Accordingly, genuine shared decision-making means that the Tasmanian Aboriginal people are central in all decision-making. Simply, this ensures that First Nations people have ownership opportunities, not just consultation, and offers discounted energy rates to all residents, not just a select few. While all the analysed documents addressed the principles of equity and inclusion at a conceptual level, the critical challenge remains in translating these recommendations into practice.

4.4 TRANSPARENCY AND ACCOUNTABILITY

Adhering to transparent processes and unbiased procedures with accountability provides all the people in the community with an equal chance to engage, benefit and contribute to the energy transition (Queensland Hydro, 2024). Accordingly, developers are committed to openly sharing the outcomes of their initiatives and investments with the community (Queensland Hydro, 2024). This transparency ensures that our stakeholders are informed about the progress and outcomes of the renewable projects. Figure 4 presents the codes (documents) and child nodes (sub-themes) connected to the transparency and accountability (parent node).

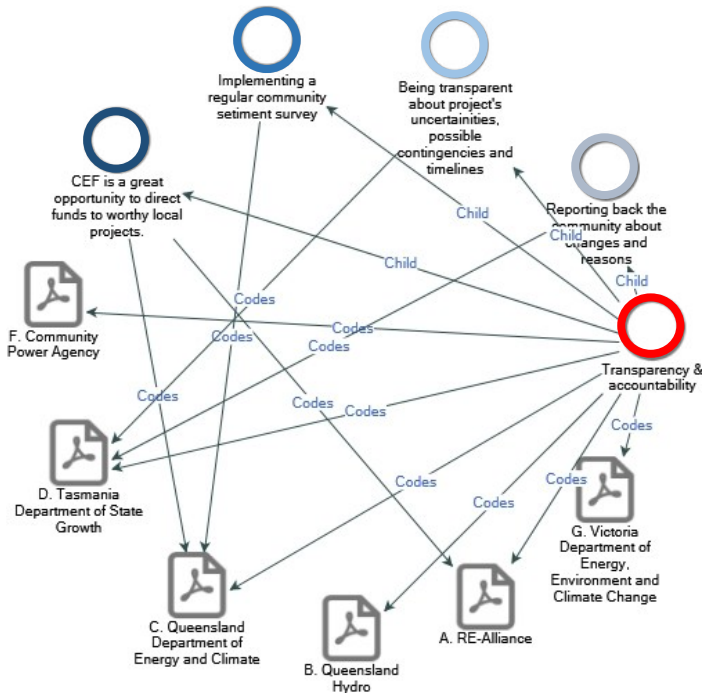


Figure 4: Transparency and accountability

While all the documents discuss the importance of transparency, in many cases, transparency is maintained primarily at the level of information provision rather than through deeper forms of engagement, such as consultation, collaboration, or shared

decision-making. As a result, transparency often remains limited to passive communication rather than active community empowerment, highlighting the need for more systematic mechanisms that embed transparency throughout all stages of engagement.

4.5 MONITORING AND EVALUATION MECHANISMS

Monitoring and evaluation of the community engagement or benefits sharing process's effectiveness were implicitly outlined in the six documents and did not appear in Re-Alliance (2024). It is important to involve communities, stakeholders, and developers in regular review and evaluation processes to assess the effectiveness of the implemented strategies. Ongoing feedback mechanisms should be established to adapt practices as needed, ensuring that projects continue to meet evolving community needs and expectations while remaining strategically aligned with the energy transition goals (Hicks & Mallee, 2023). Figure 5 presents the codes (documents) and child nodes (sub-themes) connected to the monitoring and evaluation mechanisms (parent node).

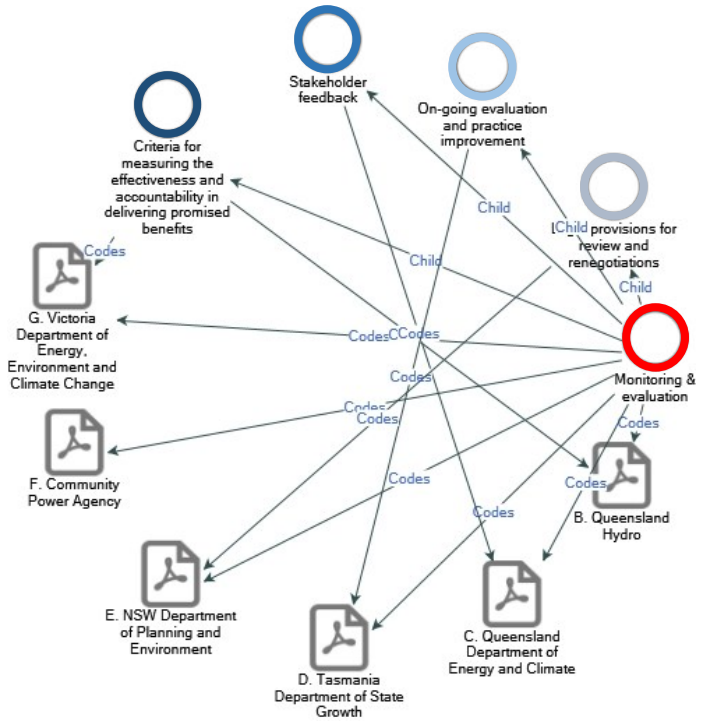


Figure 5: Monitoring and evaluation

Accordingly, coded documents have discussed broader recommendations for monitoring and evaluation without a specific timeline and stakeholder involvement. For instance, monitoring and assessing after an issue develops or while a new plan is being established, occasional community focus groups or surveys and evaluation at significant long-term milestones, are standard practices (Victoria Department of Energy Environment and Climate Change, 2021).

Nevertheless, the way of generalising the recommendations can be considered a gap that needs to be addressed. Without precise monitoring and evaluation practices, it is challenging to ensure accountability, measure outcomes, or adjust strategies in response to community feedback and evolving circumstances. With this, a distance will be created between theory and practice.

5. CONCLUSIONS, LIMITATIONS AND WAYS FORWARD

There are different types of reports, articles, and discussion papers presented by the Federal/State governments, non-governmental organisations (i.e. Clean Energy Council, RE-Alliance) to guide stimulating community engagement and benefits sharing mechanisms in the renewable energy transition. Nevertheless, these existing documents overlap the same facts, lacking important details or combining different facts, while developing broader strategies that lack defined timelines or stakeholder accountability. Therefore, this paper aimed to address the research question specified in Section 1. Accordingly, the key aspects were identified using a principles-based approach, focusing on benefits sharing mechanisms, equity and inclusion, transparency and accountability, and monitoring and evaluation. Mainly, six sub-themes were identified for "benefits sharing mechanisms" in all seven documents, with 13 references. "Equity and inclusion" for the communities has been implicitly mentioned in six documents. There were four and five sub-themes identified under "monitoring and evaluation" and "transparency and accountability", respectively, with a maximum of one sub-theme connected to two documents. The analysis revealed a lack of consistency across the documents, with noticeable overlaps and repetitions between key factors. Concepts like equity were sometimes discussed narrowly in the context of financial benefit-sharing, overlooking broader social benefits. This inconsistency risks marginalising important aspects of community engagement and highlights the need for a more systematic way of presenting findings.

Conducting an independent analysis to address the research question, this study provides an overview of the key aspects included in existing frameworks and documents. More significantly, the thematic analysis approach adopted in this study offers a proven methodology for analysing differently organised frameworks/reports. In practice, the results underscore the need for more integrated strategies that align with the project timeline and involve stakeholders, including developers, policymakers, and communities. As limitations of this study, document selection bias, along with the published time (after 2020) and selection criteria, are noted. Furthermore, although NVivo assists in managing data, the coding process remains subjective, relying on researchers' judgment. As this type of analysis in academic research using industry frameworks is rare in the renewable energy sector from a social perspective, this provides a basis for developing greater accuracy through additional documents using other techniques, such as Topic Modelling. Further, these created maps could be used and generalised for future frameworks.

6. ACKNOWLEDGEMENTS

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COMPARISON OF LEGISLATION OF UK AND SRI LANKA FOR BETTER IMPLEMENTATION OF CIRCULAR ECONOMY IN SRI LANKAN CONSTRUCTION INDUSTRY

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ABSTRACT

The construction industry (CI)is a significant contributor to worldwide environmental pollution while being a substantial user of finite resources and a substantial generator of waste. The Circular Economy (CE) concept aims to manage raw materials and minimise waste generation. The lack of relevant laws and regulations is a significant barrier to the implementation of CE. It is necessary to have a systematic approach to design and implement CE laws to cover the multi-sector dimensions of the CE concept. Limited research is available on laws and regulations related to the CE in the global and Sri Lankan contexts. This study aims to compare the legislation provisions for CE in CI in Sri Lanka and the United Kingdom (UK) for the better implementation of CE in CI in Sri Lanka. The study investigates how CE principles can be integrated into construction strategies in Sri Lanka, drawing from existing legal frameworks in the UK, and conducted through a review of legislation and policies. Findings reveal that the UK has made significant progress in embedding CE principles through legislative support and sustainable construction regulations. However, Sri Lanka is still in the early stages of this transition. This study further identified legal pitfalls in integrating CE practices, including gaps in the enforcement of CE within the Sri Lankan CI. The study concludes with key recommendations for introducing laws, legally supported CE practices in Sri Lanka, CE new legal reforms, and incorporation of CE principles into construction law.

Keywords: *Construction Industry; Circular Economy; Law; Sri Lanka; UK.*

1. INTRODUCTION

The CI sector notably accounts for over 30% of natural resource extraction and approximately 25% of global solid waste production (Benachio et al., 2020). CE practices contribute to emission reductions, decreased waste generation, and sustained economic growth (Kanwar, 2023). The CE presents a viable strategy for fostering long-term environmental sustainability by aligning economic activities with ecological principles (Geissdoerfer et al., 2017). The CI is a major contributor to environmental degradation, resource consumption, and waste generation. According to Jahan et al. (2022) the CE is

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an economic model that promotes material cycling to reduce basic material use and misuse creation. It supports sustainability by adhering to the 3Rs: reduction, reuse, and recycling. Strategies including waste reduction during product design, preventative measures, maintenance, repair, reuse, and recycling can help reach these aims. CE manages losses by exploring alternative uses and resources stored for a long duration (Alhazmi et al., 2021). As explained by Velenturf et al. (2019), the "take-make-dispose" approach of the linear economy has been altered by diminishing the steps of "take" and "dispose" across closed-loop methods such as reusing, recycling, and regeneration in the CE concept. This transformation fosters new business opportunities in areas such as remanufacturing, refurbishing, and repair, thereby supporting economic growth across countries (Hailemariam & Erdiaw-Kwasie, 2023).

Wijewansha et al. (2021) examined the practical application CE principles during the early planning and post-construction phases of Sri Lanka's building industry. By integrating considerations of rebound effects into CE practices, stakeholders can better navigate the complexities of implementing circular models and achieve sustainable outcomes (Gonçalves et al., 2022). The CI notably contributes to economic progress, but primarily through waste generation. Victar and Waidyasekara (2024) and Wijewansha et al. (2021) highlighted that construction is pivotal in fuelling economic expansion. However, it poses significant environmental challenges due to its intensive use of resources and high waste generation levels. Furthermore, CE is a driven framework for construction material preferences in Sri Lanka, featuring a '10R' hierarchy designed to promote sustainable decision-making. CE selects materials that reduce environmental impacts at every stage of their lifecycle, incorporating strategies such as refusing, reducing, reusing, and recycling. Additionally, it advocates for practices like repurposing, repairing, and remanufacturing, all aimed at enhancing resource efficiency and minimizing waste in CI (Wanaguru et al., 2022). Furthermore, regulatory provisions in the construction industry ensure compliance with environmental legislation, building regulations, and urban planning policies.

The enforcement of regulations in the CI is to minimize pollution, manage waste, and conduct environmental impact assessments governed by regulatory provisions. Regulatory provisions regulate construction activities and enforce laws to prevent environmental degradation. The collective purpose of regulatory provisions is to ensure sustainable development by regulating environmental protection, construction standards, and physical planning to promote safe, efficient, and environmentally responsible construction practices. Given the significant environmental impact of the CI , the CE is recognised as one of the most effective sustainable approaches to mitigating these adverse effects (Stošić & Šmelcerović, 2023). As Benachio et al. (2020) highlighted, the application of CE in the CI helps retain the maximum value of materials. Similarly, CE initiatives aim to minimise resource input and usage (Liu et al., 2022). Implementing CE principles in the CI contributes to waste reduction, resource conservation, and the advancement of sustainability (Hossain et al., 2020). CE practices are significant for the transition towards CE in the CI (Gamage et al., 2024; Guerra et al., 2021; Senaratne et al., 2021). Gamage et al. (2024) emphasise that implementing CE practices in a construction project requires proper planning from the design stage, as early decisions impact subsequent phases. Countries such as the UK, Australia, Germany, and China have already incorporated these considerations into their construction practices (Bleischwitz et al., 2022).

The UK has recently enacted comprehensive measures to embed CE principles in law, notably through the Environment Act 2021 and its regulations implementing the European Union's CE Package (CEP). The UK government is strongly committed to promoting the CE through various laws and regulations. One of the most important CE laws in recent years is the Environment Act 2021, which provides a legal framework for environmental protection and includes provisions for Extended Procedure Responsibility (EPR) schemes. Complementing this, the Producer Responsibility Obligations Regulations place specific requirements on businesses involved in the supply chain. The landfill regulations discourage the disposal of waste in landfills, thus making it more expensive. This law pushes businesses to consider alternatives such as recycling and reusing materials.

In addition to direct legislation, the UK government has introduced initiatives to promote energy efficiency and reduce environmental impact in the CI. The Energy Savings Opportunity Scheme (ESOS) is a mandatory program that requires businesses to conduct regular energy law. These aspects identify energy-saving opportunities, often including strategies to improve resource efficiency and reduce waste. Accordingly, the UK Environment Act 2021 addresses CE practices for the CI. Even though these legal provisions for CE are common in the UK, Laws about CE implementation in Sri Lanka are scarce.

The following legislation are related to CE in the CI in Sri Lanka:

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, Pradeshiya Sabhas Act (Local Authority legislation)
6. Construction Industry Development Act, No. 33 of 2014
7. Sustainable Development Act, No. 19 of 2017

The National Environmental Act, No. 47 of 1980, sets the foundation for environmental protection; the Urban Development Authority Law, No. 41 of 1978, focuses on planning and urban growth; the Coast Conservation Act, No. 57 of 1981, addresses coastal management and protection; and the Town and Country Planning (Amendment) Act, No. 49 of 2000, outlines land use and spatial planning. Local Authority Laws (Municipal Councils Ordinance, Urban Councils Ordinance, Pradeshiya Sabhas Act) regulate construction activities through building permits and zoning rules. The Construction Industry Development Act, No. 33 of 2014, governs the standards and development of the construction industry. Keywords such as "construction", "development activities", "waste", "resource efficiency", "waste management", and "waste disposal" were used to find relevant sections in that legislation. These legislations are highly relevant to CE implementation in CI, even though the legislations currently attempt to link with CE implementation in Sri Lanka.

The lack of adoption of law aligned with the CE practices in the Sri Lankan construction sector could result in unsustainable resource consumption (Weerakoon & Thayaparan, 2023), increasing environmental deterioration, resource reduction, and insufficient waste management practices and hindering sustainable development like other countries, as discussed in the above sections. Also no any research has found a relationship between

the CE practices and law within the CI in Sri Lanka, resulting in a significant knowledge gap. Accordingly, to fill this literature gap and the practical need, this study aims to compare the legislation provisions for CE in CI in Sri Lanka and the UK for the better implementation of CE in CI in Sri Lanka with the following three objectives:

- Identify the legislation provisions for CE implementation in CI in the UK and Sri Lankan Jurisdiction.
- Identify the pitfalls of legislation provisions for CE implementation in CI in Sri Lankan Jurisdiction.
- Propose the best practices and their main legal aspects for Sri Lanka.

2. METHODOLOGY

This study begins with a comprehensive literature review to reach findings of the research. It establishes the context of CE practice in the construction industry of Sri Lanka and other countries, and then examines legislation related to CE implementation in CI in the UK and other countries to determine the CE practices with legal aspects used in CI. A desk study tested legislation in the UK and Sri Lanka associated with CE implementation in CI. The UK present contrasting approaches in embedding CE principles in line with English Common Law principles (Castro et al., 2022). The UK has taken a proactive stance, enacting comprehensive legislation related to English Law. Sri Lankan legal system is highly influenced by English Law. Therefore, this study is limited to English Legal System. A robust literature review process strengthens knowledge advancement by integrating insights from various empirical studies and developing a structured theoretical foundation (Kraus et al., 2022). Standalone literature reviews enable researchers to critically assess existing scholarship, uncover gaps, and propose directions for future research (Snyder, 2019). The literature search was conducted across three academic databases: (i) Google Scholar, (ii) Web of Science, and (iii) Scopus. The search strategy targeted key terms such as 'Circular Economy', 'Legislation', 'UK', 'Sri Lanka', and 'construction industry'. Emphasis was placed on peer-reviewed journal articles and conference proceedings published within the last fifteen years to ensure the relevance and currency of the selected literature.

This study adopts a qualitative research approach, which is particularly well-suited for exploring the multifaceted nature of the pitfalls in CE and the legal provisions of CE practices in the Sri Lankan construction industry. Qualitative research is recognised for its capacity to provide rich, contextualized insights, especially when addressing intricate socio-economic and institutional dynamics (Ding et al., 2023; Saunders et al., 2024). The study follows a systematic research process, as illustrated in Figure 1.

The process continues with a comprehensive literature and documentary review to investigate critical aspects such as legislation related to CE implementation in CI in the UK, the pitfalls of legislation in Sri Lanka, and to propose best practices with legal aspects. The findings are analysed using manual content analysis, which is particularly effective for qualitative studies as it facilitates the extraction of meaningful insights while maintaining methodological rigour (Ullah & Ameen, 2018).

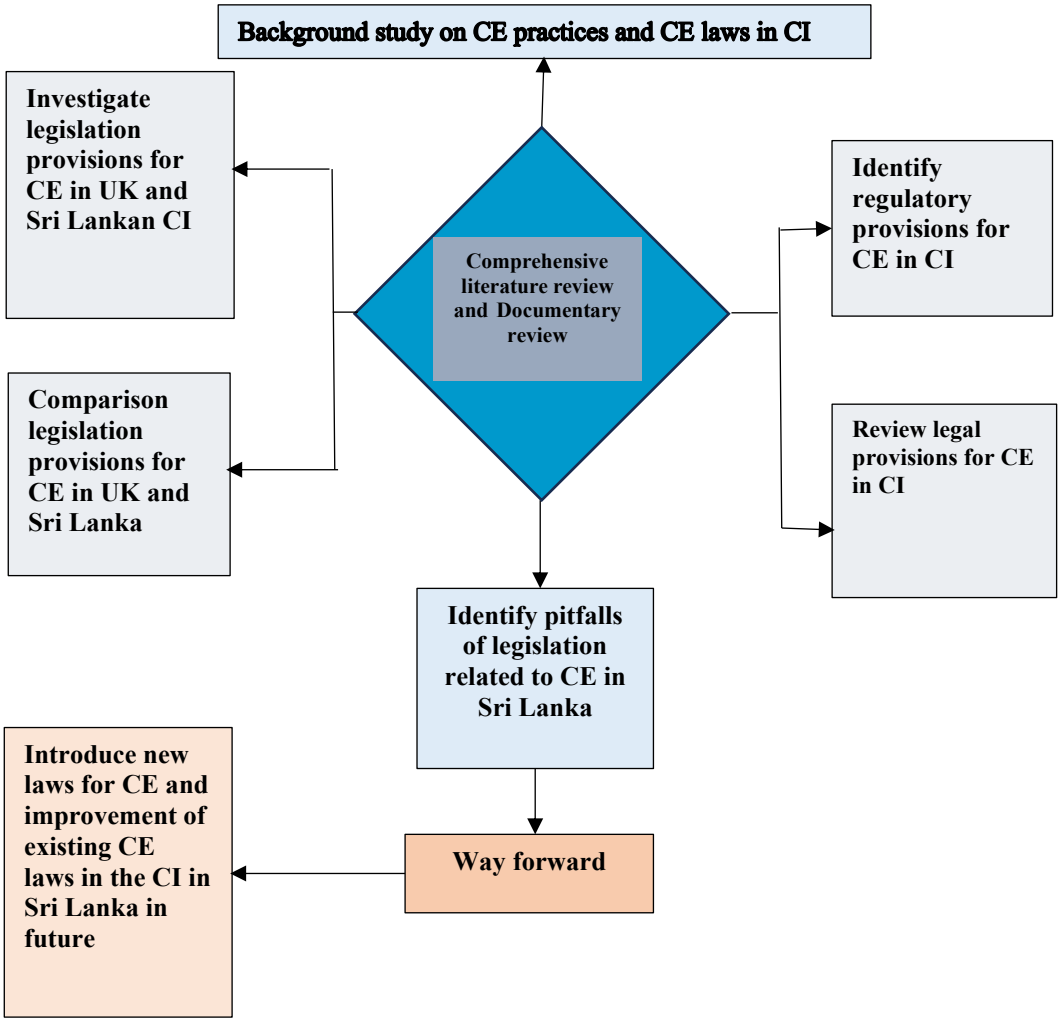


Figure 1 - Research process

3. RESEARCH FINDINGS

This study first identifies the CE and its guidance of Sri Lanka and the UK. This research helps to know about the legal aspects of CE in Sri Lankan and UK CIs. Finally, this research focused on looking into best practices of CE with legal aspects to implement in Sri Lankan CI**.**

3.1 COMPARATIVE OVERVIEW: SRI LANKAN AND UK LEGISLATION IN THE CONTEXT OF CE

The United Kingdom's Environment Act 2021 and Sri Lanka's National Environmental Act No. 47 of 1980 represent two generations of environmental governance. While both legislations target to protect and manage the natural environment, their approaches to resource efficiency, waste reduction, and sustainability. The UK Act is identified as a potential enabler for the CE process, as it helps link environmental goals with CE-driven initiatives. Through this alignment, this Act lays the groundwork for fostering sustainable construction practices across the UK. It introduces waste disposal, waste recovery, and overall waste management methods. This Act provides sustainability for the building,

thus directly affecting the CE principles. Consequently, the UK government's legal approach to CE aspects could be practiced on construction sites.

Table 1 presents a comparative analysis of CE practices and their implementation within the construction industries of the United Kingdom and Sri Lanka. The information has been synthesized from various secondary sources, including government reports, peer-reviewed scholarly articles, and industry publications. The aim is to highlight the key differences between the two countries regarding legislative frameworks, government strategies, industry adoption, and the overall maturity of CE implementation in the construction sector.

Table 1: Comparative analysis of CE practices in the UK and Sri Lanka

Aspect	United Kingdom	Sri Lanka
Legislative Framework	The UK has a strong legislative framework supporting CE, such as the Environment Act 2021 and Waste Regulations (UK Green Building Council, 2021).	Limited legislative support is available for CE in the construction sector in Sri Lanka, with no specific laws or regulations currently in place to mandate CE practices (Wijewickrama et al., 2021).
Government Strategies, Policies, and Law	National strategies such as Construction 2025 and Circular Economy Package guide CE implementation law (UK Green Building Council, 2021).	Sri Lanka lacks a formal strategy focused on adopting to CE in the construction sector (Victar & Waidyasekara, 2024: Wijewickrama et al., 2021).
Implementation Stage of Law for CE	The UK has advanced in integrating CE practices driven by policies, industry incentives, and government initiatives (Victar & Waidyasekara, 2024: Wijewickrama et al., 2021).	CE is still emerging in Sri Lanka, with awareness and implementation primarily voluntary, limited to isolated efforts (Wijewickrama et al., 2021).
Industry Adoption	High adoption of CE practices in the UK construction industry, influenced by policies and industry commitment to sustainability (UK Green Building Council, 2021).	Industry adoption is low in Sri Lanka, with implementing CE practices, due to the absence of a legal framework (Gamage et al., 2024: Wijewickrama et al., 2021)
Awareness of CE principles, law, and its Law	Extensive education and professional development programs are available to support CE practices in construction (UK Green Building Council, 2021)	Awareness in Sri Lanka are limited, focused on Circular Economy principles (Wanaguru et al., 2022; Wijewickrama et al., 2021)
Incentives and Law Enforcement	The UK government provides financial incentives, grants, and compliance monitoring to support CE adoption (UK Green Building Council, 2021).	Minimal financial incentives and weak enforcement of environmental policies in Sri Lanka hinder the widespread adoption of CE practices. (Weerakoon & Thayaparan, 2023; Wijewickrama et al., 2021)

Aspect	United Kingdom	Sri Lanka
Key CE Practices in Use	Common CE practices in the UK include modular construction, material reuse, design for deconstruction, and BIM integration (Ding et al., 2023; Saunders et al., 2024)).	Material reuse and recycling have been implemented in few projects in Sri Lanka, but large-scale adoption of CE practices remains very limited. (Gamage et al., 2024; Guerra et al., 2021; Senaratne et al. 2021)
Environmentally friendly alternatives to the industry	High adoption of CE practices in the UK construction industry. (Kraus et al., 2022).	Integrating CE principles during the early stages of design and planning can significantly enhance sustainability in construction industry by promoting efficient material utilization, minimizing waste (Wanaguru et al., 2022)

In contrast, Sri Lanka's legal framework for CE is fragmented and largely policy-driven. While principles such as waste minimization and recycling are acknowledged in the National Environmental Act and Sustainable Development Act of Sri Lanka, they are not enforced through binding obligations. Recycling and Sustainable construction practices are encouraged by institutions like CIDA, but the lack of regulatory mandates has still prevailed. Overall, Sri Lanka shows interest in CE practices, but the absence of cohesive legislation and enforcement mechanisms hampers progress compared to the UK's more mature and structured approach.

Table 2 presents a comparative analysis of CE practices with their regulatory procedure within the construction industries of the United Kingdom and Sri Lanka.

Table 2: Comparative analysis of CE practices with their regulatory framework and its procedure

Regulatory Aspects and Procedure	UK Environmental Act 2021	Sri Lankan Environmental Act 1980
Legislative Regime and Alignment with CE	Explicitly incorporates CE principles. Included detailed provisions for resource efficiency, waste minimization, extended responsibility and recycling schemes.	Focuses primarily on establishing institutional structures and general environmental protection, without specific reference to circularity, reuse of materials, or life cycle thinking in industrial processes.
Regulatory Institute and Monitoring	Established the Office for Environmental Protection (OEP) to oversee compliance, advise on policy, and enforce environmental standards, including those supporting CE transitions.	Sri Lanka's Central Environmental Authority (CEA) plays a more advisory and administrative role, lacking a dedicated mechanism for policy innovation or enforcement tailored to CE.
Compliance Applications	Strongly addresses manufacturing Tax and Producer Responsibility Obligations; it does not directly tackle construction waste, despite the significant environmental footprint of the sector.	The legislation does not classify between industrial sectors, offering any dedicated policies for construction waste or CE practices within construction and demolition activities.

Regulatory Aspects and Procedure	UK Environmental Act 2021	Sri Lankan Environmental Act 1980
Modern Policy Support Mechanisms	Include economic tools like taxes and deposit schemes to encourage waste prevention and material reuse.	Sri Lanka's Act, while establishing essential foundations such as environmental councils and local agencies, lacks economic instruments or incentives for industries to adopt circular economy practices.
Adaptability of legal framework	UK Act is forward-looking, with requirements for periodic policy reviews, measurable targets, and responsiveness to environmental data. It supports long-term planning aligned with net-zero and sustainability goals.	Sri Lanka's 1980 Act is less adaptable to emerging concepts such as the CE and does not mandate long-term target setting or regular legislative updates.

The United Kingdom and Sri Lanka present contrasting approaches to embedding CE principles into law. The UK has taken a proactive stance, enacting comprehensive legislation like the Environment Act 2021, which mandates practices such as waste minimization, recycling, sustainable design, and extended responsibility (Alhawari et al., 2021). Strong enforcement bodies and a clear policy framework support these legal requirements, positioning the UK as a leader in CE implementation across sectors, including construction. Following UK law that encourages waste reduction and environmental sustainability, the emphasis on CE principles is ingrained from the beginning of projects (UK Green Building Council, 2021).

In contrast, Sri Lanka's legal framework – though built on Acts like the NEA, CIDA, and UDA– remains fragmented and lacks enforceable mandates specific to CE practices. Policies such as the Sustainable Development Act 2017 recognize CE practices but are not backed by clear and binding regulations for the construction sector. This results in inconsistent implementation of CE with legal aspects for CI rather than systemic change.

Despite these gaps, Sri Lanka has opportunities to strengthen its CE transition by learning from a country like the UK. Introducing regulations on construction waste management, promoting reuse and recycling through legal mandates, and improving inter-agency coordination could significantly advance its efforts. Ultimately, aligning the construction law with circular principles is vital for environmental protection, resource efficiency, and long-term sustainable development.

3.2 PITFALLS OF LAWS FOR CE IMPLEMENTATION IN SRI LANKAN CI

Sri Lanka faces significant pitfalls in integrating CE principles into its construction legal framework, especially compared to the UK's more advanced and coordinated system. One of the primary issues is the fragmented legal and institutional structure, where obligations are scattered across multiple bodies without precise coordination and accountability. Unlike the UK, where oversight is streamlined under agencies like the Environment Agency and the Office for Environmental Protection, Sri Lanka lacks a centralized authority for CE initiatives, causing policy gaps and poor enforcement. There are few specific regulations and standards promoting recycling, reuse, or sustainable

construction, contrary to the UK's strict waste separation laws, landfill bans, and economic incentives like landfill taxes. Weak enforcement mechanisms, limited resources for monitoring, and a lack of penalties for illegal dumping further undermine the progress (Alhawari et al., 2021).

Sri Lanka's waste management law and market for recycled construction materials are still underdeveloped, discouraging industry participation. The Sustainable Development Act 2017 could provide a basis for future reforms. Lessons from the UK, such as implementing Extended Producer Responsibility and Mandating Construction Waste Management Plans, could guide Sri Lanka in building a more sustainable and circular construction industry. The legal aspects of CE adoption are particularly crucial, as they provide the enforceability and structure needed for wide-scale implementation. CE practices are unlikely to move beyond pilot initiatives without legal mandates or remain dependent on individual commitment rather than systemic change (Alhawari et al., 2021). The UK's integrated and enforceable legal framework supports CE goals through clear targets, economic incentives, and strong oversight, contrasting with Sri Lanka's less developed legal integration of these CE principles.

3.3 BEST PRACTICES OF CE WITH LEGAL ASPECTS FOR IMPLEMENTATION IN SRI LANKAN CI

The information discussed above provides a comparative analysis of CE practices and legislation provisions in the UK and Sri Lanka. Thereby, the study identifies the pitfalls of the current practices of CE with legal aspects in Sri Lanka. Furthermore, with the critical review CE practices and legislation in the UK, the study identifies what best practices and related legal aspects that are suitable to Sri Lanka to enhance the application of CE in CI as revealed in Table 3.

Table 3: Best practices and its legal aspects with recommendations

Strategy	Recommendations	Legal Aspect	Best practice
Pre-Construction Stage			
Sustainable design and planning	Encourage design professionals to follow CE principles (Velenturf et al., 2019).	Establish regulations mandating that new building projects include a CE evaluation in their environmental impact reports as part of a sustainability evaluation. This can be included in the National Environmental Act's current environmental clearance procedure (1980) (Wijewickrama et al., 2021).	Modify urban development and planning laws and building codes to require circularity, such as flexible and reusable design. `
Circular Procurement Practices	Implement Procurement laws and policies to use circular materials in a circular economy (Castro et al., 2022).	Set up government procurement policies and laws to use the CE practices in government and private sector	Combine the circular economy principles and procurement guidelines to improve the contractors'

Strategy	Recommendations	Legal Aspect	Best practice
		projects (Kraus et al., 2022).	awareness (Wanaguru et al., 2022).
Incentivizing and legalizing Green and Circular Certification	Offer rewards such as certifications, financial benefits, or fast-tracked permitting to developers who integrate CE principles into their project designs through legalization (Alhawari et al., 2021).	Set up a Green Building Certification that includes circular economy standards, similar to LEED, and make it compulsory for planning approval for large projects (Hailemariam & Erdiaw-Kwasie, 2023).	Collaborate with the Sri Lanka Green Building Council (SLGBC) to create a certification that includes circular economy principles in the green building process (Gamage et al., 2024).)
Awareness and Training for legal aspects of CE	Organize training and awareness programs for planners, designers, contractors, and local authorities to highlight the advantages of the CE.	Make CE training mandatory for construction professionals as a requirement to obtain or renew licenses and certifications (Victar & Waidyasekara, 2024).	Collaborate with the professions and industry organizations to provide professional development programs focused on CE basis (Weerakoon & Thayaparan, 2023)
Material Passports and Building Information Modelling (BIM)	Make it mandatory for construction projects to use Material Passports and BIM to track material use, composition, and future reuse or recycling potential at the end of a building's life cycle (Alhawari et al., 2021)	Introduce laws requiring digital documentation of materials using BIM in the planning and approval process and mandate Material Passports for all public and large-scale private construction projects (Hailemariam & Erdiaw-Kwasie, 2023).	Update local building codes to mandate BIM for large projects and create a national Material Passport database to track material data for Sri Lankan construction projects (Wijewickrama et al., 2021).
Post-Construction Stage			
Waste reduction regulations	Implement strict regulations for managing construction and demolition waste and create programs for material segregation, recycling, and reuse during and after construction (Kraus et al., 2022).	Enforce waste management regulations under the National Environmental Act, amending them to include mandatory waste reduction and material reuse targets for construction projects (Alhazmi et al., 2021)	Develop National Construction Management regulations with recycling targets and require contractors to report the amount of waste diverted from landfills (Ding et al., 2023; Saunders et al., 2024)
Material Reuse and Recycling Regulations	Set up systems for collecting, sorting, and recycling construction materials after demolition and promote using reclaimed materials in new	Enforce Extended Producer Responsibility (EPR) laws to hold contractors accountable for the disposal and recycling of construction materials, incentivizing	Introduce regulations requiring contractors to submit detailed plans for material collection and recycling during demolition or refurbishment, integrating this into existing

Strategy	Recommendations	Legal Aspect	Best practice
	projects (Ding et al., 2023; Saunders et al., 2024)	material reuse and promoting a sustainable lifecycle (Kraus et al., 2022).	waste management laws (Wanaguru et al., 2022)
Laws for Building adaptability and lifecycle management	Promote building designs that enable easy adaptation, upgrading, or retrofitting, extending the lifecycle of materials and structures (Alhawari et al., 2021)	Enforce regulations that require building projects to include plans for future adaptability and specify recyclable materials in their designs (Gamage et al., 2024).)	Update building regulations to include requirements for adaptability and lifecycle planning, ensuring developers provide provisions for future reuse or repurposing of the structure (Weerakoon & Thayaparan, 2023)
Post-construction performance monitoring regulations	Establish regulations for continuously monitoring a building's environmental performance, including energy use, waste management, and recyclability (Velenturf et al,2019).	Require Building Performance Evaluation (BPE) reports linked to Green Building Certifications, with regular inspections to ensure compliance with CE practices (Ding et al., 2023; Saunders et al., 2024)	Mandate annual sustainability audits for buildings, focusing on material reuse, energy efficiency, and recycling, supported by frameworks such as the Sri Lanka Sustainable Development Act (Wijewickrama et al., 2021).
Repair and reuse framework	Create frameworks for repairing and reusing building materials and components, promoting maintenance, refurbishment, or adaptation over demolition (Ding et al., 2023; Saunders et al., 2024)	Amend the existing legislation to include repair and reuse guidelines for construction projects, mainly residential and commercial buildings (Wijewickrama et al., 2021).	Establish a repair and reuse code of practice with guidelines for building refurbishment, enforceable through building regulations (Gamage et al., 2024)

In summary, implementing CE practices within Sri Lanka's construction sector holds significant promise for reducing environmental impact, conserving resources, and aligning with global sustainability targets. However, legal reforms must go hand-in-hand with policy innovation and industry collaboration to realize this transformation.

4. CONCLUSIONS AND RECOMMENDATIONS

This study compares the legislation provisions for Circular Economy (CE) in the Construction Industry (CI) in Sri Lanka and the UK to improve the implementation of CE in CI in Sri Lanka. It specifically focuses on integrating the law for CE principles into construction strategies. The aim was to understand the legal framework governing CE implementation and to draw comparisons between Sri Lanka and the United Kingdom. The United Kingdom and Sri Lanka present contrasting approaches in embedding CE principles in line with English common law and their legal system. The UK has taken a proactive stance, enacting comprehensive legislation. In the UK, CE has become a guiding framework for sustainable construction practices, supported by legal and

regulatory mechanisms such as the Environment Act 2021, Building Regulations, and national CE strategies. These regulations aim to minimize construction and demolition waste, encourage the reuse of materials, and set clear guidelines for sustainable design and deconstruction. The UK's legal structure also fosters innovation in materials science, green procurement, and modular construction aligning with CE objectives. On the other hand, the Sri Lankan context reveals institutional and regulatory fragmentation. Environmental impact assessments (EIAs) are legally required for specific projects, but there is no comprehensive legal framework to enforce CE principles across all construction phases. This research underscores the critical role of law in enabling circularity for a proactive, structured, and collaborative approach to embedding CE principles within all phases of the construction lifecycle in Sri Lanka.

Introducing CE laws for construction authorities, regulatory bodies, and educational institutions is necessary to create a unified vision for circularity in construction. These practices are increasingly common in the UK due to strong policy incentives and industry standards. In Sri Lanka, some of these strategies are recognized in theory. However, their practical application is limited, primarily due to cost concerns, lack of technical knowledge, and insufficient legal support.

Sri Lanka is still nascent in adopting CE principles. Although the country faces growing environmental and resource-related challenges, existing construction practices remain linear. The review of Sri Lankan legislation, including the National Environmental Act and the Urban Development Authority Law, proved that a significant gap exists in legislation that directly supports or mandates CE aligned practices in the construction sector. The absence of explicit laws for material recovery, waste segregation, and lifecycle planning further restricts the practical implementation of CE strategies on Sri Lankan construction sites. The study recommends that Sri Lanka look to the UK for direct legal transplants and adaptable CE laws that respect local government and physical planning laws.

Therefore, this study contributes to reforming Sri Lankan laws and introducing CE-specific legal instruments. This could include the development of mandatory laws for material reuse, integrating laws for project approvals, tax laws and incentives for sustainable building practices, and enforcement mechanisms to ensure compliance. Best practices, such as sustainability certifications, circular building codes, and public procurement laws, can be localized through pilot programs, stakeholder consultations, and capacity-building workshops. Expanding legal education in CE and awareness campaigns could equip professionals with the knowledge and skills to apply CE laws effectively within the boundaries of the law. This study only included theoretical conclusions from the literature review; more research incorporating empirical data from interviews is proposed.

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COMPARISON OF YOLO ALGORITHMS FOR PPE COMPLIANCE MONITORING AT CONSTRUCTION SITES

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ABSTRACT

Safety is a critical concern in the construction industry, where workers are exposed to various hazards that can lead to serious injuries or fatalities. Personal Protective Equipment (PPE) is vital in protecting the workers and increasing their safety. However, ensuring consistent PPE compliance among construction workers remains a challenge. To overcome this challenge, this study developed automated PPE compliance monitoring models through the You Only Look Once (YOLO) object detection algorithm. The variants of YOLO algorithms such as YOLOv8-s, YOLOv9-s, and YOLOv11-s were trained to identify the best performance model to detect and classify the presence of humans and four major PPE items: helmets, high-visibility vests, gloves, and boots. To prevent the overfitting of the models, early stopping with a patience level of 20 epochs was set to the models. The system was externally validated using the construction sites' images to check its applicability to the Sri Lankan context. The efficacy of each model was assessed using performance evaluation matrices such as precision-recall curves, mean Average Precision (mAP@0.5), inference time, and loss function values. The results show that YOLOv9-s outperformed the other models in overall performance even though, it went through the highest number of epochs during training. Future work can explore enhancing the YOLOv9-s model performance by integrating motion detection through IoT devices, allowing for more precise tracking of PPE compliance and reducing false detections of idle or stored PPE. This approach could significantly improve real-time monitoring of PPE compliance for worker safety at construction sites.

Keywords: *Construction; Object Detection; Personal Protective Equipment; Safety; Workers.*

1. INTRODUCTION

Personal Protective Equipment (PPE) compliance is essential in construction sites to mitigate workplace hazards and ensure worker safety since the construction industry is one of the most hazardous sectors, with a high incidence of workplace injuries and fatalities (Ajmani et al., 2024). Construction sites often present hazards including falls, slips, trips, exposure to hazardous materials, operating heavy machinery (Bedi et al., 2021) and working at significant heights (Nadhim et al., 2016). Consequently, hazards caused by these at construction sites can be severe for construction workers. Therefore,

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safety regulations mandate the compliance of PPE to mitigate the risks (Muntiyono et al., 2021). PPE compliance refers to the proper use of PPE, which significantly reduces the likelihood of workplace hazards; however, ensuring compliance remains a key challenge (Trubetskov et al., 2023). Despite safety regulations, many workers fail to wear the required PPE, partly due to the inefficiency of site supervision and shortcomings in safety management systems (Wong et al., 2020).

According to Trubetskov et al. (2023), site supervision plays a crucial role in maintaining PPE compliance; however, manual supervision is often inefficient and costly (Raoofi et al., 2024). According to Tian (2023), traditional manual supervision is costly and time-consuming for construction sites, which makes it difficult for supervisors to monitor every worker in real-time, leading to increased workplace risks. As a result, there is a growing demand for automated solutions that can enhance PPE compliance monitoring without the need for constant human involvement.

Recent advancements in deep learning and computer vision provide significant alternatives to manual monitoring. According to Pal & Hsieh (2021), deep learning enables the analysis of complex visual data, improving the accuracy and efficiency of PPE detection. Similarly, Bai et al. (2023) found that automated PPE detection using deep learning ensures more consistent and efficient monitoring. Object detection models, particularly those based on the You Only Look Once (YOLO) architecture, have demonstrated high accuracy and speed in real-time applications within the construction industry (Bai et al., 2023; Lin, 2024; L. Wang et al., 2023)

Although several studies have evaluated the performance of YOLO models in detecting PPE compliance at construction sites, there remains a lack of research focusing on the detection of multiple PPE types using the latest YOLO iterations. This study introduces the PPE detection model using YOLOv11-s algorithm and compares its performance with the models developed using YOLOv8 and YOLOv9 algorithms to determine their effectiveness in the real-time detection of helmets, high-visibility vests, gloves and boots. Each model was trained, tested and validated on construction site images.

2. LITERATURE REVIEW

2.1 SIGNIFICANCE OF SAFETY AND PPE COMPLIANCE

Construction sites inherently pose significant risks due to the nature of activities performed, the wide range of equipment in operation, and the dynamic work environment (Sanni-Anibire et al., 2020). According to recent data on occupational hazards, the construction industry continues to experience disproportionately high levels of workplace incidents. Statistics indicate that in 2022, 22.9% of all fatal accidents within the European region occurred in the construction sector. The construction risks are linked to multiple factors, including working in areas prone to trips and slips, operating heavy machinery (Bedi et al., 2021), working at heights (Nadhim et al., 2016), exposure to hazardous materials (Blaauw & Maina, 2022) and exposure to electrocution. Many of these hazards can be avoided if construction sites adhere to PPE compliance.

PPE compliance refers to the proper use of essential safety equipment such as helmets, high-visibility vests, gloves, and boots. These PPEs play a vital role in protecting workers from the construction site hazards (Al-Bayati et al., 2023). Ensuring compliance is crucial in reducing workplace hazards, yet many construction workers fail to adhere to PPE

requirements. Al-Bayati et al. (2023) identified 16 factors that influence PPE compliance in construction, with supervision being a key determinant in ensuring adherence to safety protocols. To enhance PPE compliance monitoring, effective supervision is necessary. However, in large-scale construction projects, manually monitoring compliance can be often costly, time-consuming, and inefficient (Raoofi et al., 2024). Manual monitoring also introduces challenges such as human error, resource constraints, and the inability to track every worker in real-time (Tian, 2023). Due to these limitations, researchers have explored alternative solutions through computer vision-based systems to improve PPE compliance monitoring.

2.2 AUTOMATED PPE COMPLIANCE MONITORING

The use of computer vision has revolutionised construction site monitoring using real-time object detection (Yang et al., 2024). According to Ahmed et al. (2023), computer vision can be used to automate PPE monitoring and to detect compliant and non-compliant workers in real-time. Several studies have demonstrated the effectiveness of computer vision models in detecting PPE compliance. For instance, Delhi et al. (2020), developed a Convolutional Neural Network (CNN) model to detect the presence of construction helmets and high-visibility vests. Similarly, Ahmed et al. (2023) developed a CNN model to detect helmets of different colours, high-visibility vests and safety boots.

The CNN object detection models are broadly categorised into two major types: (1) one-stage object detection and (2) two-stage object detection. The key distinction between these types lies in their approach to regional proposal generation (García et al., 2021). Two-stage detection models, such as the Region-based Convolutional Neural Network (R-CNN), first generate region proposals before classifying and localising objects (Du et al., 2020). This additional step enhances detection accuracy, making them ideal for tasks that require precise object identification. However, one-stage object detection models such as YOLO directly classify and localise the object with high speed in a single pass (García et al., 2021). This approach significantly improves detection speed, making one-stage models highly suitable for real-time applications where fast inference has a higher priority.

2.3 YOLO MODELS FOR OBJECT DETECTION

YOLO is a single-stage object detection algorithm known for its speed and accuracy in detecting multiple objects. It consists of three major components: (1) backbone, (2) neck and (3) head. According to Mahasin & Dewi (2022), the backbone acts as a feature extractor, the neck is the feature fusion module finally, the head is responsible for the classification and localisation of the object.

The YOLO family has undergone several advancements and has been widely applied for PPE compliance monitoring. Research by Delhi et al. (2020) developed a construction safety helmet and high visibility vest detection model using YOLOv3. Similarly, Velasco & Marasigan (2024) investigated the use of YOLOv7 for PPE compliance detection validating its effectiveness in real-time safety monitoring. Additionally, Guney et al. (2024) conducted a comparative study to evaluate the performance of YOLO-NAS, YOLOv8 and YOLOv9 for PPE compliance monitoring. According to Rasheed & Zarkoosh (2024), YOLOv11 is one of the latest versions of the YOLO family. Each YOLO model has variants tailored to diverse computational and application needs (Kishor, 2024). The variants of YOLOv8, YOLOv9 and YOLOv11 vary from nano to

extra-large allowing users to balance speed, accuracy and computational efficiency. The nano variant models are particularly useful for low-power devices which focus on speed, whereas the extra-large variants are useful for high-performance systems. The small model offers a balance between speed and accuracy which is suitable for medium-scale applications such as real-time PPE compliance monitoring.

2.4 SIGNIFICANCE OF THE STUDY

Studies have shown that manual monitoring of construction sites can be costly, time-consuming and inefficient. The challenges of manual construction site monitoring can be overcome by automated techniques especially by using single-stage object detection models such as YOLO algorithms. There are various advancements in the YOLO family, each consisting of a different capability. Several studies have attempted to use YOLO models for PPE compliance detections (Delhi et al., 2020; Velasco & Marasigan, 2024) and a few have carried out comparisons of YOLO models such as Guney et al. (2024). However, no studies have attempted to compare the latest iterations of YOLO, such as YOLOv11, to assess its performance in terms of PPE compliance detections. Therefore, this study was carried out to determine the best YOLO iteration for PPE compliance monitoring.

3. METHODOLOGY

According to Wang et al. (2025), YOLOv10 is an efficient model designed for general object detection; however, it does not inherently support oriented bounding box detection, limiting its suitability for applications requiring precise object localisation. Therefore, this study used three variants of YOLO algorithms such as YOLOv8-s, YOLOv9-s, and YOLOv11-s to develop three PPE detection models. The models detect humans and four essential PPEs such as helmets, high-visibility vests, gloves and boots. The models were developed on an online platform, and their performance was evaluated and compared based on PR values, mAP, and inference speed.

3.1 DATASET

One of the critical stages in developing a model using the YOLO algorithm is collecting a relevant dataset. In this study, 2,092 images were obtained from an online database called RoboFlow. This online database of images was captured from various construction sites without any specific consideration for the geographical location of the site. Therefore, a previously available dataset was suitable for this study. The same dataset of images was consistently used across training, testing, and validation phases of the model to ensure fair comparison. As such, environmental factors such as lighting conditions, weather, or site-specific occlusions were not varied or controlled. However, all photographs were taken during the day, under natural lighting conditions. The dataset was split into 70% for training, 20% for internal validation, and 10% for testing. Furthermore, custom images from local construction sites were collected to externally validate and assess the applicability of the model to the Sri Lankan projects. To maintain consistency across training, validation, and testing phases, all images were pre-processed to a fixed resolution of 640×640×3 in the Red-Green-Blue (RGB) colour scale.

3.2 MODEL TRAINING

This section outlines the training methodology applied in this study. By maintaining the same training parameters and procedures, the evaluation aimed to identify the most optimal YOLO model for PPE detection without bias from differing training setups.

3.2.1 Hyperparameter

Within YOLO models, hyperparameters play a crucial role in balancing model performance and computational efficiency. Several key hyperparameters were utilised in this study, including batch size, learning rate, momentum, and weight decay.

The dataset images were fed into the model batch-wise, with a batch size of 64 images, allowing for efficient training. The learning rate, which determines how quickly a model learns during training, was set at 0.01. The momentum, which helps to accelerate learning and smooth gradient updates, was set at 0.937. Weight decay, a regularisation technique used to prevent overfitting was set at 0.0005. These hyperparameters are preset within the model but can be fine-tuned for optimisation.

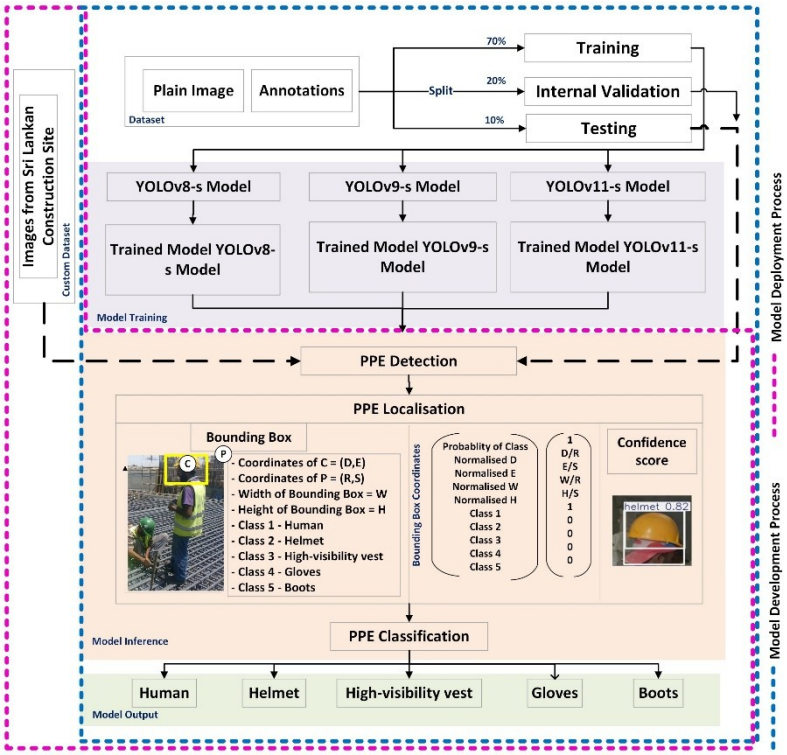


Figure 1: Overall architectural diagram for PPE detection models

Additionally, the number of epochs, which determines how many times the dataset passes through the entire training cycle, was set to 300 epochs in this study. However, prolonged training can lead to overfitting, where the model learns patterns specific to the training data but fails to generalise well to new inputs. To mitigate this, early stopping with patience set to 20 epochs was implemented. This technique prevents overfitting by stopping further training of the model when the model's performance stops improving. The patience value of 20 epochs specifies that the training will automatically stop if there is no improvement in evaluation metrics for 20 consecutive epochs. Accordingly,

YOLOv8-s, YOLOv9-s and YOLOv11-s models went through total epochs of 164, 300 and 160, respectively, during the training and validation process.

3.2.2 Training Process

After splitting the dataset, the three models were trained separately, as shown in Figure 1. The blue dotted line illustrates the model development process, while the pink dotted line represents the model deployment process. In the model development, the training phase utilised two types of input data: (1) plain images and (2) annotations. The annotation provides coordinates of the localised objects such as humans, helmets, high-visibility vests, gloves, and boots. With each training epoch, the system underwent validation. Upon completion of training, the models were further tested to determine and compare the key evaluation matrices. The time to train YOLOv8-s, YOLOv9-s, and YOLOv11-s was 1.273 hours, 3.612 hours and 1.420 hours, respectively.

3.3 MODEL VALIDATION

The validation step in YOLO models is crucial for assessing model performance and generalisation. In this study, the proposed three models underwent two phases of validation: (1) internal validation and (2) external validation. Internal validation was performed using 20% of the dataset from an online database, ensuring that the models were validated in parallel for each training iteration. This process allowed for continuous performance monitoring and determined the optimal number of epochs required for training. By analysing validation results, training was halted at the appropriate stage to prevent overfitting and ensure model generalisation.

Once the models were fully trained and tested, external validation was conducted to evaluate their adaptability to the Sri Lankan context. This phase involved testing the models on custom images collected from Sri Lankan construction sites. These images, captured using mobile phones, provided a diverse and realistic dataset which included various angles, lighting conditions, and image qualities, including both daytime and nighttime scenarios.

3.4 MODEL INFERENCE

Once the models were fully trained, they were tested using 10% of the dataset through the inference pipeline. Model inference refers to the process of using a trained model to predict outputs for an unseen dataset. In the inference pipeline, each model first detected the presence of PPE in the input image. The models then generated bounding boxes with coordinates and confidence scores, allowing them to localise humans and four PPE classes: helmets, high-visibility vests, gloves, and boots. The bounding box coordinates were determined based on key parameters, including the bounding box size, the centre coordinates of the bounding box, and the classes of detected objects within the image with human as class 1, helmet as class 2, high-visibility vest as class 3, gloves as class 4 and boots as class 5.

As illustrated in Figure 1, Point C represents the centre of the bounding box, while Point P denotes the top-right corner of the image. The confidence score associated with each bounding box indicates the model's certainty in detecting the object. While a higher confidence score signifies greater certainty, the detection threshold must be adjusted based on object size to ensure accurate classification. In this study, a confidence threshold

of 25% (or 0.25) was used to balance detection accuracy and false positives. Following localisation, the models classified the detected objects into five classes.

4. RESULTS AND PERFORMANCE EVALUATION

4.1 CONFUSION MATRIX

According to Caelen (2017), a confusion matrix evaluates the performance of classification by a model. It provides the breakdown of the model's prediction against the actual outcomes. When there are six distinct classification categories, a 6×6 confusion matrix can be used to analyse the model's performance. A 2x2 confusion matrix has been given in Table 1.

Table 1: Standard confusion matrix

	Actual Positive	**Actual Negative**
Predicted Positive	True Positive (TP)	False Positive (FP)
Predicted Negative	False Negative (FN)	True Negative (TN)

In the PPE detection models, a true positive would mean correctly detecting a class of Human or PPE, whereas a true negative would indicate correctly recognising the absence of PPE. A false positive would occur if the model mistakenly detected a different class. In the proposed models, there are five primary classes: human, helmet, high-visibility vest, gloves, and boots. These classes represent different PPE components and human presence detected within construction site images. Additionally, when none of these five classes is present in an image, it is labelled as background. During inference, if an image contains no PPE or human presence, it is classified under this background category.

Figures 2, 3, and 4 present the normalised confusion matrices for YOLOv8-s, YOLOv9-s, and YOLOv11-s, respectively. The values have been normalised to ensure comparability across different class distributions. These matrices show the accuracy of true positive classifications, reflecting how well each model classified the presence of different PPE classes. The overall accuracy of each model in correctly classifying PPE items is summarised in Table 2.

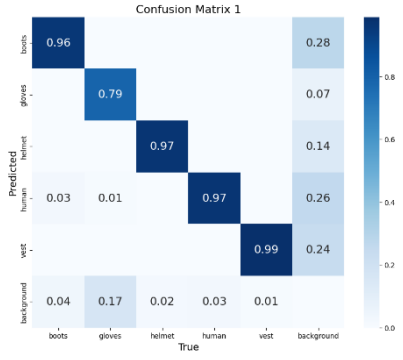


Figure 2: Normalised confusion matrix for YOLOv8-s model

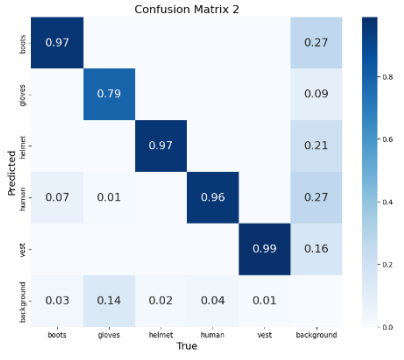


Figure 3: Normalised confusion matrix for YOLOv9-s model

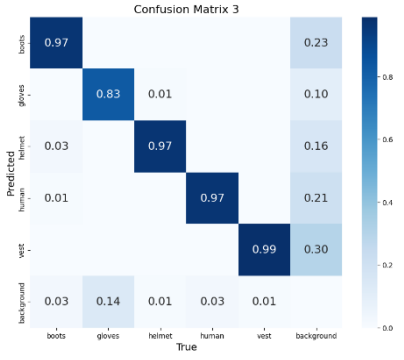


Figure 4: Normalised confusion matrix for YOLOv11-s model

Table 2: Comparison of true positive accuracy of the three models

	YOLOv8-s	YOLOv9-s	YOLOv11-s
Human	0.97	0.96	0.97
Helmet	0.97	0.97	0.97
High-visibility vest	0.99	0.99	0.99
Gloves	0.79	0.79	0.83
Boots	0.96	0.97	0.97

Across all three models, the detection accuracy for humans, helmets, high-visibility vests, and boots remained consistently high, with the high-visibility vest class demonstrating the best performance. However, gloves presented a greater challenge, as all three models exhibited comparatively lower accuracy in detecting them. Instances of misclassification were observed, where images containing no PPE classes were incorrectly classified as containing boots, gloves, helmets, humans, or high-visibility vests. This misclassification occurred across all models, indicating difficulties in distinguishing background elements from actual PPE instances. The highest misclassification rate was recorded in the YOLOv11-s model, where 30% of the misclassified cases involved the incorrect detection of a high-visibility vest in images where none were present, suggesting potential overfitting in the model.

4.2 PRECISION-RECALL CURVE

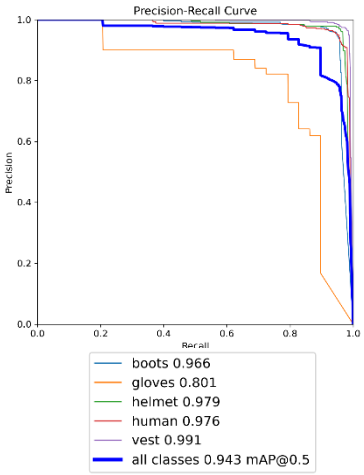


Figure 5: YOLOv8-s PR curve

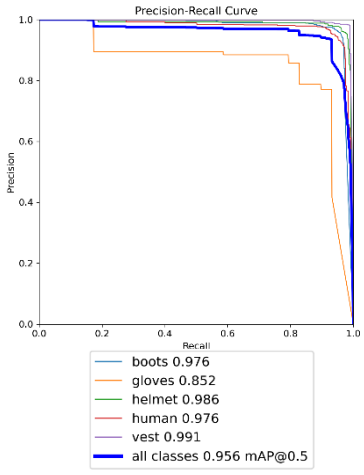


Figure 6: YOLOv9-s PR curve

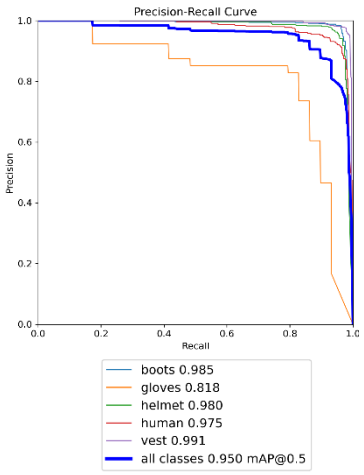


Figure 7: YOLOv11-s PR curve

The models' performance was further tested using precision and recall which are two key metrics for evaluating the performance of the YOLO models. Precision (Equation 1) measures how accurately the model identifies the true positive and shows how often the model is correct when making the classification. Recall (Equation 2), on the other hand, measures the model's ability to detect all relevant instances in a dataset and shows how well a model classifies all the actual classes.

$$Precision = \frac{TP}{TP+FP} \quad Equation\ (1) \qquad Recall = \frac{TP}{TP+FN} \quad Equation\ (2)$$

There is often a trade-off between precision and recall, where improving one may negatively impact the other. A higher precision ensures fewer false positives, while a higher recall reduces false negatives. Therefore, a Precision-Recall (PR) curve was

generated to analyse the trade-off between these two metrics and assess the overall performance of each model.

Figures 5, 6, and 7 present the precision-recall curves for YOLOv8-s, YOLOv9-s, and YOLOv11-s, respectively, in PPE detection. These curves illustrate how well each model maintained a balance between precision and recall. A higher area under the PR curve (AUC-PR) indicates better performance, as it reflects strong classification capabilities. The PR values for YOLOv8-s, YOLOv9-s, and YOLOv11-s models have been summarised in Table 3.

Table 3: Comparison of PR values of the three models

	YOLOv8-s	YOLOv9-s	YOLOv11-s
Human	0.976	0.976	0.975
Helmet	0.979	0.986	0.980
High-visibility vest	0.991	0.991	0.991
Gloves	0.801	0.852	0.818
Boots	0.966	0.976	0.985

Overall, the YOLOv9-s had the highest PR value for 4 out of 5 classes compared to the other two models which had the highest PR values for 2 out of 5 classes. This makes YOLOv9-s the most effective model in terms of precision-recall performance.

4.3 MEAN AVERAGE PRECISION (MAP)

The mAP (Equation 3) measures the average precision at a single Intersection over Union (IoU) threshold, typically set at 50% (mAP@0.5). This provides a single metric that can be used to directly compare the models' performance.

$$mAP@0.5 = \frac{1}{number\ of\ classes\ (n)} \sum_{i=1}^{n.} Average\ Precision \quad Equation\ (3)$$

The mAP scores for YOLOv8-s, YOLOv9-s, and YOLOv11-s were 0.943, 0.956, and 0.950, respectively. These results indicate that YOLOv9-s achieved the highest overall performance, followed closely by YOLOv11-s, while YOLOv8-s had the lowest mAP.

4.4 INFERENCE TIME

The inference time refers to the total time a model takes to process a new unseen image and generate a detection and classification output. A lower inference indicates faster processing, which is crucial for real-time detection applications. The inference times for the three models were 4.4 ms for YOLOv8-s, 7.3 ms for YOLOv9-s, and 5.4 ms for YOLOv11-s. These results indicate that YOLOv8-s is the fastest model, making it the most suitable for real-time PPE detection.

4.5 TRAINING AND VALIDATION LOSS

The YOLO models utilise a unified loss function to evaluate performance and prevent overfitting during training. This loss function consists of three primary components: box loss, classification loss, and distribution focal loss (DFL). The box loss ("box_loss") measures the accuracy of bounding box predictions by evaluating how well the detected object's bounding box aligns with the ground truth. This ensures the precise localisation

of PPE items. The classification loss ("cls_loss") assesses the accuracy of class predictions, determining whether the model correctly identifies PPE categories such as helmets, vests, gloves, and boots. Finally, the distribution Focal Loss ("dfl_loss") enhances refined classification by improving object boundary precision, ensuring that predicted bounding boxes align more accurately with their respective objects.

Figures 8, 9, and 10 illustrate the loss function trends for the three models. As the number of epochs increased, the loss function steadily decreased. Similarly, the precision and recall curves showed a consistent upward trend with increasing epochs. The number of epochs for each model was limited by a patience level of 20 epochs. The training and validation loss values of the three models are summarised in Table 4.

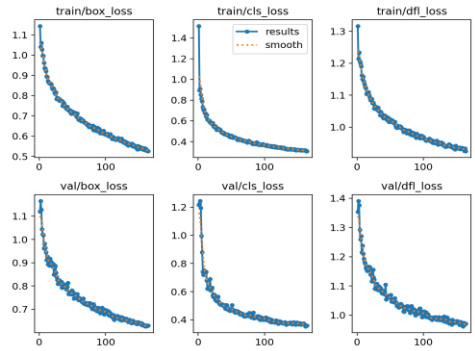


Figure 8: Loss function curve for YOLOv8-s Model for 164 epochs

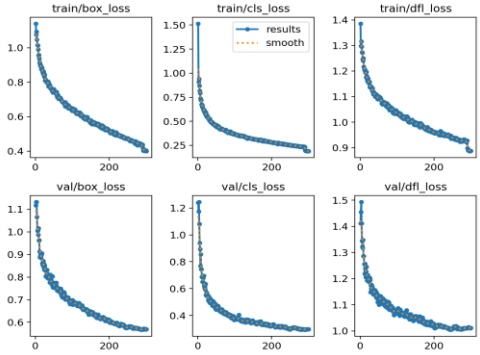


Figure 9: Loss function curve for YOLOv9-s Model for 300 epochs

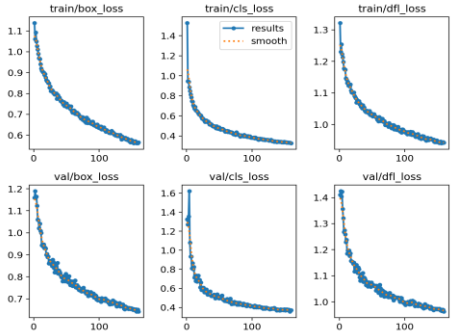


Figure 10: Loss function curve for YOLOv11-s Model for 160 epochs

YOLOv9-s, which was trained for the entire 300 epochs, achieved the lowest box loss, classification loss, and DFL loss among the three models. This suggests that YOLOv9-s had the best bounding box accuracy and classification performance. In contrast, YOLOv8-s and YOLOv11-s were trained for fewer epochs and exhibited higher loss values. The slightly higher loss values in YOLOv8-s and YOLOv11-s suggest they did not reach the same level of optimisation as YOLOv9-s.

Table 4: Comparison of training and validation loss

	YOLOv8-s	**YOLOv9-s**	**YOLOv11-s**
Training Epochs	164	300	160
Box Loss	0.5251	0.3991	0.5654
Classification Loss	0.3071	0.1903	0.3274
DFL Loss	0.9243	0.8883	0.9428

4.6 Overall Comparison of the Models

Table 5 presents the best-performing model among YOLOv8-s, YOLOv9-s, and YOLOv11-s for each performance evaluation metric. The results indicate that YOLOv9-s achieved the highest performance across all metrics, including True Positive Accuracy, PR Value, mAP@0.5 scores, and Training & Validation Loss. However, in terms of Inference Time, YOLOv8-s performed better, demonstrating a faster processing speed.

Table 5: Overall comparison of the model

	YOLOv8-s	YOLOv9-s	YOLOv11-s
True Positive accuracy	✓	✓	✓
PR Value		✓	
mAP@0.5 scores		✓	
Inference Time	✓		
Training and validation loss		✓	

4.7 Model Detections

The detections made by the models are presented in Figures 11 to 16, where each detection is marked with a bounding box and confidence score, indicating the model's level of certainty in its predictions. Comparatively higher confidence scores can be observed for the detections made by YOLOv9-s, indicating its superior performance in identifying PPE with greater certainty. Some inaccuracies were observed in the detections, suggesting areas for improvement. These limitations can be addressed by further training the models using a larger and more diverse dataset to enhance detection accuracy.



Figure 11: Detection by YOLOv8-s



Figure 12: Detection by YOLOv9-s



Figure 13: Detection by YOLOv11-s



Figure 14: Detection by YOLOv8-s



Figure 15: Detection by YOLOv9-s



Figure 16: Detection by YOLOv11-s

5. CONCLUSION AND RECOMMENDATIONS

This study explored object detection for PPE compliance monitoring using YOLOv8-s, YOLOv9-s, and YOLOv11-s models. A dataset from an online database was utilised for training, enabling the models to detect the presence of humans and four essential PPE items, including helmets, high-visibility vests, gloves, and boots. The models were evaluated based on precision-recall performance, mean Average Precision (mAP@0.5), inference time, and loss function analysis to determine their effectiveness in real-time PPE detection. Among the three models, YOLOv9-s demonstrated the best overall performance, achieving the highest mAP@0.5 and the lowest loss values, making it the most optimised for PPE compliance monitoring. However, YOLOv8-s had the fastest inference time. This study contributes to construction safety by identifying an optimal YOLO-based model for PPE detection in construction safety monitoring. However, the model is limited to detecting only helmets, gloves, high-visibility vests, and safety boots, as other essential PPE, such as eye or hearing protection, was not considered. Additionally, factors such as varying lighting and weather conditions were not considered, which may affect generalisability.

While the proposed models effectively detected PPE compliance, future research should focus on enhancing PPE monitoring by incorporating personalised PPE requirements based on specific worker roles rather than relying on generalised detection using YOLOv9-s. Additionally, integrating motion analysis would improve real-time tracking accuracy. This enhancement would also help distinguish actively worn PPE from idle or stored equipment, reducing false detections and improving overall system reliability.

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COMPETENCIES OF CONSTRUCTION PROFESSIONALS TO PERFORM CIRCULAR ECONOMY PRACTICES: A SYSTEMATIC REVIEW

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ABSTRACT

The urgent shift towards sustainable construction is not merely a technical endeavour but also a transformation in professional practices. Central to this transformation is the Circular Economy (CE), which champions resource efficiency, design for reuse, and waste minimisation. Despite this, the successful implementation of CE in the construction sector hinges on professionals equipped with the required and evolving competencies. Hence, this research aims to investigate the competencies required by construction professionals to perform CE practices. To achieve this aim, the study synthesises fragmented literature to construct a cohesive and comprehensive understanding of CE competencies of construction professionals. A systematic literature review was conducted using 29 articles, applying the PRISMA framework and the Scopus database, and employing both content and descriptive analyses. The analysis revealed a rich compilation of competencies, clustered into several categories including critical and creative thinking, project coordination and interface, and software and data proficiency. Moreover, it identifies profession-specific competencies for key roles such as project managers, engineers, architects, BIM managers, and quantity surveyors. However, the findings also underscore a considerable gap in both geographic and professional representation, highlighting the marginalisation of certain regions and roles in existing CE literature. Finally, this study offers a common and profession-specific compilation of CE competencies, which can guide academia in curriculum development, inform industry training programs, and support policymakers in designing frameworks to accelerate CE adoption across the built environment.

Keywords: *Competencies; Construction Professionals; Circular Economy (CE).*

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1. INTRODUCTION

Amidst the crisis of resource scarcity and the urgent call for sustainability, the Circular Economy (CE) has emerged not merely as a solution but as a transformative vision for the future of industry (Mies & Gold, 2021). As described by the Ellen MacArthur Foundation (EMF), CE is a regenerative and restorative industrial model that embraces both technical and biological cycles (Ellen MacArthur Foundation, 2013). Since its bold entrance in the late 1990s, the CE has been able to infiltrate industries globally, while promoting reuse, recycling, and the extension of product life cycles (Mhatre et al., 2021; Victar et al., 2024). Being responsible for 40% of the total global waste, the adoption of CE strategies in the construction sector is considered essential for creating a more sustainable, resource-efficient, and resilient future (Vergani et al., 2024). Traditional linear waste management practices of generating, collecting, and disposing of waste have significantly contributed to resource depletion, increased greenhouse gas emissions, and environmental degradation (Quashie et al., 2024). To counter these impacts, the CE concept has been introduced to reshape the industry's future (Quashie et al., 2024). Accordingly, the CE-applied construction industry is referred to as ‘circular construction’ (Gamage et al., 2024). Circular construction is a regenerative process that seeks to eliminate unnecessary resource consumption, environmental degradation, and ecological harm (Vergani et al., 2024). Furthermore, Ghisellini et al. (2018) emphasised the importance of embedding circular thinking throughout the construction supply chain. Moreover, with its vast environmental, social, and economic footprint, the construction sector can drive CE forward and create lasting value (Çimen, 2021).

The construction sector today remains fragmented, often hinging on the contributions of individual actors and small enterprises (Bakos & Schiano-Phan, 2021). As Stephan and Athanassiadis (2018) argued, CE becomes attainable only when professionals step forward not just as participants, but as pioneers driven by the motive to create circular construction solutions. Chang and Hsieh (2019) supported this, highlighting the urgent need for professionals who understand value beyond the linear. This transition is not just a technical shift but a profound transformation that hinges on human capability (Victar et al., 2024). Professionals now stand at a crossroads, bearing the weighty responsibility of translating sustainability visions into practical, project-level realities as the circular built environment does not materialise on its own but by those with the courage and competencies to lead it (van Stijn & Gruis, 2020). To rise to this challenge, professionals must be armed with a dynamic portfolio of competencies. According to Kibert (2016), the successful implementation of CE practices demands technical precision, managerial foresight, and entrepreneurial daring. Recent literature, including Bertozzi (2022) highlighted that construction professionals need to bridge knowledge gaps, adopt technical skills, and embrace collaboration to effectively integrate CE principles into their projects. Authors further mentioned that technical competence powers the innovation of circular systems, managerial competence ensures these systems are not just imagined but executed, and entrepreneurial competence fuels the discovery of untapped opportunities that CE unlocks. Despite the growing emphasis on the CE, professionals in the construction industry still lack clarity on the specific competencies needed to implement it effectively (Quashie et al., 2024). Although literature outlines various Competencies for the linear-to-circular transition, translation of this knowledge into practice is still lacking. As a result, the uncertainty among professionals becomes a major barrier, and

CE efforts often fail not due to a lack of ambition but because the professionals lack the competencies to deliver it (Vergani et al., 2024).

To better understand the human capabilities required to drive circular construction forward, it is important to clarify what is meant by "skills" and "competencies." In the literature, the terms have often been used interchangeably. For example, Vergani et al. (2024) referred to them as skills, while others such as Quashie et al. (2024) used the term "competency skills." In contrast, Victar et al. (2024) and Bjerke and Amoudi (2024) emphasised "competencies" as a more comprehensive concept. The term 'competency' itself is rooted in the Latin word competentia, meaning "is authorised to judge" or "has the right to speak" (Caupin et al., 2006), pointing to its deeper connotation of legitimacy and authority in action. In this research, competencies are understood as a blend of knowledge, skills, and capabilities that individuals must possess to effectively carry out their responsibilities (Wong, 2020). Since the majority of reviewed articles refer to them as competencies and professional organisations similarly adopt the term, this study consistently uses the term competencies throughout. The individuals this study focuses on are "construction professionals". The construction industry comprises a workforce and professionals. The workforce comprises skilled and semi-skilled labourers, technicians, support staff, and supervisors whose roles typically do not require advanced professional qualifications (Chan & Kaka, 2007). In contrast, Construction professionals are specialised experts such as architects, surveyors, engineers (civil, mechanical, electrical), quantity surveyors, and other key actors who contribute to decision-making and implementation throughout the construction lifecycle (Vergani et al., 2024). They manage various aspects of a project, including design, structural stability, financial oversight, and resource organisation (UKEssays, 2018).

Despite the growing body of literature on CE competencies in the construction industry, existing studies tend to focus either on general, non-role-specific competencies or on selected professions. Sanggoro et al. (2024) examined how core engineering competencies support CE implementation using Importance-Performance Analysis (IPA) with certified engineers in Indonesia. Dautremont and Gobbo (2025) explored collaborative CE practices across micro, meso, and macro levels in circular construction ecosystems, identifying interlinked activities among all stakeholders. Bjerke and Amoudi (2025) discussed the role of architects in integrating CE principles, while Vergani et al. (2024) emphasised the importance of systems thinking and interdisciplinary collaboration for engineers and architects working towards circularity. Gibbin et al. (2023) highlighted project managers' roles in translating CE goals into project execution strategies through leadership and coordination. Studies, including Victar et al. (2024), addressed quantity surveyors' involvement in recycling and reuse across multiple project stages. Existing research often explores CE from a general or role-specific perspective, but the findings are scattered and lack integration. Without a synthesised understanding of the professional competencies necessary to support circular construction, efforts to embed CE principles into construction practice would be difficult and uninformed. Therefore, this research aims to investigate the competencies required by construction professionals to perform CE practices, achieved through a systematic literature review. The following objectives were addressed.

1. Conduct a descriptive and content analysis of competencies required by construction professionals to perform CE functions.
2. Compare and contrast the competencies required by different professionals

3. Identify the common competencies required by construction professionals to perform CE practices

2. RESEARCH METHODOLOGY

A systematic literature review (SLR) is crucial in construction research to expand knowledge on specific topics (Chen et al., 2022). SLRs offer a transparent, unbiased, and replicable approach to synthesising existing research by following a predefined protocol, enabling comprehensive analysis and evidence-based conclusions that support credibility (Jesson et al., 2011). This study used the Scopus database to locate scholarly articles on competencies required for professionals in circular construction due to its reliability and extensive use in the field, as revealed by Ghaleb et al. (2022). The PRISMA framework was adopted for its clarity, transparency, and structured methodology (Shahruddin & Zairul, 2020). PRISMA integrates the PICO approach to formulate precise research questions (Hosseini et al., 2024), essential for a successful review. To ensure transparency and the rigorous review process, Figure 1 presents the PRISMA flow diagram used to illustrate the systematic screening and selection of literature.

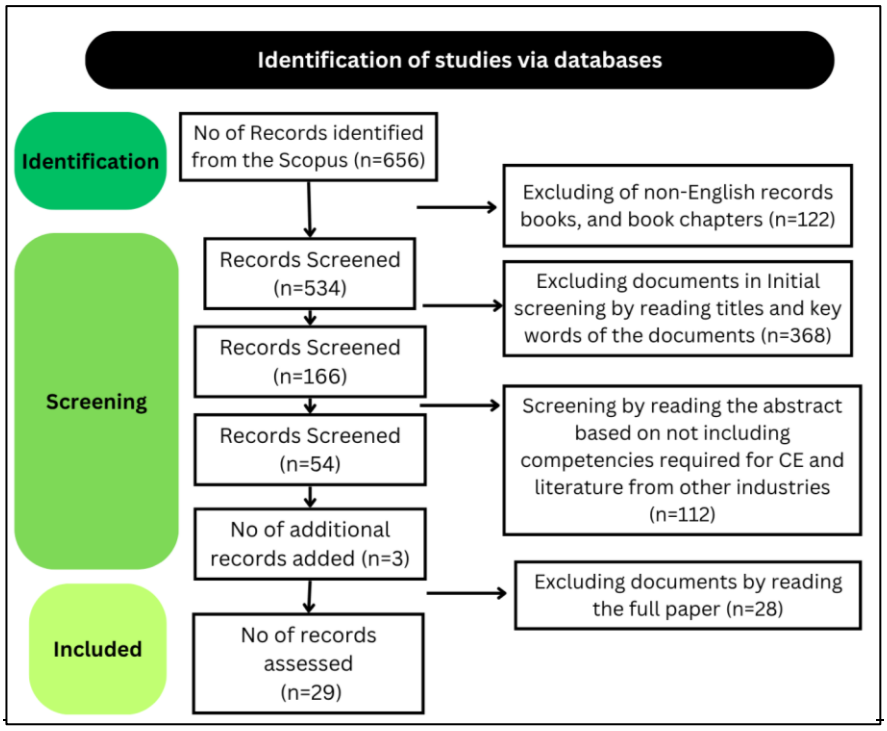


Figure 1:PRISMA flow diagram used for the study

The main search string used to retrieve bibliometric data related to the research area of concern was: ("Circular Economy" OR “Regenerative economy” OR “Zero-waste economy” OR “Cradle-to-cradle” OR “Circular built environment”) AND ("Competenc*" OR "Skill*" OR "Capabilit*" OR "Qualificat*" OR "Expertis*" OR "Knowledg*" OR "Train*") AND (“Construction industry” OR “Construction projects” OR “Construction field” OR “Construction business” OR “Construction sector” OR “Built Environment” OR “Building sector” OR “Quantity Surv*” OR “Project Manag*” OR “Civil Enginee*” OR “Archit*”). Next, the screening process was performed by including journals, conference papers, reviews, etc. Accordingly, 656 articles were selected from the search protocol. Due to language barriers, 11 non-English articles were

excluded. 111 books, book chapters, letters, and notes were excluded as they lack peer review and are prone to becoming outdated.

From the remaining pool of 534 papers, 166 were initially shortlisted based on their titles and keywords. Subsequently, 112 documents were excluded as they were either product-focused or unrelated to the construction sector. Meanwhile, three additional articles were incorporated into the repository after a comprehensive review of their full text, as the title or the abstract did not imply any relevance towards skills, but the full body text did. During the final screening phase, papers that offered limited insight into the CE competency requirements of professionals, or those that focused on occupations only tangentially related to the construction industry, such as real estate agents, were also removed. As depicted in Figure 1, this rigorous process resulted in a final selection of 29 papers. These shortlisted studies were examined through both content analysis and descriptive analysis. The content analysis was used to review the paper's contents thoroughly in broader themes, such as (1) Common competencies required by construction professionals and (2) competencies required by different professionals to perform CE functions. The research findings are presented in the two sections of the 'Findings and Discussion' section.

3. FINDINGS AND DISCUSSION

The findings and discussion section discloses the findings generated by descriptive and content analysis. Content analysis analyses sources in a systematic and objective manner, providing reliable insights that inform action (Mayring, 2021). Meanwhile, descriptive analysis supports identifying trends and variations through a focus on the who, what, where, when, and extent of phenomena (Cote, 2021). This combination provides a comprehensive understanding of the subject researched.

3.1 DESCRIPTIVE ANALYSIS

The publication trend of empirical studies conducted over the past years and the profession-wise distribution of related studies across geographical areas are insights through descriptive analysis.

3.1.1 Publication Trend from 2019 to 2025

The rise of CE principles in construction has increasingly drawn academic attention, particularly in terms of the competencies required for effective implementation. Figure 2 illustrates how scholarly publications on CE-related competencies in the construction sector have evolved over recent years.

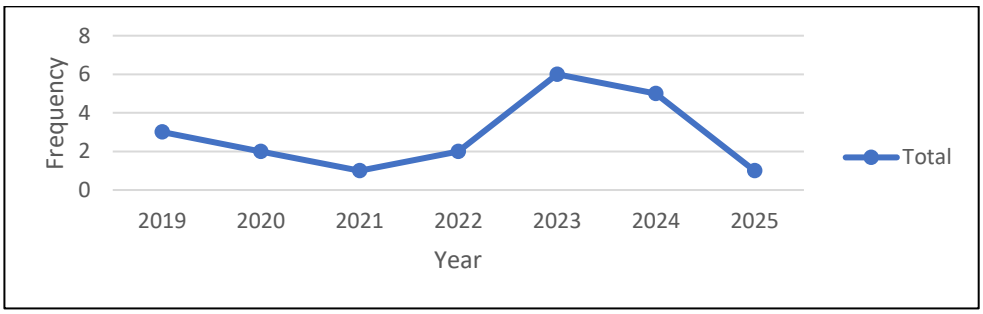


Figure 2: Publication Trend since 2019

The temporal distribution of the reviewed journals reveals a clear upward trend in academic interest surrounding CE competencies within the construction sector. Although the concept of CE began gaining traction globally in the late 1990s, its application to construction professional competencies did not appear in the academic literature until 2019, based on this dataset. This delay could be attributed to the initial focus on establishing a theoretical foundation for CE in construction, while comparatively limited attention was given to identifying and developing the specific competencies required by professionals to effectively implement CE principles. The earliest contributions in 2019 include three publications. This level of output remained relatively modest through 2020 and 2021, representing a formative phase in the discourse. However, a notable increase occurred in 2023, with six publications, followed by five more in 2024. This surge likely reflects a post-pandemic shift in priorities, with increased emphasis on professional competencies, and CE transitions within the built environment. However, the observed reduction in publications for 2025 is due to the SLR being conducted during the first quarter of the year, and publications from the remaining months were not included.

3.1.2 Geographical Distribution

Understanding the geographical origins of research on CE competencies within the construction sector provides vital insights into patterns of global scholarly engagement and regional research priorities. Figure 3 presents the distribution of reviewed publications by country, thereby highlighting both the breadth of international contributions and existing gaps in the current body of literature.

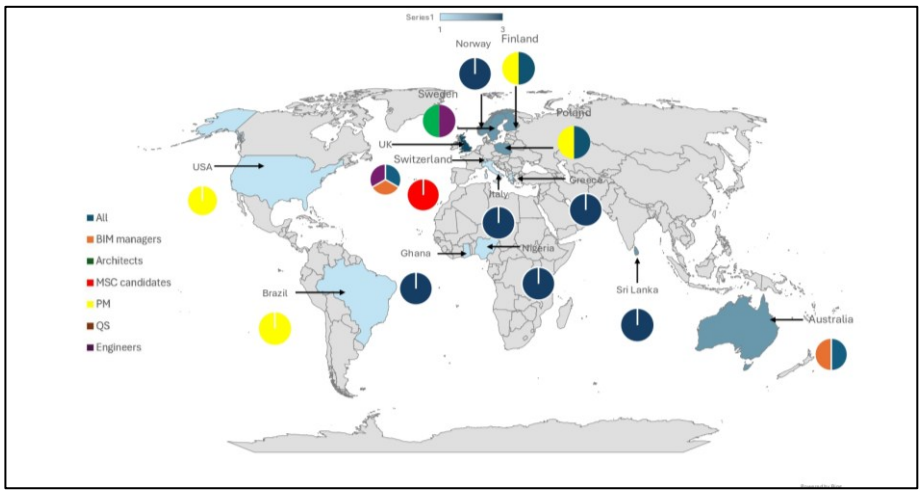


Figure 3: Geographical distribution of publications

The systematic literature review reveals a geographically diverse interest in the competency requirement of construction professionals, with journal articles originating from 17 different countries. As Figure 3 presents, the United Kingdom leads with three publications, covering roles such as engineers, BIM managers, and general CE practices, suggesting a strong national focus on sustainable construction leadership. Countries like Finland, Poland, and Norway follow closely with two studies each, demonstrating notable contributions from Europe. A promising aspect of the review is the inclusion of developing countries such as Nigeria, Ghana, Sri Lanka, and Brazil, each contributing at least one study. These contributions align well with the findings of Quashie et al. (2024), which emphasised the relevance of CE principles in contexts where rapid urbanisation, waste management challenges, and the need for resource efficiency are becoming

increasingly critical. However, the relative lack of representation from Asia and the Middle East points to gaps in the global dialogue that future research could address.

Figure 3 further demonstrates a variety of construction professionals, emphasising that CE adoption requires cross-disciplinary engagement identified during the SLR. Project managers appeared most frequently, with four studies focused on their role in enabling CE through project planning, procurement strategies, and lifecycle thinking. Engineers, while only represented in a few studies, are recognised for their technical contribution. BIM managers appeared in 2 articles from England and Australia, signalling growing attention to how digital tools like Building Information Modelling can support CE decision-making. Quantity Surveyors (QS), represented by two studies from Sri Lanka, highlighted the role and competencies of a QS in the 3R concept-infused CE. One unique entry involves MSc candidates in Switzerland, indicating that CE competencies are increasingly being embedded in academic curricula. Over half of the studies do not focus on a specific role, instead addressing the broader spectrum of CE competencies required by professionals across the construction sector.

3.2 CONTENT ANALYSIS

The CE competencies of construction professionals in a common context as well as profession-specific competencies have been discussed in the content analysis.

3.2.1 CE Competencies

The successful implementation of CE practices in construction demands a profession-specific understanding of relevant competencies. Table 1 below provides a synthesised overview of competencies mapped to key construction roles, reflecting the differentiated yet complementary contributions of each profession toward circularity.

Table 1: Circular economy competencies for construction professionals

Competency	Relevant Profession	Sources
Critical & Creative Thinking: Critical thinking, Creative thinking, Creativity, Foresighted/anticipatory thinking, Positive thinking	Common	3,6,7,8
Problem Solving and Structuring: Complex problem-solving, Problem-solving, Problem structuring, Troubleshooting operational errors	Common	3,5,6,7,8
Decision Making and Judgement: Decision making, Judgment and decision making, Originality judgment	Common	5,6,7
Numeracy and Mathematical Reasoning: Numeracy, Mathematics, Mathematical reasoning	Common	6,7
Analytical and Hypothesis Testing: Analytical thinking, Hypothesis testing, Predictive analysis, Quality control analysis	Common	6,8
Communication: Communication, Effective Communication, Speaking, Active listening, Reading comprehension	Common	3,6,7
Negotiation and Persuasion: Negotiation, Persuasion, Relationship competency	Common	5,6,7
Teamwork and Collaboration: Teamwork, Collaboration, Understanding team dynamism, Interpersonal competence	Common	3,5,6,7,8

Competency	Relevant Profession	Sources
Cultural and Social Awareness: Cultural intelligence, Addressing generational differences, Social perceptiveness, Social awareness	Common	1,6,7
Leadership and Direction: Leadership, Leadership competency, Provision of direction to inspire others, Developing teams, Transforming followers into leaders, Empowering others, Resilience	Common	3,4,6,8
Project Coordination and Interface: Effective coordination and integration of stakeholders, Interface management, Coordination, Operations analysis	Common	2,4,6,7
Resource and Process Management: Management of financial/material/personnel resources, Process management, Material Logistic Plan Implementation, connecting reverse logistics with users, Upcycling	Common	3,6,7
Equipment and Site Management: Equipment maintenance, Operation monitoring, Operation and control, Installation, Repairing, Equipment selection	Common	6,7
Onsite Execution and Practical Competencies: Onsite practical skills, Specification writing, Using suitable structural systems/materials, Suitable site characteristics, understanding wear, value perception, and engineering use	Common	1,3,4,8
Self and Stress Management: Stress management, Self-confidence / Self-control, Resilience, Positive thinking;	Common	6
Empathy and Caring: Empathy, Caring, Humanity, Emotional reasoning, Interpersonal sensitivity	Common	6,8
Adaptability and Flexibility: Adaptability, Adaptability competencies, Cognitive flexibility	Common	6
Curiosity and Active Learning: Curiosity, Active Learning, Learning Strategies, Understanding factors affecting user experience.	Common	6,7,8
Ethical and Entrepreneurial Mindset: Ethical competencies, Entrepreneurship competencies, Service orientation, circular business model integration	Common	3,6,8
Design for Circularity: Eco-design, designing for multiple-use cycles, lean design and construction, cradle-to-cradle principles, built environment restoration, water-sensitive and wetland design.	Common	1,9
Impact Assessment: Sustainability assessment and benefits, rating systems and certification, CE social impacts, environmental assessment methods, social life cycle assessment, circular impact assessment, circular scope definition	Common	1,9
Waste Minimisation: Waste efficient procurement knowledge, Ability to manage waste, Ability to create and implement waste management plan, Personnel commitment to pursuing a solution to waste minimisation, Waste avoidance cost accounting	Common	1,3,6,8
Programming and Tech Design: Technology design, Programming, Technology Design and Programming	Common	6,7

Competency	Relevant Profession	Sources
Software and Data Competencies: Software competencies, Competencies for specific tools, Data analytics, Data management competencies	Common	6
Cybersecurity and Digital Identity: Computer security, Digital identity, Digital rights, Digital Security	Common	6
Digital Fluency and Leadership: Digital literacy, Digital communication, Digital use, Digital strategy, Digital leadership, Digital emotional intelligence	Common	6
Systems Thinking and Evaluation: System thinking, Systems analysis, Systems Evaluation	Common	1, 6, 7
Specialised Quantity Surveying Competencies: risk management, procurement advice, resource management, cost control, cost planning, feasibility studies, value engineering, cost estimation, Life cycle cost analysis, cost-benefit analysis, data standardisation and modelling, embodied ecology costing, and sustainability advisory.	Quantity Surveyor	13
Specialised Architecture, Engineering, and Construction Competencies: 3D printing in construction, technical and geographic insight, CE challenges in real estate, urban mining, energy minimisation and monitoring, aquifer storage and water quality issues, Madaster vision for material passports, non-renewable tech and energy trade, functional and physicochemical building blocks.	Engineers, Architects	9
BIM-Integrated Competencies: 3D modeling, Digitalisation, Quantity takeoff and phase planning, Standardisation and flexibility, Asset and component maintenance, Use visual models to reduce rework, BIM interoperability for waste management, Auto-capture design parameters, Extract waste data from design models, BIM for lifecycle waste management, Use BIM for construction waste analysis, Specify materials from models to reduce variation, Extract material quantities from models, Volumetric modular design application, Integrate construction sequencing early, Modular construction techniques,	BIM Managers	10,11

Sources - (1-Quashie et al., 2024; 2- Hendrianto et al., 2024; 3- Botchway, et al.,2023; 4- Wuni & Shen, 2022; 5-Harala et al., 2023; 6- Siriwardhana & Moehler, 2023; 7- Burger et al., 2019; 8-Górecki,2019; 9- Vergani, et al., 2024; 10-Bjerke & Amoudi, 2024; 11-Ganiyu et al., 2020; 12-Wrase et al., 2023; 13-Victar et al., 2024; 14-Jääskä 2021)

Quashie et al. (2024) identified the competencies driving circularity in the construction industry within developing economies, emphasising the unique, context-specific skills needed in low- to middle-income countries. Drawing from such diverse insights, Table 1 was developed through a structured synthesis of original competencies from multiple sources, categorised into 30 thematic groups such as critical and creative thinking, project coordination, BIM-integrated competencies, and software and data proficiency. While some categories are profession-specific, most are broadly applicable across construction roles. These competencies include skills essential for addressing complex sustainability challenges, supporting stakeholder engagement, and integrating circular principles in projects. Additionally, digital literacy, programming, and data proficiency reflect the

industry's shift toward technology-driven solutions. Competencies, including design for circularity, impact assessment, and systems thinking are key to embedding circular economy principles in construction practices.

3.2.2 Profession-Specific Competencies

Table 1 presents a diverse range of competencies tailored to key professional roles within the circular construction industry. Górecki (2019) emphasised leadership, emotional reasoning, operational analysis, and interpersonal sensitivity as critical competencies for Project Managers to make sustainable decisions, while Jääskä (2021) highlighted collaboration, decision-making, and problem-solving. Vergani et al. (2024) contributed technical and sustainability-related competencies for Architects and Engineers, including 3D printing as well as technical and geographic insight. Bjerke and Amoudi (2024) identified BIM-related skills such as digital modelling, standardisation, and phase planning that support waste minimisation and adaptability. Ganiyu et al. (2020) further explored BIM's role in waste analysis, modular construction, and logistics optimisation. Wrase et al. (2023) proposed a holistic framework of governance, ethics, and digital transformation to prepare CE-ready graduates. Victar et al. (2024) mapped Quantity Surveyors' roles to the 3R (Reduce, Reuse, Recycle) principles, highlighting competencies like life cycle costing and value engineering.

Accordingly, role-specific competencies vary significantly depending on professional focus. Quantity Surveyors, for instance, are primarily concerned with financial and resource efficiency, possessing advanced capabilities in procurement advice, cost control, life cycle cost analysis, and sustainability-related costing methods (Victar et al., 2024). In addition, certain common competencies such as impact assessment align more closely with Quantity Surveyors, given their involvement in project feasibility evaluations and life cycle cost analysis (Senaratne et al., 2024). Meanwhile, BIM managers demonstrate distinct digital fluency, with competencies in 3D modelling, modular construction, lifecycle waste analysis, and integrating digital tools like BIM for circular design and waste reduction (Bjerke & Amoudi, 2024). These variations demonstrate how each profession supports circular economy goals from different angles, reinforcing the need for role-specific competency frameworks tailored to their functions within the construction ecosystem. However, although these studies present profession-specific competencies, the majority of the identified competencies remain relatively general rather than deeply profession-specific, highlighting a notable gap in the existing literature.

3.2.3 Paving the Way Forward for CE Implementation by Construction Professionals

Despite increased academic attention, existing literature still lacks a holistic understanding of how competencies are distributed across different professions and global contexts. One of the most critical gaps lies in the limited focus on specific construction professions. For instance, PMs were the most frequently examined profession, appearing in only five out of twenty-seven studies despite the availability of a few existing research on professions such as Engineers, Architects, QSs, and BIM managers (Górecki, 2019; Victar et al., 2024; Ganiyu et al., 2020). However, key contributors to on-site performance, including site supervisors, MEP engineers, planning engineers, draftsmen, and construction foremen, remain largely unaddressed. Moreover, most of the studies that attempted to identify competencies remain relatively general, indicating a significant gap in deeply profession-specific competency mapping within the

current CE literature. If such detailed mappings were available, the construction industry would be better positioned to maximise the benefits of CE practices by aligning skills development precisely with practical implementation needs. There are also notable geographical imbalances in research coverage. Most contributions originate from European nations such as the United Kingdom, Finland, and Poland (Burger et al., 2019). Most contributions originate from the United Kingdom accounting for three publications focused on engineers, BIM managers, and general CE practices while regions experiencing rapid urban growth, including Southeast Asia, the Middle East, Africa, and Latin America, receive little to no representation. As emphasised by Quashie et al. (2024), these regions encounter unique challenges such as informal labour structures, limited training access, and regulatory fragmentation. Addressing such realities requires context-specific competency frameworks that align with local needs and priorities. Moving forward, there is a need to expand profession-specific studies to include the full range of construction roles involved in circular construction. Additionally, future research should be more geographically inclusive, with a particular emphasis on underrepresented regions where CE adoption can deliver the most transformative impact. Only through such comprehensive efforts can the construction industry be truly equipped to support the global transition to a circular and sustainable built environment.

4. CONCLUSIONS AND RECOMMENDATIONS

This study provided a structured synthesis of the competencies required by construction professionals to implement CE practices, using a systematic literature review approach. It identified common competencies and mapped role-specific competencies across various professions within the sector. Despite the growing academic interest, the current literature remains limited in geographic and professional scope, underscoring the need for a more inclusive understanding of CE competencies in construction. To advance the implementation of CE in the built environment, the following recommendations are proposed. (1) Expand research coverage to include underrepresented regions such as Southeast Asia, the Middle East, and parts of Africa and Latin America, where the built environment is growing rapidly, (2) Conduct profession-specific studies to identify detailed competency frameworks for a broader range of construction roles (3) Promote interdisciplinary education and training programs that align with the identified competency categories, ensuring professionals are prepared for practical CE challenges.

This study contributes to the growing CE literature in construction by identifying both common and profession-specific competencies needed for CE transitions. It presents competencies such as systems thinking, digital fluency, and design for circularity while mapping competencies for key roles, including PMs, QSs, and BIM managers. The research also highlights regional and professional gaps, where most identified skills are general rather than CE specific, with limited representation from countries like China and India, and roles such as site supervisors. These findings guide future, more inclusive CE competency research. However, the analysis was based solely on secondary data, without field-level validation from industry practitioners. Nevertheless, the study systematically synthesises fragmented literature to construct a cohesive and comprehensive understanding of the competencies required by construction professionals to implement CE practices effectively.

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COMPETENCY REQUIREMENT FOR PROFESSIONALS INVOLVED IN PUBLIC CONSTRUCTION PROCUREMENT PROCESS: A REVIEW

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ABSTRACT

Due to its complexity and a series of interdependent activities, public construction procurement (PCP) is often prone to problems such as cost overruns, time overruns, quality compromises and fraud and corruption. These problems ultimately lead to disputes challenging value for money (VFM), which is anticipated particularly in public construction projects. The success of public construction projects ensures VFM, and it is heavily dependent on the competencies of professionals involved in the procurement process. It was revealed that limited research has been conducted, shedding light upon the competencies required by the professionals in the procurement team specifically for the public construction procurement process. Therefore, the research aimed to explore competencies required by professionals, such as Quantity Surveyors, Engineers, and Architects, who are engaged in the procurement team in the public construction procurement process. The research is conducted with a particular focus on laying the foundation to explore these competencies to overcome the identified problems. Accordingly, a comprehensive literature review was conducted. The findings revealed 14 problems in the public procurement process (PPP), and the competencies expected from the leading professionals in the procurement team, including Engineers, Architects, and Quantity Surveyors, were detailed and analysed according to the competency requirements of the selected professional institutes. The findings suggest that procurement professionals must possess a robust understanding of legal, financial, and technical aspects, alongside strong communication and negotiation skills, to navigate the complexities of public construction procurement. The findings of this research will contribute to minimising disputes and improving the efficiency of public construction procurement processes.

Keywords: *Competencies; Disputes; Procurement Team; Public Construction Procurement; Sustainability.*

1. INTRODUCTION

The construction industry is a key contributor to the national economy of any country (Oguntona & Aigbavboa, 2020). Construction procurement plays a crucial role in achieving project goals and defines the structure of responsibilities among participants

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(Gajaman et al., 2019). Within the construction industry, PCP accounts for a substantial proportion of the national economy, leveraging public investment, infrastructure facilities and enabling employment while guaranteeing VFM (National Procurement Commission [NPC], 2024; Uduwage-Don et al., 2024). However, due to its inherent complexity, public procurement is often prone to problems such as additional costs, delays and poor quality, which can escalate into disputes, consuming a substantial amount of money and time (Dita et al., 2020). Therefore, avoiding conflicts at the outset is advantageous, as effectively addressing the problems can prevent them from escalating into disputes (Mitkus & Mitkus, 2014; Gajaman et al., 2019).

Since the construction procurement is a structure which represents a shared responsibility among the parties, problems can be addressed effectively, and successful execution of procurement activities in the right manner is ensured when the professionals possess the requisite expertise (Gajaman et al., 2019; Shehu et al., 2019). Similarly, Komakech (2016) emphasised that, given the complexity and risks involved in public procurement today, the procurement team should possess specific competencies to perform efficiently, maximise VFM, and reduce corruption. The study focuses on Architects, Quantity Surveyors, and Engineers, as they are the key professionals directly involved in pre-contract activities and are formally recognised in relevant institutional competency frameworks (Construction Industry Development Act, 2014).

Effective public procurement is essential for good public services and good government. Since the government spends money on behalf of taxpayers, it is essential for the government to apply the highest professional standards (Publications Office of the European Union, 2020). Therefore, in order to ensure meeting the required quality of the public needs, the public procurement workforce is required to undergo professionalisation (Publications Office of the European Union, 2020).

Problems in the PPP can lead to disputes in the post-contract stage if the problems are not effectively addressed. Poor quality performance, cost overrun, risk overrun, deliverables not fit for purpose, lack of communication, fraud and corruption, and shortage of highly qualified and motivated professionals are some of the problems that ultimately result in disputes (Asiedu et al., 2021; Gunawardana et al., 2021; Uduwage-Don et al., 2024; Ayopo et al., 2016; Naude, 2017; Adhikari, 2015; Construction Industry Development Act, 2014). Therefore, to minimise and avoid disputes, the client needs to obtain services from a professionally well-trained staff of procurement professionals to address these problems. When appointing the procurement team, clients must have a thorough understanding of the required competencies essential for successful PCP.

Even though studies have been conducted on knowledge requirements for the procurement process (Shehu et al., 2019; Komakech, 2016), competencies for Quantity Surveyors (Chamikara et al., 2020; Yogeshwaran et al., 2018), and construction project managers (Moyo & Chigara, 2023) as well as for dispute management (Rajapakshe, 2019), limited research has focused on the competencies required by the professionals in the procurement team specifically in PCP. Thus, there is a need to fill this knowledge gap by comprehensively investigating and synthesising the required competencies of the procurement team involved in PCP based on the existing literature, which primarily focuses on individual professionals. Therefore, this paper aimed to review the competencies required by Architects, Engineers and Quantity Surveyors for the PCP process. The objectives of the research are to analyse the problems in PPP and to

investigate the competencies required by the professionals in the procurement team of public construction projects.

This paper initiates with an introduction followed by the research methodology, the research findings, discussion, contribution of the research and conclusion with recommendations.

2. RESEARCH METHODOLOGY

Research methodology is identified as a series of steps followed by a researcher with the aim of solving a research problem in a logical manner (Kumar & Praveenkumar, 2025). A literature review represents an organised, transparent and replicable process for existing literature (Snyder, 2019). In order to ensure the quality and credibility of the literature review, it is essential to scrutinise high-quality sources such as journal articles, books, and conference proceedings with proper citations (Xiao & Watson, 2019). Therefore, this research relied on journal articles, books, and conference papers to guarantee the reliability and academic consistency of its findings.

Accordingly, this study adopted a comprehensive literature review approach to explore the updated and structured overview of the existing body of knowledge on competency requirements for professionals involved in PCP (Pautasso, 2019). In order to ensure the quality of the review, relevant articles were identified through databases confining to Scopus, ScienceDirect, and Google Scholar using keywords including "competency requirements," "construction procurement," "public construction projects," and "professional competencies in construction". The search was limited to publications from 2001 to 2025 and restricted to English language sources. Studies were included if they discussed competencies in the context of construction procurement, particularly within public sector projects. Non-peer-reviewed articles, non-English studies, and studies unrelated to construction were excluded.

Likewise, a comprehensive literature review was carried out to achieve the aim and objectives of the study by using well accepted academic databases, as noted above, and filtering a sufficient number of relevant research publications through keyword searches while excluding outdated studies. A background study and comprehensive literature review were conducted to examine the PPP, its problems, and competency requirements expected by the Engineers, Quantity Surveyors and Architects. Moreover, the findings were also extended to include the literature from the sources of professional institutions. The study is not limited to the Sri Lankan context and global contexts were considered.

3. RESEARCH FINDINGS

3.1 PUBLIC CONSTRUCTION PROJECTS

Public construction projects are often funded through taxes or government loans and are typically managed by government agencies or private contractors (Delmon, 2017). They are essential to infrastructure development, covering a wide range of sectors such as transportation, education, and healthcare (United Nations Development Programme, 2017). Additionally, these projects contribute to the achievement of sustainable development goals by promoting social, economic, and environmental sustainability (Uenk & Telgen, 2019). Overall, public construction projects play a crucial role in shaping the built environment and fostering economic growth and advancement. They

require careful planning, management, and funding to ensure that they meet the needs of communities and provide lasting benefits for years to come (Uenk & Telgen, 2019).

3.2 PUBLIC PROCUREMENT PROCESS

3.2.1 Public Procurement

Public procurement involves acquiring significant inputs for public investments through the most appropriate means of public funds or external funds and guided by the core principle of VFM (National Procurement Commission [NPC], 2024). PCP is a subset of public procurement which refers to the process by which public bodies acquire goods, services, or works from selected suppliers, from routine goods to large-scale contracts for infrastructure projects (Office of Government Procurement, 2019). Public procurement is now recognised as a profession that plays a key role in the effective management of public resources (Ambe & Badenhorst-Weiss, 2012). PCP plays a vital role in infrastructure development and significantly contributes to the national economy, especially in developing countries like Sri Lanka (Uduwage-Don et al., 2024; Central Bank of Sri Lanka [CBSL], 2014).

3.2.2 Procurement Process

The construction procurement process is a complex process that involves several stages and is essential for establishing and managing contracts (Diófási-Kovács & Tátrai, 2025). There are various construction procurement methods, such as Traditional, Design and Build, Management Contracting, Construction Management, Partnering, Public Private Partnerships, Private Finance Initiatives, and Collaborative Agreements that are selected based on the client's specific project requirements (Osifo, 2024). This research is focused on the procurement process based on the traditional procurement system.

Successful construction procurement depends on aligning each activity within the procurement process with professionals who possess the necessary competencies (Shehu et al., 2019). Further to the author, by performing duties and tasks in an appropriate manner, problems can be avoided beforehand without escalating them into conflicts and finally into disputes.

3.3 PROBLEMS IN PUBLIC PROCUREMENT PROCESS

PPPs are susceptible to problems that diminish VFM, erode public trust, delay project delivery, and compromise quality, affecting successful completion (World Bank, 2018). These problems and poor procurement practices can be identified as the prominent causes for hampering the economic growth of a country (Delmon, 2017; Raymond, 2008). Irrespective of whether a country is developed or developing, problems are prevalent in the PPP. The following Table 1 outlines problems in the PPP in the construction industry.

Table 1: Problems in public procurement process

Problem No.	Problem in the public procurement process	Authors
P-01	Cost overrun	1, 12, 15, 25, 26
P-02	Time overrun and delays in project implementation	1, 12, 15, 22, 25
P-03	Poor quality performance	6, 9, 10, 11, 20, 22, 24, 25, 26

Problem No.	Problem in the public procurement process	Authors
P-04	Deliverables not fit for purpose	3, 4, 8, 9, 13, 14, 25
P-05	Inadequate social and environmental cost valuation	4, 8, 25
P-06	Lack of communication	2, 15, 5
P-07	Risk Management Failures (Risk Overrun)	1, 12, 15, 25
P-08	Outdated Technology	6, 9, 10, 11, 25
P-10	Inadequate VFM assessment	6, 7, 9, 25
P-11	Shortage of highly qualified and motivated professionals	28, 17
P-12	Biased award procedures	27
P-13	Price inflation and overcharging	24
P-14	Recalling the tendering process	19

1.Dubois and Gadde (2002), 2. Chartered Institute of Building (CIOB, 2010), 3. Jones (2007), 4. Organisation for Economic Cooperation and Development [OECD] (2007), 5. Raymond (2008), 6. Walker and Brammer (2009), 7. Dawson et al. (2011), 8. Ameyaw et al. (2012), 9. World Bank (2023), 10. Amemba et al. (2013), 11. Adhikari (2015), 12. Decarolis and Palumbo (2015), 13. Ogunsanya et al. (2019), 14. Naude (2017), 15. Gyawali et al. (2018), 17. Chigudu (2014), 18. Musanzikwa (2013) 19. Uduwage-Don (2024) 20. Dinar & Zayed (2012) 21. Jones (2007) 22. Asiedu et al. (2021), 23. Chimwani et al. (2014) 24. Dinar and Zayed (2012) 25. Gunawardana et al. (2021), 26. Weisheng et al. (2013), 27. Jaafar and Radzi (2013), 28. Ofori (2007)

According to Sinha (2018), common problems in public construction projects include delayed project delivery, poor project planning, cost overruns, poor quality, corruption, safety concerns, inadequate project management skills, and lack of stakeholder engagement (Sinha, 2018). Lack of communication has been identified as one of the major problems in procurement through a survey conducted in the United Kingdom (CIOB, 2010). Among the problems shortage of highly qualified and motivated professionals in public procurement is responsible for the low reputation and undervaluing of public procurement (Ofori, 2007). Jaafar and Radzi (2013) stated that the problems originate with the industry players, who often possess insufficient knowledge of the procurement process. Conversely, disputes in public construction projects frequently arise from various procurement problems within the procurement process itself.

Similarly, disputes can significantly affect construction projects, leading to problems such as project delays, cost overruns, reputational damage and strained relationships among stakeholders (Alaloul et al., 2019; Rauzana, 2016). Therefore, proactive conflict management concentrating on the approach to prevent or mitigate problems from the inception of the project is essential for effectively resolving conflicts and disputes (Mitkus & Mitkus, 2014). In another standpoint, rather than conflict management, it is more effective to address the problems in PPP to minimise subsequent disputes. By fostering awareness and offering targeted training on the causes and prevention of disputes, the construction project leaders can focus on improving the competencies of the procurement team.

3.4 PROFESSIONALS IN THE PROCUREMENT TEAM

"Procurement professional" is defined as an individual who possesses professional qualifications in procurement from a recognised institution and is expected to possess a range of skills to manage the procurement process (Basheka, 2010). Moreover, Kaufman et al. (2017) stated that procurement professionals are not 'purchasing agents', but managers who possess physical and intellectual knowledge.

Public Procurement and Asset Disposal Act No. 33 of 2015 defines a "Professional" as an individual possessing professional qualifications in a specialised area and who is engaged in practising a skill or trade and has completed relevant formal academic and professional training, including practical learning through apprenticeship or tutelage under the supervision of a suitably qualified and experienced individual in the relevant field. Jabar (2012) argued that pre-contract stage activities are carried out by a number of stakeholders, such as the employer and the design team professionals, such as Engineers, Architects, Quantity Surveyors, Land Surveyors, Landscape Architects and Interior Designers. Meanwhile, many researchers have highlighted that most of the problems occur due to errors caused by professionals such as Architects, Engineers and QSs, which leads to disputes (Yadollahi et al., 2014; Francis et al., 2022). Therefore, this research focuses on Engineers, Architects, and Quantity Surveyors from the above identified professionals who are involved in the procurement action in PPP. Similarly, under the Construction Industry Development (CIDA) Act no 33 of 2014, these qualified persons are identified as Engineers, Architects, and Quantity Surveyors who are in consultation with the relevant professional bodies in Sri Lanka. In order to have the best performance in procurement, it is crucial to have competent procurement professionals (Rathod, 2011 as quoted in Shehu et al., 2019; Chimwani et al., 2014).

3.5 COMPETENCIES REQUIRED FOR PROCUREMENT TEAM MEMBERS

Karna and Gotovac (2015) define competency as a combination of skills, knowledge, and abilities necessary to achieve satisfactory performance within an organisation. Moreover, Paloniemi (2006) defined competence as the integration of knowledge, skills and attitudes. Therefore, "Skill" is a subset of "Competency" which must be enhanced along with personal qualities (Karunasena et al., 2015). Knowledge refers to awareness of factual information, while skills refer to the ability to apply knowledge to specific circumstances (Baartman & de Bruijn, 2011).

Further, Briscoe et al. (2001) categorised skills as hard skills, which are primarily vocational, and soft skills, which are non-specific and acquired through on-the-job experience. According to Roggema-van (2004), a competent professional can apply the necessary expertise along with effective behaviour in practice. Furthermore, experience is a key competency that supplements educational qualifications and technical skills (Paloniemi, 2006).

Given the complexity of construction projects and the diverse nature of work involved in public procurement, procurement professionals are required to possess a wide range of skills, knowledge and experience to enhance procurement performance (Chimwani et al., 2014). Therefore, Fazekas and Blum (2021) emphasised the growing importance of identifying, developing and assessing the competencies of public procurement officers to ensure compliance with legislation and obtain VFM. Raymond (2008) stated that professionalism involves education, qualifications, and ethical conduct. Further, the

author contended that scholars have to showcase professionalism and competence while executing their responsibilities within their field of study. Jones (2007) argued that possessing procurement capacity involves understanding internationally recognised procurement principles, being knowledgeable about national laws, regulations and procedures, and maintaining a commitment to ethical responsibilities.

Summarised competencies and skills expected from Architects, Engineers and Quantity Surveyors are presented in Table 2 as identified by the reputed professional bodies and previous studies.

4. DISCUSSION

The study highlights the critical role of professional competencies, particularly among Architects, Engineers, and Quantity Surveyors in ensuring the success of public construction projects by effectively addressing issues prevalent in the PPP. Accordingly, the study identified 14 problems and 31 competencies. Out of the 14 problems corruption, and fraud risks, and poor-quality performance were the most frequently cited in the literature. While each profession has different roles, many important competencies are shared. For example, all three professionals need good communication, problem-solving, and decision-making skills. Findings further revealed that Engineers focus more on safety and planning, Quantity Surveyors handle cost and contracts, and Architects lead the design. However, by working together with the right mix of skills, problems and disputes in projects can be avoided. Even though soft skills such as teamwork, ability to act fairly and impartially are rarely highlighted, they are highly valued in professional standards, implying the importance in practice to avoid conflicts. Furthermore, the study emphasises the need for ethical conduct in public procurement to prevent corruption and ensure transparency.

Addressing competency gaps, by promoting the recruitment and training of competent procurement professionals for public procurement, not only improves individual project outcomes but also contributes to the broader objectives of sustainable development by promoting efficient use of public resources and delivering higher quality infrastructure that serves communities effectively.

. Table 2: Competencies expected from Engineers, Quantity Surveyors and Architects

Competency Group	Engineer		Quantity Surveyor		Architect	
	Competencies	Ref	Competencies	Ref	Competencies	Ref
Knowledge and application of Construction Technology	Knowledge and practical application of engineering principles	[1]	Knowledge on Construction Technology (construction processes, building materials and suitability to project climate)	[2]	Knowledge of Construction Technology and Design development.	[4], [5]
Producing Designs to satisfy Overall Requirement	Design work and drawings and design Calculations	[1], [9]			Marketing Studies, Feasibility Study, Concept Design and Schematic Design, Design Development, Specification writing	[4], [5]
Cost Estimation, Management and Reporting	Managing and planning budgets	[1]	Cost Estimation, Management and Reporting	[2], [3]	Manage and plan budgets	[4], [5]
Procurement and Tendering	Design work and drawings	[1]	Procurement advice/Procurement and Tendering	[2]	Procurement advice/ Procurement and Tendering	[4], [5] [8]
Contract Administration	Manage and plan budget, tasks, resources	[1]	Contract Administration and knowledge on contractual implications	[2]	Administer the building contract impartially between the client and the contractor.	[4], [5], [8]
Legal knowledge and Understanding	Knowledgeable about relevant legislation	[1], [9]	Understanding regulations and guidelines related to construction	[2]	Building and other legislation, knowledge on statutory requirement and consultation with authorities	[4], [5] [8]
Agreement Drafting Skills			Agreement drafting skills	[2]	Agreement drafting skills	[5]
Financial Management	Commercial leadership – manage and plan budget	[1]	Understand accounting principles and economic concepts	[2]		

Competency Group	Engineer		Quantity Surveyor		Architect	
	Competencies	**Ref**	**Competencies**	**Ref**	**Competencies**	**Ref**
Competence in Dispute Resolution	Competence in Dispute resolution	[1]	Competence in Dispute resolution	[3]	Competence in Dispute resolution	[8]
Ethical Practice	Ethical Practice	[1], [9]	Ethical Practice	[2]	Comply with the code of professional conduct set by SLIA	[4], [8]
Risk Management	Risk Management	[1]	Risk Management	[2]		
Scope and Change Management	Manage budget	[9]	Variation process up to finalization of variation accounts	[2]	Variation orders, advise the client of the consequences of the subsequent changes on the cost and programme.	[4], [5], [8]
Co-ordination and Integration	Provide technical, commercial and managerial leadership	[1]	Co-ordination and Integration	[2]	Co-ordination and Integration	[4], [5], [8]
Health and Safety Management	Health and Safety Management	[1], [9]				
Quality Management	Quality management	[1], [9]		[3]	Inspection/Quality control	[8]
Time Management	Effective project planning	[1], [9]	Time Management	[3]	Time Management	[5]
Leadership and Management	Leadership and management	[1]	Leadership and Management		Leadership and Management	
Resource Management	Manage and plan resources	[1]	Resource Analysis and Management	[2]		
Data and Information Management	Data and Information Management	[1]	Data and Information Management	[2]	Data and Information Management	[5]
Analytical Skills	Analytical Skills	[1]	Analytical Skills	[2]	Analytical Skills	[4]
Logical Thinking	Logical Thinking	[1], [9]	Logical Thinking	[7]	Logical Thinking	[7]

Competency Group	Engineer		Quantity Surveyor		Architect	
	Competencies	Ref	Competencies	Ref	Competencies	Ref
Evaluation Skills	Evaluate solutions	[1]	Evaluating variations, tender evaluation, evaluation of design solutions	[2]	Tender evaluation, valuation of variations	[4], [5]
Skills in Interpreting	Interpretation Skills	[1]	Interpretation Skills	[2]	Interpretation Skills	[5]
Decision Making Skills	Making decisions	[1]			Decision making Skills	[5]
Computer Skills	Use of computer applications relevant to engineering	[1], [9]	Use of computer applications relevant to quantity surveying.	[2]	Computerized analysis and modelling	[5]
Planning Skills	Effective project planning solutions	[1]	Project implementation and procurement plan	[2]	Planning Skills	[4], [5], [8]
Communication Skills	Communication skills	[1], [9]	Communication and presentation skills	[2]	Communication and presentation skills	[4], [6]
Team Working Skills	Team working Skills	[1]	Team working skills		Selection and engagement of consultants	[5]
Emotional Intelligence and Cultural Competence	Treats people with respect	[1]	Treats people with respect		Treats people with respect	[5]
Ability to Act Fairly and Impartially	Ability to act fairly and impartially	[9]	Ability to act fairly and impartially		Ability to act fairly and impartially	[5]
Self –Development Skills	Continuous professional development	[1]	Continuous professional development	[2]	Continue with her/his own professional development	[8]

[1] (Institution of Engineer's Sri Lanka [IESL],2022), [2] (Institute of Quantity Surveyors Sri Lanka [IQSSL], 2020), [3] (Australian Institute of Quantity Surveyors [AIQS], 2012), [4] (Sri Lanka Institute of Architects [SLIA], 2015), [5] (SLIA, 1998), [6] (Ministry of Works and Human Settlement, 2021), [7] (Rajapakshe, 2019), [8] (SLIA, 2014), [9] (Engineers Australia, 2023)

5. CONTRIBUTION OF THE RESEARCH

The findings of the research contribute to both academic fields and industry practice. For academia, the research provides a cornerstone for further studies to explore the linkage between identified problems and the competencies required to address them according to each profession. For the industry, it offers clients a better understanding of recruiting suitably competent professionals to their procurement teams while enabling professionals to self-direct competency development. Moreover, professional institutes can utilise the findings to conduct workshops, continuous professional development activities, seminars and courses to ensure that the respective professionals possess the lacking competencies. By promoting the recruitment and development of competency-equipped professionals, other than minimising disputes, this research also supports the integration of sustainability principles into procurement practices, contributing to the delivery of sustainable public construction projects.

6. CONCLUSIONS AND RECOMMENDATIONS

This study was designed to investigate the competency requirements of the professionals in the procurement team in the PCP by conducting a comprehensive literature review. PCP is often prone to problems such as time overrun, cost overrun and quality compromises, leading to disputes and challenging to this principle of "VFM". The study identified 14 problems, and it is essential to avoid these problems at first instance as they may consume a lot of money and time to resolve. It was understood that the problems could be overcome by building up the necessary competencies by the professionals in the procurement team. Architects, Engineers and Quantity Surveyors are mainly focused on the study since most of the problems stem from the activities performed by them. Accordingly, 31 relevant competencies were identified as essential for effectively addressing these procurement challenges and ensuring the success of public construction projects.

Based on the findings of the study, it is recommended that future researchers conduct empirical studies to establish links between the identified competencies and specific problems in the PPP. Moreover, a competency framework is recommended to develop linking each competency to the relevant professionals, which could serve as a practical tool for public sector recruiters to assess and select competent professionals for procurement teams, ultimately enhancing the effectiveness and accountability of PCP.

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CONSTRUCTING NATIONAL POLICY FOR FUTURE GENERATIONS: A DESIGN APPROACH TO CHILDREN'S BOOKS

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ABSTRACT

Constructing policies that serve future generations requires approaches that are not only inclusive and forward-thinking but also grounded in the lived realities of their primary users, in this case, children. In 2023, the National Consortium for Children's Books (NCCB) was established in Sri Lanka to address challenges in the children's literature sector and fulfil national educational objectives. A central goal was the development of the National Policy for Children's Books (NPCB). This paper discusses the collaborative, design-driven approach utilized in formulating NPCB content, highlighting the innovative integration of design thinking into national policymaking. The process, structured through five iterative action research cycles, employed convergent and divergent thinking to identify systemic gaps, redefine stakeholder roles, and introduce specialized professional titles, such as 'Art Director', 'Creative Consultant', and 'Editor'. Ultimately, a unified publishing framework was crafted, specifically tailored to Sri Lanka's unique socio-cultural context, integrating fields like marketing, child psychology, design, and law to elevate the quality of children's books. One major outcome was the identification of essential policy content, articulated under eight goals that encapsulate the principles and values guiding the creation and distribution of children's books. This study illustrates the transformative potential of integrated design approaches within policymaking, providing a replicable model for similar global contexts. With the public review of NPCB launched in September 2024, this initiative represents a significant milestone in embedding design into the development of national policy frameworks towards a sustainable future.

Keywords: *Action Research; Children's Books; Design Thinking; Policy Development; Publishing Ecosystem*

1. INTRODUCTION

Developing national policies, performing research, and creating detailed guidelines are essential for enabling developing countries to address developmental challenges—such as poverty, inequality, and lack of access to education according to United Nations International Children's Emergency Fund and United Nations Children's Fund (United Nations Educational, Scientific and Cultural Organization, 2009; Wagner, 2014; World Bank, United Nations Educational, Scientific and Cultural Organization, & United Nations Children's Fund, 2021). However, sustainability often eludes these initiatives due to fragmented approaches within national book ecosystems (Altbach, 1993; Garzon, 2005; Jacobs, 1998; Hallewell, 1992). Countries like Sri Lanka face significant economic

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constraints that hinder the establishment and growth of robust publishing industries, which are further exacerbated by a limited market size, underdeveloped commercial infrastructure, and linguistic diversity (Garzon, 2005). Sri Lanka's challenges reflect broader trends in the Global South. For instance, South Africa experienced brief periods of publishing growth in the mid-20th century but did not achieve sustained success. Similarly, in Brazil, figures such as Juracy Feitosa Rocha attempted systemic change (Altbach, 1993), yet such initiatives often remained isolated. Economic instability, insufficient state planning, and inadequate cultural production channels consistently obstruct sustainable publishing industry development (Garzon, 2005).

Despite its adult literacy rate of 92.4%, Sri Lanka's local publishing industry faces compounded challenges, including inconsistent and fragmented policy efforts. As a developing country ranked 73rd on the Human Development Index, Sri Lanka also faces significant economic constraints (Knoema, 2024) that hinder sustainable book publishing efforts, despite its adult literacy rate having steadily increased from 2001 to 2021. Historical initiatives, such as the establishment of the 'Book Trust' in the 1960s under the Ministry of Cultural Affairs, failed to achieve their full potential and were eventually abolished by government authorities. Furthermore, UNESCO's global efforts between 1966 and 1972, through a series of regional meetings focused on book development, underscored the critical need for books—termed "book hunger", highlighting their importance for literacy and as essential tools for educational, scientific, technological, and socio-economic advancement. As a result, the meetings recommended the establishment of National Libraries among UNESCO member countries (Barker & Escarpit, 1973). Following these recommendations, the National Book Development Councils were established under the Ceylon National Library Services Board Act No. 17 of 1970 (Ceylon National Service Board Act, 1970). It was through this legislative framework that the National Library of Sri Lanka was later officially established on April 27, 1990. The Ceylon National Library Services Board was tasked with promoting library services and a reading culture across the country. Over time, this board evolved in function and structure. In 1970, it also facilitated the establishment of the Sri Lanka National Book Development Board, which focused specifically on promoting the publishing industry and book development. Later, through Act No. 51 of 1998 (National Library and Documentation Services Board Act, 1998), the original Ceylon National Library Services Board was restructured and renamed the National Library and Documentation Services Board (NLDSB). The National Library and Documentation Services Board (NLDSB), operating under the Ministry of Education, is responsible for developing and coordinating library services, documentation, and information management across Sri Lanka. Since 1984, the NLDSB has managed the Publication Assistance Project, aiming to support authors and enhance the quality of local publications (National Library of Sri Lanka, n.d.). Meanwhile, the Sri Lanka National Book Development Board was re-established in 2018, aiming to revive and consolidate efforts to support national book development, publishing standards, and stakeholder coordination. However, in 2022, the Sri Lankan government formally dissolved the National Book Development Council, citing concerns over its performance and aligning the decision with a broader national agenda to streamline and restructure state institutions, following a cabinet directive (Ministry of Education, 2022). This move reflected persistent political challenges in maintaining a cohesive and sustainable national book development policy framework.

Despite these structural shifts, Sri Lanka has witnessed consistent yet isolated progress in publishing-related efforts. Notable contributions have come from the National Library of Sri Lanka, which has published several guidelines and handbooks. Among these include the handbook titled *"Methodology of Children's Book Composition: A Pilot's Guide to the Layout of the Front Pages, Table of Contents, and Back Pages of a Children's Book"* (Gunathilake & Bopitiya, 2018). Another key initiative was a national research project conducted in collaboration with the School Library Development Branch of the Ministry of Education, titled *"Evaluation of Children's Literature"* (Ministry of Education, 2019). These efforts highlight the relevance of individual stakeholder contributions, although they often function in silos without coordinated alignment.

Similarly, Room to Read – Sri Lanka, an international non-governmental organization (INGO) working in partnership with the Ministry of Education, has made significant contributions to children's literacy through its extensive programmes. These include the publication of high-quality children's books and capacity-building workshops for local writers and illustrators (Room to Read, 2014). However, due to INGO regulations, these books are not commercially sold, resulting in limited distribution and access. In higher education, institutions such as the National Institute of Library and Information Sciences (NILIS) at the University of Colombo, and the Department of Library and Information Science at the University of Kelaniya, continue to offer Library Science education that emphasizes the importance of reading, literature, and information management (University of Colombo, n.d.; University of Kelaniya, n.d.). Additionally, the University of Moratuwa offers a studio-based project on book and editorial design as part of its Bachelor of Design Degree Programme at the Department of Integrated Design, within the Media and Communication Design specialization stream (University of Moratuwa, n.d.). While undergraduates frequently develop book concepts and design prototypes, the transition to publication remains limited due to insufficient collaboration with the commercial publishing sector.

Meanwhile, the Sri Lanka Book Publishers Association plays a critical role in sustaining the industry through book production and imports. It also organizes major public events, including Sri Lanka's largest book fairs in Colombo and Kandy, helping to promote reading and generate economic benefits for all member publishers (Sri Lanka Book Publishers Association, n.d.).

Despite these diverse and meaningful initiatives, the lack of integrated collaboration among key stakeholders of the private and public sectors responsible for creation, publishing, distribution, knowledge dissemination, and review continues to hinder the growth of a cohesive national publishing ecosystem. Most critically, these efforts often overlook the most important stakeholder: the child reader, whose needs and perspectives should be at the heart of every publishing initiative. Therefore, the aim of this research is to develop the content and structure of Sri Lanka's National Policy for Children's Books (NPCB) through a design-led, action research methodology, in order to address systemic fragmentation in the children's publishing ecosystem and create a sustainable, inclusive, and child-centred policy framework.

2. BACKGROUND: NCCB AND THE DESIGN-DRIVEN POLICY APPROACH

In response to the recognized lack of collaboration within the Sri Lankan publishing industry, the National Consortium for Children's Books (NCCB) was established in 2023 with discussion that began in 2022 with the above-mentioned and many other members representing the children's book publishing ecosystem of Sri Lanka (Ministry of Education, 2022; National Consortium for Children's Books [NCCB], 2023). The NCCB is spearheaded by the Educational Publication Advisory Board of the Ministry of Education with Room to Read (RtR), Sri Lanka, which supports children's literature through extensive global experience. Leveraging their expertise and funding support, the NCCB incorporates key stakeholders from various institutions including the National Institute of Education (NIE), the National Library and Documentation Services Board (NLDSB), the Primary Education Branch of the Ministry of Education, and members representing state universities involved in relation to the book publishing ecosystem-University of Colombo, University of Kelaniya University and University of Moratuwa.

The NCCB was established with the aim of enhancing the quality and global competitiveness of Sri Lanka's children's literature by addressing long-standing fragmentation in the sector. A central outcome of this collaborative effort was the formulation of the National Policy for Children's Books (NPCB), which focused on its most essential stakeholder: the child reader.

To formulate the required content for the National Policy for Children's Books (NPCB), it was essential to identify root causes and systemic gaps within the publishing ecosystem, while prioritizing the needs of child readers. To achieve this, the appointed Editor-in-Chief of the NPCB—who is also the author of this paper—collaborated in a series of workshops using both divergent and convergent thinking techniques. These workshops involved discussions, focus group activities, mapping exercises, and iterative content drafting. Initiated in July 2023, these activities are still ongoing. However, this paper focuses specifically on the process leading up to the public review of the NPCB, launched in September 2024 (National Consortium for Children's Books, 2024; Presidential Media Division, 2024; Onlanka News, 2024). Drawing on her background as a design educator and member of the NCCB, the Editor-in-Chief approaches the identification and development of policy content as a 'design problem.' Design is fundamentally understood as a problem-solving activity, encompassing cognitive processes such as creativity, iteration, and analogy (Meslec, Graff, & Clark, 2020; Wiltschnig, Christensen, & Ball, 2013). Accordingly, this paper frames the development of NPCB content as a response to an authentic human need, shaped through innovative, interdisciplinary, and adaptive design approaches. As Victor Papanek asserted in Design for the Real World, design must serve as a highly creative, cross-disciplinary tool capable of addressing genuine human needs effectively (Amir, 2004).

3. METHODOLOGY: A DESIGN THINKING FRAMEWORK

Design emerges as a critical tool for bridging theory and practice (Holmström, Ketokivi, & Hameri, 2009; Nijhawan, 2017). Often described as both a verb and a noun, design encompasses the processes of planning, creating, and adapting means to achieve specific ends (Buchanan, 2001). This dual nature underscores design's problem-solving, creative,

and cognitive dimensions, making it an ideal approach for addressing systemic challenges in policy-making (Amir, 2004; Cross, 2001). In this study, the aim was to identify and develop policy content framed as a 'design problem' within the fragmented children's book publishing ecosystem, placing the child as the key stakeholder and end-user.

To solve the defined 'design problem'—which also served as the core research question—a series of three residential programmes and a pilot training initiative in children's book creation (focused on picture books) were conducted from July 2023 to August 2024. These initiatives began with a series of workshops aimed at identifying and defining the problem, followed by the development and delivery of practical solutions. The overall design application was implemented through five iterative action research cycles. Each cycle served a distinct purpose: (1) Identify and Review, (2) Formulate and Clarify, (3) Define, (4) Map, and (5) Establish (see Figure 1 for an overview of the five cycles of action research). These phases align with the foundational structure of action research—identifying a problem, planning, taking action, observing outcomes, and reflecting for improvement (Kemmis & McTaggart, 1988; Reason & Bradbury, 2008). However, this research reframed those steps through a design thinking lens, aligning each cycle with the needs of the children's publishing ecosystem and the developmental focus of the policy.

4. THE ITERATIVE PROCESS OF THE FIVE ACTION RESEARCH CYCLES

The five action research cycles were conducted as iterative, participatory inquiries, each structured around the core phases of planning, acting, observing, and reflecting. This cyclical framework allowed the research to remain responsive and grounded in stakeholder input.

4.1 CYCLE 01

Focused on identifying and reviewing existing content relevant to the development of the NPCB. This involved a literature review conducted by two working groups: Group 1 focused on the author, editor, and content development perspective, while Group 2 examined illustration and design aspects of children's books.

The outcome of this stage resulted in two distinct presentations. Group 1 systematically structured the content and outlined key aspects for inclusion in the policy, such as the definition of a child, book types and genres, social and cultural context, forms of editing, knowledge of literature, specifics related to Sri Lanka (including the Sinhala and Tamil communities), language use, and more. Meanwhile, Group 2 highlighted gaps in the literature on aspects like remuneration, illustration styles, the need for specialized editors focusing on visual and narrative elements, the necessity of a standardized or fair payment plan, agreements between publishers and authors, inclusivity of gender and culture, involvement of various stakeholders, and the requirements of children as the end users of the books (Education Publication Advisory Board & Ministry of Education, 2023).

Overall, this stage identified a wide range of content to be included in the policy and recognized the undocumented nature of stakeholder roles and publishing practices in Sri Lanka's children's book ecosystem. This insightful discovery necessitated the next approach.

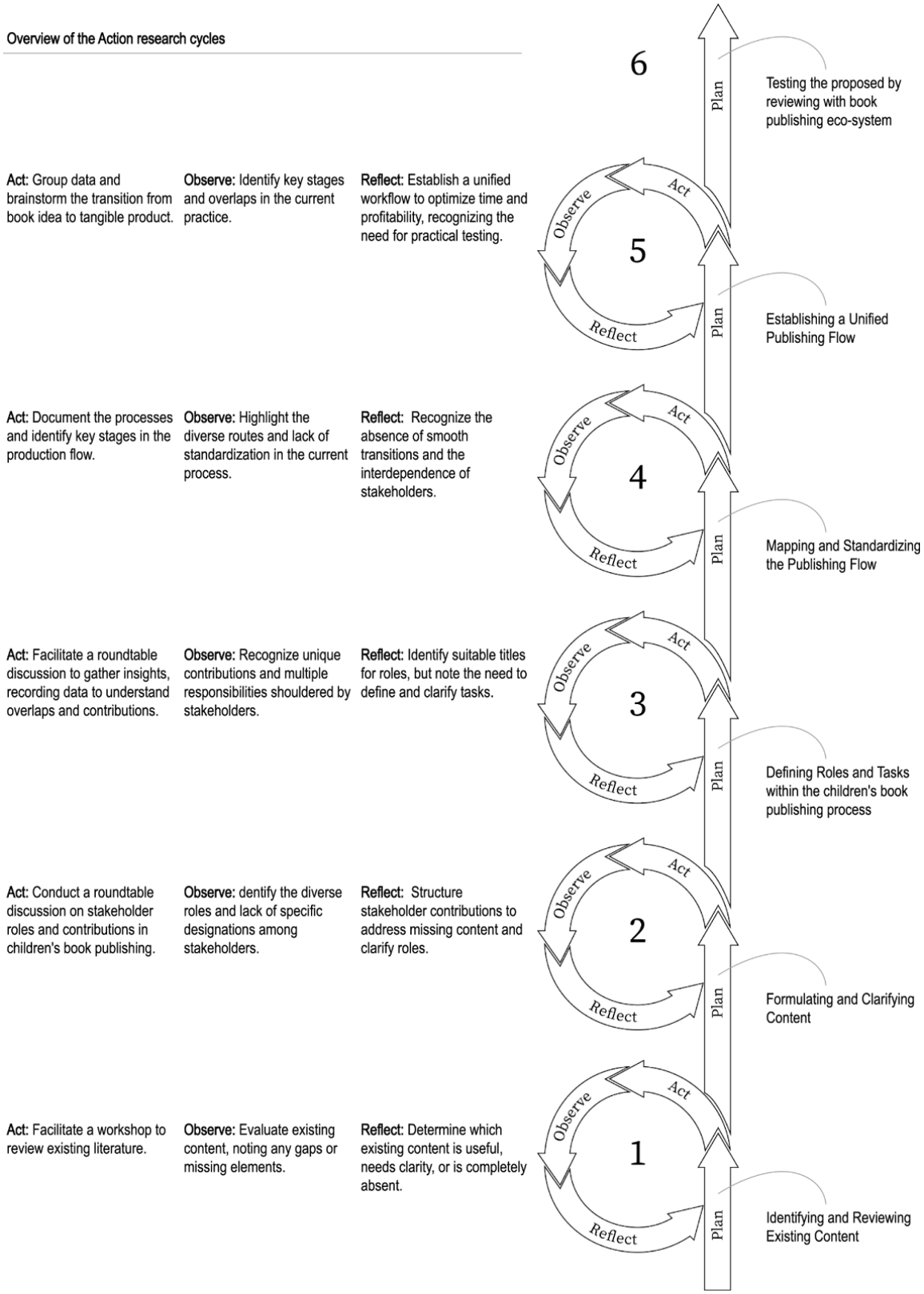


Figure 1. Overview of the five action research cycles

4.2 CYCLE 2

Focused on clarifying missing data and structuring the previously undocumented elements. It sought to define the roles and contributions of stakeholders within current publishing practices. This cycle was conducted through a roundtable discussion, where participants articulated their tasks, responsibilities, and professional designations within the publishing process. The session featured a diverse range of contributors, including writers, illustrators, language editors, translators, educators, policymakers, publishers, readers, and critics, who shared valuable insights from both local and international experiences.

Participants compared their roles and reflected on overlapping functions in the book production process. A key finding during this stage was the absence of formal education or training programmes in children's publishing in Sri Lanka. The discussions revealed that most professionals in the sector are self-taught, leading to varying skill levels and informal role definitions. For instance, after an illustrator completes their work, files are passed to individuals with titles such as typesetter, layout artist, digital designer, or simply designer, despite differing technical responsibilities. These individuals may be part of a publishing house, a print bureau, or freelance networks (Education Publication Advisory Board & Ministry of Education, 2023).

This stage confirmed the existence of pivotal yet inconsistently named roles in the children's book publishing process. It highlighted the urgent need for formal recognition of professional designations and clearer task descriptions aligned with global standards.

4.3 CYCLE 3

Focused on defining roles and tasks within the children's book publishing process. This stage included a round-table discussion to gather insights and document data, with the aim of clarifying designations and determining appropriate titles for individuals contributing to the publishing journey. Key questions addressed during the session included: What is each participant's role? What professional title do they hold? What is the equivalent international title? What specific tasks do they undertake, especially when fulfilling multiple roles?

The findings revealed that most stakeholders perform several duties across different stages of the publishing process. For example, a publisher might play a central role in the book launch phase but have limited involvement during the creation stage. Similarly, an illustrator proficient in design software may also function as a typesetter during both the creation and production phases. Furthermore, roles such as 'language editor' and 'translator' frequently overlap with other responsibilities due to the lack of formally trained professionals and the prevalence of self-taught individuals in the industry. This multitasking often results in higher compensation for individuals and reduced labour costs for publishers (Education Publication Advisory Board & Ministry of Education, 2023).

As part of this cycle, efforts were made to align locally used titles with international standards. For instance, the role commonly referred to as 'designer' in the Sri Lankan context was mapped to international designations such as 'art director,' 'book editor,' 'book designer,' or 'editorial designer'. Conversely, individuals primarily focused on layout and print production were more accurately described as 'typesetters,' although the broader label 'designer' remains widely used. The discussions highlighted the flexible and sometimes ambiguous use of these titles, emphasizing the need to formalize and

distinguish professional designations, especially in the absence of a regulatory framework in the Sri Lankan publishing sector.

The discussion led to the classification of existing roles and the recommendation to introduce new titles while phasing out those that no longer align with international best practices. For instance, the title 'designer' was proposed to be redefined as 'art director'—a new designation in the Sri Lankan context—while the current use of 'designer' was recommended to be replaced with 'typesetter' to avoid misinterpretation. The finalized list of titles was considered representative of the key stakeholder roles in the Sri Lankan publishing industry. In cases where responsibilities remained unclear, the stakeholder's title was noted for further review.

This cycle identified approximately 15 stakeholder titles and underscored the need to formalize and expand professional designations to address current gaps in practice. It emphasized the importance of clearly articulating each stakeholder's roles and responsibilities within the publishing journey, laying the groundwork for the next stage of the research (Education Publication Advisory Board & Ministry of Education, 2023).

4.4 CYCLE 4

Focused on mapping the actual publishing routes followed by the stakeholders identified in the previous cycle. A large whiteboard served as the primary visual tool, featuring a sketch of a human stick figure on the far left to represent stakeholders, and a series of illustrated children's books on the far right to symbolize the diversity of existing and potential genres and formats. Participants were asked to envision themselves as the stick figure and narrate their journey toward creating a published children's book.

Data were gathered through both individual reflection and collaborative discussion. Participants described their journey from ideation to final product, highlighting key stages where multiple stakeholders collaborate to achieve shared outcomes. For instance, during the printing phase, although each stakeholder is responsible for a different task, their collective objective remains the same: to deliver a complete, high-quality book.

Through this collaborative mapping process, 16 key stages in the existing publishing workflow were identified. However, it became evident that many of these stages involved overlapping responsibilities (Education Publication Advisory Board & Ministry of Education, 2023). For example, after the initial stages of ideation, plot development, and story sketching, some authors approached publishers directly, while others collaborated with illustrators first. These variations revealed inconsistencies, inefficiencies, and redundancies within the current system.

As a result, this cycle highlighted the urgent need to reduce overlaps and streamline the publishing process by clearly identifying, naming, and sequencing the key stages of children's book production in Sri Lanka.

4.5 CYCLE 5

Focused on establishing a unified, linear workflow that all stakeholders could adopt—thereby optimizing time, improving collaboration, and enhancing profitability. The previous cycle had confirmed that stakeholders within Sri Lanka's children's publishing industry follow different, often fragmented, routes to produce a published book. To address this, the workshop coordinator—who is also the author of this paper—introduced

the concept of transitioning from an intangible product (a book idea) to a tangible, market-ready publication.

All previously mapped and divergent publishing paths were consolidated into a coherent linear process with the active participation of workshop attendees at the third residential programme. A brainstorming session was conducted, during which the five stages of the Stanford Design Thinking method were restructured and expanded into eight clearly defined stages. Each stage was paired with a guiding question to ensure clarity of purpose and to align stakeholder responsibilities. Particular attention was paid to clarifying roles for individuals handling multiple responsibilities (Education Publication Advisory Board & Ministry of Education, 2023).

For example, if an individual functioned as both publisher and printer, this framework enabled them to differentiate their tasks within each stage. In cases where roles such as 'art editor' were previously undefined in the Sri Lankan context, this process also outlined necessary responsibilities and highlighted opportunities for training and professional development.

The outcome of this cycle was the formulation of an eight-stage linear publishing model, ranging from ideation to impact. (1) The Ideation Stage focused on identifying the initial inspiration and exploring the intangible concept of a children's book (What sparked the creation of this book, and how will it fulfil the needs of its audience?). (2) The Refining Stage emphasized evaluating and refining the idea based on child-focused and market considerations (How will the book be developed to align with children's needs and preferences?). (3) Empathizing with Stakeholders involves clarifying the roles and contributions of all participants in the publishing process (Who will be involved, and what additional expertise is required?). (4) The Prototyping and Production Readiness stage centred on finalizing content, illustrations, and administrative requirements (What steps are needed to make the book production-ready?). (5) Empathizing and Testing ensured the book met audience and stakeholder expectations through final feedback loops (What adjustments are necessary before printing?). (6) The Finishing Stage addressed final production checks and market preparation (Are all aspects finalized and have stakeholder concerns been addressed?). (7) Launching and Promotional Efforts planned the introduction of the book to its audience (How will the book reach children, and what promotional strategies are planned?). Finally, (8) Scaling and Impact ensured the book's broader reach. They assessed its effect on children's reading experiences (What impact does the book have, and how is it sustained within educational ecosystems?) (National Consortium for Children's Books, 2024; Presidential Media Division, 2024; Onlanka News, 2024).

The structure of this research aligns with the Double Diamond framework, which outlines a design process through phases of divergent and convergent thinking. The first diamond—composed of Cycles 1 and 2—focused on discovering and defining the policy problem through participatory exploration and clarification of stakeholder perspectives. The second diamond—encompassing Cycles 3 to 5—emphasized the development and delivery of a coherent policy solution, culminating in a unified publishing framework. The visual model below (Figure 2) illustrates how these five action research cycles map onto the Double Diamond process, demonstrating the transformation of fragmented publishing practices into a structured national policy framework.

This stage concluded with the confirmation of a finalized linear production flow, offering a replicable model for the Sri Lankan publishing industry. It also marked the transition to a critical next step: identifying and articulating the scope of the policy across four key areas— (1) Producing Quality Books Over Quantity, (2) Understanding the Child Reader's Psychology and Development, (3) Standardizing the Publishing Process, and (4) Defining Roles and Responsibilities of Stakeholders. These thematic areas were then expanded into eight clearly defined goals, which collectively serve as the foundation for formulating the mission and vision of the National Policy for Children's Books (NPCB).

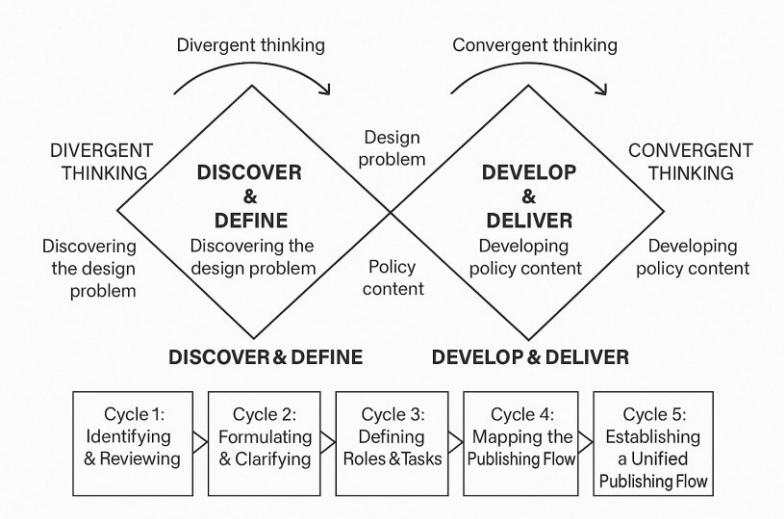


Figure 2. Mapping the five action research cycles to the double diamond framework

5. DISCUSSION

The formulation of the NPCB content was grounded in a design-led methodology, which unfolded through five iterative action research cycles. Each cycle served as both an exploratory mechanism and a diagnostic tool to respond to the fragmented publishing ecosystem, but also as a diagnostic tool, highlighting challenges that demanded policy-level interventions.

Table 1 summarizes the five action research cycles and how each contributed to the scope, goals, and vision of the National Policy for Children's Books (NPCB). Rather than emerging from abstract or predetermined frameworks, the policy goals were developed organically from the issues identified within each action cycle. This ensured that the goals addressed practical publishing gaps and stakeholder needs, while remaining anchored in the developmental requirements of the child, the primary user.

Cycle 1, Identifying and Reviewing Content, revealed a lack of cohesive content frameworks and underscored the scarcity of child-focused, culturally relevant, and developmentally appropriate materials. For instance, while some existing books promoted literacy, they lacked systematic attention to genre, age appropriateness, and Sri Lankan socio-cultural identity. These insights directly contributed to the articulation of the goals: Enhancing Quality and Accessibility and Supporting Child Development. The need to shift from quantity to quality, and to ground publishing decisions in developmental psychology (e.g., Piaget's stages), also emerged from this cycle.

Cycle 2, Formulating and Clarifying Stakeholder Roles, uncovered blurred and overlapping professional responsibilities. This ambiguity highlighted the need for a goal focused on building a Collaborative Ecosystem and another aimed at Promoting Inclusivity and Equity. The process of clearly defining roles, while advocating for the equitable inclusion of both formally trained and self-taught professionals, responded directly to these structural gaps.

Table 1: Summary of action research cycles and their contribution to policy scope, goals, and vision

Cycle	Purpose	Contributed to Policy Scope	Related Policy Goals	Link to NPCB Vision
Cycle 1: **Identify and Review**	Identified gaps in child-focused content, literature standards, and Sri Lankan socio-cultural representation.	Understanding the Child Reader's Psychology and Development	Enhancing Quality and Accessibility; Supporting Child Development	Rooting content in child development needs
Cycle 2: **Formulate and Clarify**	Clarified stakeholder roles and contributions; addressed informal and overlapping responsibilities.	Defining Roles and Responsibilities of Stakeholders	Building a Collaborative Ecosystem; Promoting Inclusivity and Equity	Equitably involving all contributors
Cycle 3: **Define**	Classified professional titles and aligned local roles with international standards.	Aligning Roles and Standards with Global Practices	Aligning with Global Standards; Positioning Sri Lanka as a Global Contributor	Elevating professional standards for global relevance
Cycle 4: **Map**	Mapped fragmented publishing flows and identified inconsistencies across stakeholder pathways.	Standardizing the Publishing Process	Sustainable Publishing Practices; Encouraging Lifelong Reading	Creating streamlined, repeatable production workflows
Cycle 5: **Establish**	Developed and finalized a unified eight-stage publishing model with guiding questions and standardized processes.	Producing Quality Books Over Quantity	All eight goals synthesized and finalized	Translating findings into a visionary, actionable policy framework

Cycle 3, Defining Roles and Tasks marked a turning point in role classification. Through guided questions such as "What is your professional title?" and "Which international title aligns with your role?"—participants revealed the absence of recognized professional

standards. For example, individuals referred to as "designers" were often functioning solely as typesetters or layout artists, which diverged from global norms. These revelations informed the goals of Aligning with Global Standards and Positioning Sri Lanka as a Global Contributor. This cycle underscored the value of international benchmarking to elevate the global standing of Sri Lankan literature.

Cycle 4, Mapping the Publishing Flow, exposed redundancies, bypassed stages, and inconsistent workflows. For example, some authors skipped editorial reviews entirely or proceeded directly to print with unstructured manuscripts. These inefficiencies indicated a lack of standardized publishing procedures. As a result, the policy introduced goals related to Sustainable Publishing Practices and Encouraging Lifelong Reading. By formalizing the publishing process, the policy aimed not only to ensure quality but also to support a child's continuous engagement with books from ideation to access.

Cycle 5, Establishing a Unified Publishing Flow and Finalizing Policy Content synthesized the findings of all previous cycles and culminated in the development of an eight-stage linear production model—from ideation to impact. Each stage incorporated a guiding question to provide stakeholders with a clear purpose aligned with policy objectives. This model served as the operational backbone of the NPCB, supporting all eight policy goals, including sustainable systems, equitable distribution, and global competitiveness. Importantly, the conclusion of this cycle initiated the formal articulation of the NPCB's vision, mission, and strategic goals.

6. CONCLUSION

The five cycles were more than research phases, they were diagnostic, iterative, and participatory processes that applied the core tenets of design thinking. Divergent thinking facilitated the identification of multiple perspectives and overlooked problems; convergent thinking enabled the structuring of these insights into actionable solutions.

By reframing systemic publishing challenges as "design problems," the policy development process became deeply grounded in real needs rather than assumptions. Each cycle acted as a mirror, reflecting the industry's current state, and as a compass, directing the course of reform. The outcome the NPCB's vision and eight strategic goals—is a direct response to these findings, grounded in reality.

This approach demonstrates how design thinking, when embedded into national policy-making, can lead to practical, inclusive, and adaptive frameworks. It offers a replicable model not only for other cultural sectors in Sri Lanka but also for global contexts where design, education, and policy intersect.

With the public review of the National Policy for Children's Books launched in September 2024 (National Consortium for Children's Books, 2024; Presidential Media Division, 2024; Onlanka News, 2024), this initiative marks a significant milestone in embedding design into the development of national policy frameworks. It reflects a forward-thinking commitment to creating a sustainable, collaborative, and child-centered publishing ecosystem—one that serves both current educational needs and the aspirations of future generations.

As this iterative process continues to unfold, the feedback gathered through public consultations and focused group discussions with relevant authorities will further refine and strengthen the policy. Thereafter, the NPCB is on course to be presented for Cabinet

approval, positioning it as a model for policy development through inclusive, design-led innovation.

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COPING STRATEGIES ADOPTED BY INHABITANTS WITH ASBESTOS CEMENT ROOF HOUSES IN SOUTH AFRICAN LEGACY TOWNSHIP

Nonhlanhla Maphoso[1] and Christopher Amoah[2]

ABSTRACT

The apartheid regime's housing development policy, whereby asbestos was used in roofing these houses, still exists in several towns in South Africa. One such community is Phomolong, where several houses are still roofed with dilapidated asbestos, posing a threat to households living in these houses. The study aimed to ascertain the coping strategies adopted by the inhabitants to navigate the challenges posed by the asbestos-cement roofing in Phomolong. A qualitative research approach was adopted to interview inhabitants living in asbestos-cement-roofed houses in Phomolong via face-to-face interviews with a structured interview guide. The interviews were recorded, transcribed and analysed using a thematic content analysis approach to identify main and sub-themes. The findings show that Phomolong inhabitants with asbestos-cement roofed houses experience several challenges. In coping with these challenges, inhabitants adopt strategies including placing materials such as tyres and rocks on roofs, sealing and painting roofs inside, placing buckets when it rains, and using binding wire on walls to hold roofing, among others. Due to the post-apartheid government's slow pace in replacing asbestos-cement roofing from legacy houses, inhabitants continue to experience hardships, forcing them to adopt an unconventional strategy to survive living in these houses. This situation, therefore, leaves them exposed to dangers associated with asbestos, posing further health risks to the community. The study contributes to the growing academic knowledge of challenges related to asbestos-containing material (ACMs) in non-occupational settings. It has outlined the lived experiences of a legacy township's inhabitants in South Africa, challenges and strategies they used to contain them, thereby making their plight further known to the government for possible intervention.

Keywords: *Asbestos; Cement Roof; Coping Strategies; Houses; Legacy Townships; South Africa.*

1. INTRODUCTION

South Africa's asbestos cement roofs have come into the spotlight with media coverage of the State Capture Commission's report. As a result, there has been public fear regarding the possible impacts of asbestos cement roofs in non-occupational settings (Gibson et al.,

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2021). Communities will continue to live with these asbestos cement roofs for decades before removing them completely, making it essential for academia to bring attention to the challenges associated with them (Gibson et al., 2021). This study investigates the challenges that inhabitants face in asbestos-cement roofed houses in a South African legacy township of Phomolong. Some previous studies believe there is no scientific proof outlining the exposure threshold free from asbestos; as such, all forms of asbestos are carcinogenic (Frank & Joshi, 2014). Additionally, Kottek and Yuen (2021, p.158) state that "the measurability or non-measurability of risk does not indicate the public health significance of the risk". This means that epidemiology has limited ability regarding the measurability of people living or working around Asbestos-Containing Materials (ACMs); such communities living with these materials cannot be ruled out of risk.

The traditional perspective that does not see ACMs as a risk argues that asbestos bound to some bonding agent, such as cement, posed no danger. However, there is growing evidence that this is not the case, as these ACMs age and can get damaged (Ervik et al., 2021). ACMs can be regarded as materials that create an ongoing risk of asbestos exposure. This could result from renovations, damage, replacement, weathering or natural disasters (Kottek & Yuen, 2021). In support of this statement, Oberta et al. (2018) illustrated that uncoated asbestos fibres get released. Similarly, Ervik et al. (2021) found that asbestos cement roof weathering in the layer of loosely bound fibres on the surface occurs.

According to the National Institute for Communicable Diseases of South Africa (NICD) (2010), reporting on a study conducted by Phillips et al. (2009) states that the presence of asbestos cement roofs on houses that were built over 50 years ago presented a concern. This provides more evidence than what had initially been erroneously found in previous studies. Phillips et al. (2009), using 61 households, provided evidence that asbestos was present in the soil around all these houses. It was proven that weathering of asbestos cement roofs around these houses had occurred and resulted in the leaching of asbestos.

Considering the findings by Phillips et al. (2009), it can be suggested that all asbestos exposure should be regarded as a risk. Thus, the presence of asbestos cement roofs in Phomolong poses risks for the residents. According to Bates (2020), asbestos abatement continues to be slow in the Free State province; thus, the effects of these asbestos cement roofs on the residents should indicate the sense of urgency for their removal, especially those damaged. Additionally, some households scheduled for the asbestos removal project in the Free State are uninformed of the dangers of damaged asbestos cement roofs (Felix, 2021). Despite these ascertions, past studies have not significantly dealt with how inhabitants staying in these houses manage to navigate the challenges posed by these dilapidated asbestos-roofed houses. For instance, Bates (2020) focused on the corrupt activities associated with the asbestos roof removal in the Free State, whilst Cilia et al. (2025) focused on the weathering aspects of the asbestos roof. Likewise, Gibson et al. (2021) and Kottek and Yuen (2021) focused on the health aspects of asbestos cement roofs on inhabitants. As such, it is necessary to identify how the residents of Phomolong are coping with the challenges posed by the dilapidated asbestos roofing and make it known to the policy implementers.

2. LITERATURE REVIEW

2.1 ASBESTOS CONCEPT

According to Hart (1988), the term asbestos has a Greek origin and stands for an "inextinguishable flame". Asbestos refers to a group of fibrous silicate minerals (Cilia, et al., 2025). These naturally occurring minerals are broadly grouped into two types, namely, amphiboles and serpentines. When assessed microscopically, one key differentiating characteristic is that straight needle-shaped fibres characterise the amphibious group, while the serpentine group has spiral fibres (Frank & Joshi, 2014; Hart, 1988).

The amphiboles group consists of amosite, crocidolite, tremolite, anthophyllite, and actinolite, respectively, commonly referred to as brown-, blue-, grey-, yellow-, and green-asbestos. In contrast, serpentines mainly consist of only one type of asbestos, named chrysotile, commonly known as white. Only the amosite, chrysotile and crocidolite were mined in South Africa (Hart, 1988). Globally and in South Africa, the commonly found asbestos type used in producing ACMs (such as asbestos cement roofs) is chrysotile (Frank & Joshi, 2014). The popularity of using ACMs in construction was attributed to the asbestos mineral characteristics: impeccable heat resistance, durability and somewhat weatherproof (Ervik et al., 2021). Additionally, the low-cost factor that these products offered made them a common choice. There are over 3000 products in which asbestos has been used (Subramanian & Madhavan, 2005). These products were used in construction and industries such as power engineering, transport, and textiles (Szymanska & Lewandowska, 2019).

2.2 ACM MANAGEMENT AND REMOVAL CHALLENGES

Studies documenting asbestos cement roof weathering specifically can be traced back to the 1980s (Spurny, 1989). According to a Polish study by Szymanska and Lewandowska (2019), several challenges can arise during the disposal of asbestos or ACMs. The first is that the co-financing mechanisms to facilitate removal projects can have slow implementation. Secondly, they do not have a complete inventory list of existing ACMs and locations. This can result in incomplete information for proper management and removal project planning. The third is that in cases where government interventions are not in place, not all communities have prepared or have the means to organise their ACM removal projects. As such, they continue living with them (even when damaged). The last challenge is that society may have a high number of people with little awareness of the harmful effects of asbestos waste on human health or how to properly handle the removal of such material to minimise atmospheric dispersion of the asbestos fibres.

In Africa, where several countries are dealing with ACMs installed over fifty years ago, are now presenting a problem of hazardous waste management and have been associated with other varied problems (Gebremedhin et al., 2018). According to Lacourt et al. (2013), irrespective of the considerable academic interest in studies related to exposure to asbestos, be it directly or indirectly or the aftereffects, there is still a vast number of countries that produce or use ACMs and those that use poor ACM disposal methods.

2.3 LEGISLATION RELATED TO ACMS IN SOUTH AFRICA

Nationally, the phasing out of asbestos in South Africa began in 2004 and was solidified by the approval of regulations prohibiting the use, processing, and import/export of asbestos or ACMs in 2008 under the guidance of the Environment Conservation Act of 1989. Initially, it regulated asbestos and ACMs through the Asbestos Regulation (2001), which related to the employer or self-employed person. This restricted them from doing work that may harm any person because of asbestos exposure. However, this regulation was repealed by the Asbestos Abatement Regulations (2020), which came into effect on 10th November 2020, with exceptions on two regulations (regulations 3 and 20) only coming into effect 18 months after the effective date mentioned. This change has made regulations more aligned with international standards, such as the clear labelling of asbestos waste as per United Nations (UN) Recommendations on transporting dangerous goods (Collier & Ilsley, 2020).

As per the regulations, several conditions must be met when conducting ACM removal activity. These are:

1. A registered asbestos contractor must carry out the work (types 2 and 3) with an asbestos removal certificate.
2. Before the removal, all asbestos materials that may become airborne must be identified to prevent exposure and adequate control measures must be placed.
3. The handling and disposal of the ACM must be done following Regulation 21 of the Asbestos Regulations 2020.
4. When the removal and disposal of existing asbestos roof sheets are completed, a certificate that indicates the safe disposal of the hazardous material must be produced.

Some of the differences between the old and new regulations include dividing work into three types of asbestos. Under the new regulations, only types two and three require that they be carried out by contractors registered as asbestos specialists. Additionally, now it is mandatory to conduct an asbestos inventory and risk assessment and to create a management plan for removal, repairs and phasing out (Collier & Ilsley, 2020).

3. RESEARCH METHODOLOGY

3.1 RESEARCH APPROACH

This research adopted the qualitative research approach. The quantitative research approach is regarded as objective in nature, while qualitative research is subjective. Creswell & Creswell (2017) define qualitative research as an approach that explores the understanding and meaning of a social or human problem experienced by an individual or a group. The decision on which approach to adopt mainly depends on the purpose of the study and the type of data required (Naoum, 2019). Since the study's purpose is to ascertain the lived experiences of how inhabitants with dilapidated asbestos-cement roofed houses cope, the qualitative research approach was suitable as it allowed the researcher to focus on gaining in-depth stories of the participants.

3.2 TARGET POPULATION AND SAMPLING METHODS

The population of this study consisted of the inhabitants of asbestos-cement roofed houses in the Phomolong township. The study adopted the purposive sampling method.

Purposive sampling was selected because it involves carefully selecting potential participants who could provide insight into the lived experiences of asbestos-cement roofed houses (Kumar, 2014). The participants' inclusion criteria for this study were people residing in Phomolong who had lived in asbestos-cement roofed houses for over a year and were willing to partake in the study. Thus, inhabitants residing in Phomolong but staying in houses without asbestos-cement roofs and those who have lived in asbestos-cement-roofed houses for less than a year were excluded.

3.3 DATA COLLECTION METHOD

The semi-structured interviews with participants were conducted by the researcher visiting the study site during weekends to increase the chances of finding more participants at home who have time to spare for the interviews. When entering a potential participant's house, the researcher entered with a third party accompanying them to ensure their safety and permission to conduct an interview. If granted, the researcher and participant would then conduct the interview. The third-party accompanying the researcher would wait outside to ensure the confidentiality of the participant. The interviews with the participants were conducted in Sesotho, IsiXhosa, or English, depending on the participant's preference. The interviews started with the researchers formally introducing themselves to establish rapport and explaining the purpose and other information about the study. This included asking permission to record the interview and their willingness to partake. When participants agreed, the researcher asked them to sign the consent form. The researcher recorded the interviews. Each interview took about 20 to 30 minutes to complete. To anonymise and separate the different participants, the researcher allocated each participant a unique participant number, such as P1, P2, etc. The interview guides had three parts: the participants' demographic information, the challenges they experienced and the coping strategies to overcome them. In all, 11 participants were interviewed, and although the researcher reached saturation after conducting the 10th interview.

3.2 DATA ANALYSIS

The data analysis process within the qualitative approach is when the collected data is processed by organising, analysing, and interpreting the data (Johnson & Christensen, 2019). The data collected were analysed using the thematic content analysis approach. This analysis approach was chosen as it is an analysis that allows novice researchers to better understand how qualitative data analysis is conducted, with the vast literature available. In this analysis approach, the data were reduced, displayed, and then coded to identify emerging themes and create a narrative (Johnson & Christensen, 2019). The data was processed by translating and transcribing the interviews, familiarising the researcher with the data. This was done by reading through the transcriptions, identifying the initial patterns from the transcripts, and using the initial patterns to identify the main patterns. Similar themes were then grouped into themes and sub-themes. The Excel statistical tool was then used to calculate the frequencies and percentages of the participants' demographic data and formulate the theme items.

4. FINDINGS

4.1 DEMOGRAPHIC DATA OF PARTICIPANTS

The table presents the demographic data of the participants sampled. Male participants constitute 55% males and females 45%. Most participants (91%) have lived in the house for over 5 years. Most participants (73%) indicated that the asbestos cement roofs are over 30 years old. 82% of the participants' houses are owned by the participants' late parents or grandparents. 55% of the participants reside in four-roomed houses, whilst 45% reside in three-roomed houses. The employment analysis indicated that 55% were either unemployed or studying.

Table 1: Demographic factors of participants

Demographic factors		Number of participants	Percentages
Gender profile of participants	Male	6	55%
	Female	5	45%
	Total	**11**	**100%**
Number of years as a resident in the current house	Under 5 years	1	9%
	Between 5 and 30 years	3	27%
	Over 30 years	7	64%
	Total	**11**	**100%**
The estimated number of years the current roof has been used	Under 5 years	0	0%
	Between 5 and 30 years	3	27%
	Over 30 years	8	73%
	Total	**11**	**100%**
Ownership status of houses where participants live	Owned by late parent(s)/grandparent(s)	9	82%
	Renting	2	18%
	Total	**11**	**100%**
House Size where participants live	3 rooms	5	45%
	4 rooms	6	55%
	Total	**11**	**100%**
Employment status	Unemployed	4	36%
	Self/temporarily employed	3	27%
	Employed	2	18%
	Student	2	18%
	Total	**11**	**100%**

4.2 COPING STRATEGIES

Having identified the challenges faced by the participants, such as poor living conditions inside these houses, difficulty in maintaining the asbestos roof, removal and disposal difficulties and health concerns, they asked the participants to describe navigation

strategies to overcome their challenges with asbestos-cement roofed houses. The responses to the coping strategies were analysed to determine initial patterns, coded, and grouped into the different themes, as presented in Table 2. This table indicates three strategic coping mechanisms used by the participants, namely sealing and painting roofs inside, placing materials such as tyres and rocks on roofs and other intermediate strategies such as placing buckets when it rained and binding wires on walls to hold down the roofs.

Table 2: Participants' coping strategies for asbestos cement roof challenges

Main themes	Sub-themes
Placing material on the roof	Tyres and rocks
	Replacement sheet - asbestos or corrugated iron sheets
Sealing and painting the roof inside	Sealing holes from inside
	Painting the roof inside
Other strategies	Placing buckets
	Binding wire on walls

4.2.1 Theme 1: Placing Material on the Roof

The first strategic theme mentioned by the participants is placing materials on the roof when raining and providing support to roofs on windy days. Four participants placed tyres or rocks on their asbestos cement roofs. It was established that they do this as a preventative measure to prevent their roofs from getting blown away. During site visits, the researcher also noticed that this strategy was used in different asbestos-cement roofed houses in the neighbourhood. Depicting these strategies, Figure 1, picture A, illustrates two households where the material was placed on roofs to support the roof against the wind. The comments made by participants P1 and P10 also gave directions for their reasons for putting these on the roofs.

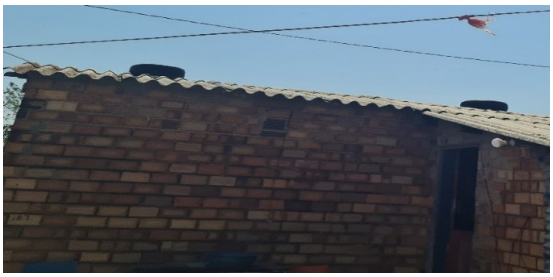
P10: *"... This is why we put tyres to secure the roofs from flying away",*

P1: *"To prevent it from going up we have placed rocks on top of roofs".*

Other participants indicated that they sourced replacement sheets of asbestos or corrugated iron sheets. They stated that the asbestos-containing cement material sheets could not be bought, so they sourced them from people who had removed their asbestos roofs. For example, P2 said the corrugated iron sheets are sourced second-hand or purchased at a building supply shop.

P2: "*If it gets a hole for example, you get another piece from someone else who has taken it out and close the space in your house"*

The sheets are replaced or placed on top/below the existing asbestos sheet. In most instances, these were installed near the chimney or where there were big holes in the sheet. For instance, Figure 1, picture B indicate houses where this strategy was used. Noticeably, they additionally place supportive material, in this case, rocks. The first image also illustrates where corrugated iron was added under the asbestos-containing roof, where the redundant chimney is located.



Picture A



Picture B

Figure 1: Pictures of an unsecured asbestos roof support against the wind

4.2.2 Theme 2: Sealing and Painting the Roof Inside

The second strategic theme discussed is sealing holes inside the roof to avoid stepping on the asbestos cement roof, which breaks easily and paints to enhance its appearance, minimise dust and temporarily make sealant stick on the roof. Eight participants stated they tried to seal holes from the inside. While most use this strategy, it is temporary and sometimes used as a minimisation strategy instead of prevention. It is a minimisation strategy because it may not completely prevent water from coming in, as the hole would still be visible from the outside. Still, it would decrease the amount of water drips into the house compared to when it is left unsealed. This strategy was seen in Figure 2, picture D, where the participants used sealants such as silver waterproof tape and multipurpose glue. This indicates its fragility, and the only condition people are willing to seal it. Some participants indicated they painted their roofs inside. They, however, had different reasons for painting them. An example is in Figure 2, picture C, where the participant painted it to make it look better.

P4: *"We paint it to get rid of the water stains".*

P11: *"After patching it, I paint it to try and keep it glued to the roof".*



Picture C: Dusty roof painted over



Picture D: Dusty roof painted over

Figure 2: Pictures of a painted asbestos roof to improve its aesthetics.

For instance, P5 indicated that it is difficult to wash the roof; thus, they painted it to improve the colour, which subsequently peeled off. Additionally, P11 stated that it becomes a bit better when you apply water paint. One participant, P7, said he had painted it a while back and would only be repainting it. His rationale for this is based on the idea that the roofs may be removed any day, and he is worried he would have wasted his money if he painted it today and it gets removed soon after.

P5: *"You see also with the paint; over time it gets removed".*

P7: "*I painted it a while back and did not after as they had said they would remove them. So, I will paint it today and tomorrow they come and remove it while I spent my money to buy the paint".*

4.2.3 Theme 3: Other Coping Strategies

Participants indicated other strategies they use besides those discussed in the previous sections. These were to place buckets where roofs leak and add binding wires on the walls to support the poles and roof during windy days. Six participants stated they place buckets inside their houses when rainwater drips to prevent their furniture from getting wet and the house from getting messy. While no images were acquired indicating the buckets being used, some participants pointed out places where water drips typically when it rains. For example, P6 pointed out the holes and suggested that they place buckets in those areas during rainfall.

P6: *"Here we have holes; we just put a bucket in most cases"*

Figure 3, picture E, illustrates some of the areas where buckets are used to collect the water from the roof during rain, as pointed out by the participants.



Picture E Picture F

Figure 3: Pictures of a leaking asbestos roof where buckets collect the water during rainfall, and binding wires are installed to the external walls to hold the roof structure.

The other strategy for the participants' houses was to install binding wires around the external walls attached to the roofing poles. Four participants stated this strategy, and the researcher observed this during the site visits. For instance, P1, in explaining why they had installed these, noted that the father installed the binding wires.

P1: *"My dad before he passed added binding wires to hold the poles down - this has been an issue for ages now".*

Figure 3, picture F, illustrate different participants' houses where this strategy was observed.

5. DISCUSSION

The inhabitants of asbestos-cement roofed houses used six coping strategies in Phomolong; none of these were cited in academic literature. The identified coping strategies were used to minimise the challenges related to dust, wind, rain, and physical damage to roof sheets. This study did not identify the coping strategies that Obminski (2022) posited, such as having good ventilation for air exchange and decreasing the concentration of asbestos dust inside a building. The physical conditions and limited finances may have limited this strategy's use. For example, changing the standard windows to add bigger ones would require the participants to have money to buy the

windows and get them fitted. Additionally, observed cracks on the structural walls could be another limiting factor in why this strategy is not used there. Gibson et al. (2021) state that communities have and will continue to live with asbestos cement roofs for decades. The findings of this study support and provide evidence for this notion. It was observed that most participants (64%) have lived in these houses for over thirty years and recall these houses being older than that. Additionally, considering the challenges identified, inhabitants of asbestos-cement roofed houses in Phomolong have been forced to adopt coping strategies. Kottek and Yuen (2021) state that although asbestos removal is ongoing, inhabitants devise several means of dealing with the current challenges. These coping strategies are used to minimise the challenges related to dust, wind, rain, and physical damage to roof sheets. Bonifazi et al. (2018) suggest that, because of the status of many asbestos roof houses, serious intentions must be made by the authorities to address the inhabitants' challenges. Gil et al. (2024) identified that many asbestos roof covering conditions were hazardous to the inhabitants; they used several means to contain the dilapidated state. This, they indicate, was a great concern for the community. Likewise, Martínez et al. (2024) identified that several people's strategies for controlling their asbestos roofs were insufficient; they proposed that authorities identify the state of the various roofs and develop prioritised intervention strategies to mitigate the problem. In support of this, Saba et al. (2024) posit that roofing materials also play a significant role, with thermoacoustic roofs reducing emissions compared to asbestos cement roofs. These concerns confirm the findings of this study, where people need an urgent intervention from the government to address their concerns about the asbestos roof. Authorities must ensure that replacing asbestos cement roofs with the urgency it deserves to address inefficient practices adopted by the inhabitants, which more often pose a health risk to them.

6. IMPLICATION OF THE FINDINGS

The findings show that the government policy on removing asbestos cement roof houses in legacy townships, like the case study town in South Africa, has failed to achieve its goal. Thus, posing a health-related risk to the inhabitants of these houses and the communities at large. The study also identified during the site visit that many community members are still using asbestos to construct informal houses and fences around their houses, oblivious of the danger it poses to their health. This calls for the government to intensify the public health education within these communities and address the elimination of asbestos roof policy with more urgency.

7. CONCLUSION AND RECOMMENDATION

Over a decade ago, the South African government embarked on a programme to remove asbestos roofing from all the legacy township houses. However, this attempt has not been materialised, with many houses in rural areas having dilapidated asbestos roofs posing danger and maintenance challenges to the inhabitants. Considering the environmental risk to society and communities, this asbestos roof removal must be done. As such, these inhabitants cannot remove them unless the government agency responsible for this task executes the removal in compliance with the environmental regulations. The study, therefore, sought to explore the lived experiences of the inhabitants of asbestos-roofed houses to bring their ordeal to policymakers so that they could revisit perhaps the asbestos removal programme abandoned over the years. The study identified many challenges the

inhabitants face, including health, poor living conditions, and maintenance issues. To overcome these challenges, they apply several strategies, including placing material on the roof, sealing and painting the roof inside and other strategies. This situation poses health risks to the inhabitants, especially during the winter and rainy seasons. The study, therefore, recommends urgent government interventions to remove these roofing materials to ensure healthy living conditions for the inhabitants. The government can also engage with private organisations to promptly facilitate the removal of roofing. The government can also engage non-governmental organisations to assist these inhabitants in removing the asbestos roof and replacing it with the appropriate roofing materials. The community councillors must agitate and draw the urgency of this asbestos roof phenomenon to the government and other municipal leaders to ensure the problem is resolved. The limitation of the study is that a case study approach for a specific setting, thus the findings may not be generalised. Future studies must examine the challenges of the government in executing the asbestos roof removal programme since its inception, which has led to several communities still having these roofs on their houses.

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CRITERIA FOR SELECTING RETROFITTING OPTIONS FOR HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS

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ABSTRACT

The heating, ventilation, and air conditioning (HVAC) systems are among the largest consumers of energy within buildings, constituting about 51% of the overall energy consumption. Thus, implementing energy retrofit measures can yield a noteworthy reduction in energy consumption of buildings. However, the process of selecting suitable energy retrofit options is complex and requires consideration of numerous different criteria. This research aims to propose a comprehensive set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. Through a thorough literature review and expert interviews with respondents selected using purposive sampling in which the collected data were analysed using manual content analysis, 35 sub-criteria that should be considered when selecting HVAC retrofitting options for commercial buildings in Sri Lanka were identified. These were categorised under 07 main criteria as Economic factors, Technical properties, Physical properties, Flexibility, Reliability, Comfortability and Environmental aspects. Thus, the findings mark the first step in developing a structured approach for evaluating and selecting HVAC retrofit options, streamlining decision-making processes, and potentially leading to more efficient and cost-effective building upgrades.

Keywords: *Commercial Buildings; Evaluation Criteria; Heating, Ventilation, and Air Conditioning (HVAC) Systems; Retrofit Options.*

1. INTRODUCTION

The construction industry significantly contributes to global energy consumption (Madushika et al., 2023). Buildings alone account for about 36% of global final energy use and nearly 40% of total direct and indirect CO_2 emissions (Y. Wang et al., 2022). Both residential and commercial buildings demand substantial energy for heating, cooling, lighting, and operating various equipment and systems (Hong et al., 2015). Therefore, building energy efficiency retrofits are considered essential for achieving energy reduction and sustainable development goals (X. Liang et al., 2015).

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The heating, ventilation, and air conditioning (HVAC) systems are among the largest consumers of energy within buildings, constituting about 47% of the overall energy consumption (Hong et al., 2015). In parallel, lighting accounts for approximately 25% of total energy usage (Dolšak, 2023). Specific components like vertical transportation, pumps, and related equipment collectively represent around 5-10% each. The cumulative effect of HVAC and lighting system energy usage typically constitutes around three-quarters of the aggregate energy demand for buildings (Y. Wang et al., 2022).

Retrofitting refers to the process of adding new technology or features to existing systems that were not present during their initial construction phase (J. Liang et al., 2018). This is particularly relevant in the context of HVAC systems in commercial buildings, where the goal is to enhance energy efficiency, reduce operational costs, and minimize maintenance expenses. This process aims to curb energy consumption and advance energy efficiency enhancements (Fasna & Gunatilake, 2019). Retrofitting projects for existing HVAC systems aim to address inefficiencies and integrate advanced technologies to enhance performance (Ligade & Razban, 2019). Common retrofit measures include upgrading to energy-efficient components, implementing advanced control strategies, and optimizing system operation through continuous monitoring and diagnostics (C. Liu et al., 2023).

The process of selecting suitable energy retrofit options is complex and requires a well-organised, step-by-step approach (Ma et al., 2012). For instance, Krajčík et al. (2023) has highlighted the need for a comprehensive retrofit evaluation encompassing economic, risk, social, environmental, and health impact assessments. However, despite the benefits of HVAC retrofitting, there is a lack of comprehensive guidelines and frameworks for implementing these projects effectively (Amanda & Sanjei, 2019). This is particularly pertinent in the context of Sri Lanka, where the commercial building sector faces unique challenges in implementing retrofit projects. Local climatic conditions, building designs, and occupancy patterns must be carefully considered to ensure the success of retrofit initiatives (De Silva & Sandanayake, 2012). Additionally, local environmental regulations and energy policies play a crucial role in shaping retrofit strategies.

Despite the recognised benefits, the process of selecting appropriate retrofit options is complex and often lacks a standardised framework, particularly in developing countries such as Sri Lanka. Hence, this research aims to propose a comprehensive set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. The findings of this study provide the basis for developing a structured decision-making framework for selecting HVAC retrofitting options for Sri Lankan commercial buildings using multi-criteria decision making.

2. LITERATURE REVIEW

2.1 ENERGY CONSUMPTION IN BUILDINGS

Heating, Ventilation, and Air Conditioning (HVAC) systems are critical components in buildings, significantly impacting their overall energy consumption (Hong et al., 2015). HVAC systems are responsible for approximately 39% of the total energy consumption in commercial buildings (Nalley & LaRose, 2022). This substantial proportion underscores the importance of HVAC systems in the broader context of building energy management. The efficiency of HVAC systems is vital not only for reducing energy consumption but also for maintaining indoor air quality and thermal comfort, which are essential for occupant health and productivity (Ma et al., 2012). Despite their importance,

many existing HVAC systems are outdated and operate inefficiently, leading to high energy usage and increased operational costs (Ligade & Razban, 2019). Additionally, maintenance costs for HVAC systems can be substantial, further adding to the operational expenses of commercial buildings (Y. Wang et al., 2022). Consequently, improving HVAC system efficiency is a critical focus area for reducing building energy consumption and associated costs.

In the Sri Lankan context as well, the energy consumption in commercial buildings is notably high, primarily due to the extensive use of HVAC systems, which can represent up to 60% of a building's total energy consumption (Kumar & Raposa, 2020). This high percentage underscores the critical need for energy-efficient retrofitting solutions to reduce energy consumption and operational costs. Urban commercial buildings in Sri Lanka rely heavily on HVAC systems for cooling and ventilation, resulting in substantial energy demands (Kumar & Raposa, 2020). By implementing energy-efficient HVAC retrofits, these buildings can achieve significant energy savings, contributing to the country's overall energy efficiency goals.

2.2 HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS

Commercial buildings are structures primarily used for business activities, including offices, retail spaces, hotels, and educational institutions (Hong et al., 2015). These buildings significantly contribute to energy consumption due to their extensive use of lighting, heating, ventilation, and air conditioning (HVAC) systems. In the Sri Lankan context, commercial buildings are typically concentrated in urban areas such as Colombo, Kandy, and Galle, where the demand for energy is high to maintain comfortable indoor environments (Sustainable Energy Authority of Sri Lanka, 2020).

Given Sri Lanka's tropical climate, air cooling systems are essential, whereas heating systems are seldom used. The country experiences high temperatures and humidity levels throughout the year, making cooling systems critical for occupant comfort. Districts such as Colombo and Gampaha, which are highly urbanized and densely populated, rely heavily on air conditioning systems to provide a comfortable indoor climate (Sustainable Energy Authority of Sri Lanka, 2020). This necessity underscores the importance of efficient HVAC systems in these regions. Retrofitting such systems can involve upgrading components to more energy-efficient models, integrating advanced control systems, and optimizing the overall system performance to reduce energy consumption (Madushika et al., 2023). This process not only enhances the efficiency but also extends the lifespan of the HVAC systems.

2.3 RETROFITTING HVAC SYSTEMS

Existing HVAC systems, particularly package units, often face numerous issues as they age. Common defects include reduced efficiency, frequent breakdowns, and increased operational costs due to wear and tear (Karunaratne & De Silva, 2019). After five years, systems typically begin to show signs of inefficiency, and by ten to fifteen years, the frequency of repairs and maintenance increases significantly, often leading to higher energy consumption and operational disruptions. Retrofitting offers a viable solution to these identified defects (Ligade & Razban, 2019).

Retrofitting involves the process of adding new technology or features to existing buildings to improve their functionality, efficiency, and sustainability (Ebrahimi et al.,

2023). Building retrofits can encompass various aspects, including structural, energy, and aesthetic improvements. Energy retrofits, a subset of retrofitting, specifically focus on enhancing the energy performance of buildings to reduce energy consumption and operational costs (Y. Liu et al., 2023).

Building retrofits are particularly important in commercial buildings, where energy consumption is significantly high due to extensive use of HVAC systems, lighting, and other equipment (Mohamed & Wang, 2020). The major advantages of retrofitting over other methods, such as complete system replacement, include cost-effectiveness and minimized disruption to building operations. Retrofitting allows for incremental improvements without the need for extensive downtime, making it a practical option for commercial buildings that cannot afford long periods of inactivity (Karunaratne & De Silva, 2019). Moreover, retrofitting enhances the sustainability of buildings by reducing energy consumption and greenhouse gas emissions, contributing to broader environmental goals.

Retrofitting in commercial buildings can lead to substantial energy savings by implementing advanced technologies and optimizing energy management systems (Hong et al., 2015). For instance, upgrading to high-efficiency HVAC systems can drastically reduce energy usage, while smart building technologies can further enhance energy efficiency by optimizing the operation of various systems within the building (C. Liu et al., 2023).

HVAC retrofitting typically encompasses several measures, including upgrading HVAC equipment, improving insulation and sealing, and implementing advanced control systems (Bird et al., 2022). Notably, these measures aim to enhance the energy performance of the building while ensuring occupant comfort. This often yields long-term benefits by reducing energy costs and carbon footprints (Ma et al., 2012). By upgrading components such as compressors, fans, and control systems, the efficiency of aging HVAC systems can be significantly improved. Additionally, retrofitting can involve implementing advanced monitoring and control systems that optimize the operation of HVAC units, thereby reducing energy consumption and enhancing performance (Madushika et al., 2023). For instance, replacing old, inefficient chillers with high-efficiency models can result in substantial energy savings and improved reliability. The process of selecting suitable energy retrofit options is complex and requires consideration of numerous criteria that may change depending on the context. Hence, there is a need to clearly identify a set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka.

3. RESEARCH METHODOLOGY

A comprehensive literature review was conducted to identify the evaluation criteria for HVAC retrofit options. The search was carried out in databases such as Science Direct, Web of Science, and Scopus, and included keywords such as “retrofit”, “energy efficiency”, “criteria”, and “evaluation”. The search was limited to the papers published in the 20 year period between 2005 and 2024. Altogether, 56 journal papers were selected for the identification of criteria through the above systematic selection process. Then, interviews with three industry experts were conducted to refine and confirm the relevance and importance of each identified criterion, ensuring that they would be grounded in practical and expert knowledge. The small sample helped to facilitate researchers’ close

association with the respondents and allowed fine-grained, in-depth interviews (each interview lasted for over 60 minutes) to be carried out on the selection criteria. Further, the selected respondents could be considered as experts in the research area possessing over 15 years of first-hand experience in HVAC retrofitting. Table 1 presents profile of the three experts interviewed.

The expert interviews were conducted as semi-structured interviews with an iterative and interactive process. The interviews were carried out in an iterative process with each expert's views been considered by the others. The first expert's decision was communicated to the second expert, facilitating a more comprehensive discussion and a refined consensus. Subsequently, during the interview with the third expert, the previous experts' opinions were presented to provide context and foster a deeper dialogue. The final decision was reached through a rigorous analysis of all three expert perspectives, coupled with a synthesis of existing knowledge from the literature. This allowed for a detailed review of the criteria and their application to the local context. Manual content analysis was used to analyse both the literature review and interview data to identify the evaluation criteria. The findings presented in this paper mark the first step in a broader research study aimed at developing a structured decision-making framework for selecting HVAC retrofitting options for Sri Lankan commercial buildings using multi-criteria decision making.

Table 1: Profile of interview respondents

Respondent	Designation	Current Sector	Experience (Years)	Qualifications		Awareness	
				Educational	Professional	HVAC	Retrofit
R1	Director (Facility Manager)	Consultant	30	M.FM, BSc. Eng	Chartered FM	Well	Well
R2	Manager (Facility Manager)	Contractor	15	BSc FM, Dip in Arb.	Chartered FM	Well	Well
R3	Manager (Engineer)	Contractor, Lecturer	33	PhD, M.Eng, BSc Eng	Chartered Engineer	Well	Aware

4. FINDINGS AND DISCUSSION

4.1 OVERVIEW OF RETROFITTING HVAC SYSTEMS IN SRI LANKAN COMMERCIAL BUILDINGS: FINDINGS FROM EXPERT INTERVIEWS

Retrofitting commercial buildings involves enhancing energy efficiency and operational performance through various methods. Experts generally agree on the significance of this practice, albeit with nuanced perspectives. For instance, R1 described retrofitting as upgrading existing systems to modern standards, focusing on energy efficiency. Similarly, R3 emphasised the addition of new components to boost energy performance, while R2 pointed out the replacement of outdated systems. Collectively, these views

underline retrofitting as a comprehensive approach aimed at modernisation and energy optimisation.

Regarding HVAC systems in Sri Lankan commercial buildings, a clear preference for package systems in light commercial buildings is evident. R1 and R2 mention the use of water-cooled package systems due to their balance of cost and efficiency.

4.2 CRITERIA FOR SELECTING HVAC OPTIONS

Table 2 summarises key criteria identified from literature that should be considered when selecting HVAC retrofitting options. These criteria highlight the essential factors that can influence the success and effectiveness of such projects.

Table 2: Criteria for selecting HVAC options: Findings from literature review

Criteria/Sub-criteria	Sources	Description
Economic Factors		
Capital Cost	[5] [6] [15] [16]	Initial expenditure required to implement a retrofit project
Maintenance Cost	[5] [6] [15] [16] [17]	Ongoing expenses for the upkeep of the retrofitted system
Operational cost	[5] [6] [12] [19] [21]	Day-to-day expenses involved in running the retrofitted systems
Payback Period	[5] [6] [12] [14] [18]	The time it takes for the investment in retrofitting to be recovered through cost savings
Life-Cycle Cost (LCC)	[5] [6] [15] [16] [18]	Total cost of owning, operating, and maintaining a building system over its entire life span
Insurance cost	[9]	Expenses related to insuring the retrofitted systems
Technical Properties		
Water Consumption	[18] [19]	The amount of water used by the HVAC system
Energy Consumption	[5] [6] [12]	The total energy used by the HVAC system
CO2 emission	[5] [12] [15] [20]	The amount of CO2 produced by the HVAC system
Refrigeration coefficient	[18] [19]	Efficiency measure of the refrigeration cycle in HVAC systems
COP (Coefficient of Performance)	[21] [22] [23]	A ratio that measures the efficiency of HVAC systems
Humidity control	[5] [6] [7] [8]	The system's ability to regulate indoor humidity levels
Physical Properties		
Area requirement	[5] [6] [12]	Space needed to install and operate HVAC systems
Indoor Appearance	[25] [26]	The aesthetic impact of HVAC systems within the building interior
Outdoor Appearance	[25] [26] [27] [28] [29]	The visual impact of HVAC systems on the building's exterior

Criteria/Sub-criteria	Sources	Description
Loss of usable floor space	[5] [6] [12]	Space that becomes unusable due to the installation of HVAC systems
Noise level	[5] [6] [12]	The amount of noise generated by the HVAC systems
Flexibility		
Installation flexibility	[5] [6] [30] [31] [32] [33]	Ease of installing retrofit systems in existing buildings
Integration flexibility	[5] [6] [30] [31] [32] [33] [34] [35]	Ability of new systems to integrate with existing infrastructure
Ease of maintenance	[35] [40] [41] [42] [43]	Simplicity and convenience of maintaining the retrofitted systems
Future flexibility	[36] [37] [38] [39]	Capacity for future expansions or modifications
Reliability		
Lifetime	[5] [6] [12] [41] [44] [45] [46]	Expected operational life span of the retrofitted system
Lead time	[5] [6] [12] [47] [48]	Time required to implement the retrofit
Repair time	[5] [6] [47] [48] [49]	Time required to fix issues in the retrofitted systems
Vendor availability	[15] [50]	Accessibility of suppliers and maintenance services for the retrofitted systems
Comfortability		
Degree of compatibility	[1] [2] [3] [4] [5]	How well the retrofitted system integrates with the existing building infrastructure
Occupants' health and safety	[5] [6] [9] [10]	Impact of HVAC systems on the well-being and safety of building occupants
Thermal comfort	[13] [14]	The ability of HVAC systems to maintain comfortable temperature and humidity levels
Cleanliness	[13] [14]	The system's ability to maintain a clean indoor environment

[1] (Fisk, 2017) [2] (Batterman et al., 2017 [3] (Mendell et al., 2013) [4] (Wargocki & Wyon, 2013) [5] (Shahrestani et al., 2018) [6] (J. Wang et al., 2009) [7] (Soyguder et al., 2009) [8] (Altun & Yalcinoz, 2008) [9] (Kim et al., 2016) [10] (Yang et al., 2014) [11] (Korkas et al., 2015) [12] (Arroyo et al., 2016) [13] (Heinzerling et al., 2013) [14] (W. Wang et al., 2018) [15] (Stadler et al., 2009) [16] (Chinese et al., 2011) [17] (Au-Yong et al., 2014) [18] (Alipour et al., 2015) [19] (Chakrabarti & Das, 2015) [20] (Alanne et al., 2007) [21] (Yu & Chan, 2005) [22] (Koury et al., 2001) [23] (Mirinejad et al., 2008) [24] (Afram & Janabi-Sharifi, 2014) [25] (Peng et al., 2019) [26] (H. Wang et al., 2023) [27] (Helmis et al., 2007) [28] (Yi et al., 2005) [29] (Tan & Glicksman, 2005) [30] (Wane & Nagdeve, 2012) [31] (Lalji, 2011) [32] (He et al., 2009) [33] (Sudhan, 2011) [34] (Mohebbi et al., 2020) [35] (Zavala, 2013) [36] (Hovgaard et al., 2012) [37] (Sossan et al., 2016) [38] (Kremers et al., 2013) [39] (Niro et al., 2013) [40] (Kusiak et al., 2010) [41] (Tu et al., 2016) [42] (Lu et al., 2005) [43] (Zaheer-uddin & Zheng, 2000) [44] (Ataş et al., 2017) [45] (Lin & Yeh, 2007) [46] (Aynur, 2010) [47] (Stephens et al., 2010) [48] (Siegel, 2016) [49] (Cetin et al., 2014) [50] (Lund et al., 2015)

The literature review identified altogether 31 sub-criteria that should be considered in selecting HVAC options. These 31 sub-criteria were categorized under 06 main criteria as given in Table 2. These criteria and sub-criteria were then refined and checked for relevance and importance to the study context through the expert interviews.

In instances where all three experts reached a consensus on accepting or rejecting a given criterion, the final decision was made accordingly. However, in cases where there was a single dissenting opinion, careful consideration was given to the differing perspectives, alongside a thorough examination of relevant literature, before a final determination was made. If only one expert rejected a criterion, it was kept, as the other two experts provided good reasons for its inclusion. These decisions were also supported by information found in existing research. The goal was to create a clear and comprehensive set of criteria for evaluating HVAC systems relevant to the local context that everyone could understand.

Table 3 provides the findings of the expert interviews in relation to the above.

Table 3: Criteria for selecting HVAC options: Findings from expert interviews

Criteria/Sub-criteria	Interviewee			Decision
	R1	R2	R3	
Economic Factors				
Capital cost	Accepted: Critical for initial capital budget assessment	Accepted: Fundamental for financial feasibility studies	Accepted: Essential for upfront cost evaluation	✓
Maintenance cost	Accepted: Influences lifecycle operating expenses	Accepted: Integral to total cost of ownership	Accepted: Affects long-term sustainability	✓
Operational cost	Accepted: Impacts ongoing operational efficiency	Accepted: Vital for energy expense management	Rejected: Variability challenges in cost prediction	✓
Payback period	Accepted: Key for evaluating return on investment	Rejected: Difficulties in accurate financial forecasting	Accepted: Important for financial justification	✓
Life-Cycle Cost (LCC)	Accepted: Crucial for overall cost-benefit analysis	Accepted: Core to comprehensive cost management	Accepted: Essential for total cost considerations over time	✓
Insurance cost	Accepted: Not pivotal for technical retrofit decision-making	Accepted: Minimally impacts project viability	Accepted: Irrelevant to core retrofitting parameters	✓
Technical Properties				
Water consumption	Moved: Peripheral to core HVAC functions	Moved: Insignificant impact on system performance	Moved: Relevant in specific environmental compliance cases	

Criteria/Sub-criteria	Interviewee			Decision
	R1	R2	R3	
Energy consumption	Accepted: Directly correlates with system efficiency	Accepted: Critical for reducing energy costs	Accepted: Fundamental to operational performance	✓
CO_2 emission	Rejected: Lesser immediate retrofit impact	Accepted: Important for environmental sustainability	Accepted: Crucial for regulatory compliance	✓
Refrigeration coefficient	Accepted: Relevant for cooling systems' efficiency	Rejected: Limited applicability outside specific contexts	Rejected: Not widely applicable across HVAC systems	×
COP (Coefficient of Performance)	Accepted: Indicates system performance efficiency	Accepted: Benchmark for energy performance	Accepted: Standard measure of system efficiency	✓
Humidity control	Accepted: Critical for indoor air quality and comfort	Rejected: Region-specific importance	Accepted: Essential for maintaining occupant comfort	✓
Degree of compatibility		Moved: new upgrades should match the existing system	Moved: Include compatibility as a key criterion in your evaluation framework for retrofitting options	+
Physical Properties				
Area requirement	Accepted: Essential for system integration within space	Accepted: Important for retrofit space planning	Rejected: Retrofit should adapt to existing spatial constraints	✓
Indoor appearance	Accepted: Influences occupant perception and satisfaction	Accepted: Affects aesthetics and user experience	Accepted: Enhances interior environmental quality	✓
Outdoor appearance	Accepted: Impacts external aesthetics and compliance	Accepted: Important for building facade integration	Accepted: Vital for architectural harmony	✓
Loss of usable floor space	Rejected: Already consider that as "Area Requirement"	Rejected: Overlap with “Area Requirement"	Rejected: Better consider Area requirement	×
Noise level	Accepted: Crucial for ensuring acoustic comfort	Accepted: Integral to environmental comfort standards	Accepted: Reduces noise pollution and enhances usability	✓
Flexibility				
Installation flexibility	Accepted: Facilitates integration into existing structures	Accepted: Reduces installation complexities	Accepted: Enhances adaptability to building layouts	✓

Criteria/Sub-criteria	Interviewee			Decision
	R1	R2	R3	
Integration flexibility	Accepted: Ensures seamless system integration	Accepted: Promotes compatibility with existing infrastructure	Accepted: Critical for comprehensive retrofit solutions	✓
Ease of maintenance	Accepted: Simplifies maintenance, reducing lifecycle costs	Accepted: Decreases operational disruptions	Accepted: Essential for ongoing system reliability	✓
Future flexibility	Accepted: Allows for future technological upgrades	Accepted: Essential for scalable retrofit solutions	Accepted: Facilitates future system enhancements	✓
Energy source flexibility	Accepted: Adapts to diverse energy inputs	Accepted: Supports sustainable energy transitions	Accepted: Enables flexibility in energy sourcing	✓
Reliability				
Lifetime	Accepted: Indicates durability and long-term serviceability	Accepted: Reduces frequency of replacements	Accepted: Ensures long-term operational stability	✓
Lead time	Accepted: Affects project timeline and resource allocation	Accepted: Important for scheduling and logistics	Accepted: Critical for timely project execution	✓
Repair time	Accepted: Minimizes downtime, enhancing operational continuity	Accepted: Reduces maintenance impact on operations	Accepted: Vital for quick recovery and serviceability	✓
Vendor availability	Accepted: Ensures access to essential parts and services	Accepted: Facilitates reliable maintenance and upgrades	Accepted: Critical for continuous system support	✓
Comfortability				
Occupants' health and safety	Accepted: Directly impacts well-being and regulatory standards	Accepted: Fundamental to occupant safety	Accepted: Ensures compliance with health codes	✓
Thermal comfort	Accepted: Affects energy efficiency and occupant comfort	Accepted: Integral to environmental control	Accepted: Essential for maintaining optimal indoor climates	✓
Cleanliness	Accepted: Impacts air quality and cleanliness	Accepted: Integral to maintaining hygienic conditions	Accepted: Essential for occupant health and satisfaction	✓
Environmental Aspects				
Carbon emissions	Moved: Aligns with global sustainability goals	Moved: Essential for environmental stewardship	Moved: Critical for meeting modern environmental standards	+

Criteria/Sub-criteria	Interviewee			Decision
	R1	R2	R3	
Water consumption		Moved: Important for water conservation	Moved: Aligns with eco-friendly practices	+
Type of refrigerant	Added: Affects global warming potential and ozone depletion		Added: Critical for environmental compliance	+
Renewable energy sources		Added: Facilitates transition to greener energy sources	Added: Essential for sustainable energy integration	+
Waste management	Added: Enhances sustainability and reduces retrofit impact	Added: Vital for minimizing environmental footprint	Added: Integral to eco-friendly retrofit practices	+

The experts agreed to move "Water Consumption," "CO_2 Emission," and "Refrigeration Coefficient" from the "Technical Properties" category to the "Environmental Aspects" category. This change better reflected the environmental impact of these factors. "CO_2 Emission" was renamed "Carbon Emission" for clarity. Expert R2 suggested adding a new criterion, "Degree of Compatibility," under "Technical Properties," which expert R3 also agreed with. If two out of the three experts rejected a criterion, it was removed. For example, "Loss of Usable Floor Space" was removed because it was considered similar to "Area Requirement," which was already included. Similarly, “Refrigeration Coefficient” was also removed as this was not widely applicable across HVAC systems. Figure 1 provides the finalised evaluation criteria for selecting HVAC options.

Economic Factors (E) **E1** Capital Cost **E2** Maintenance Cost **E3** Operational cost **E4** Payback Period **E5** Life-Cycle Cost (LCC) **E6** Insurance cost	**Technical Properties (T)** **T1** Water Consumption **T2** Energy Consumption **T3** CO_2 Emission **T4** Refrigeration coefficient **T5** COP (Coefficient of Performance) **T6** Humidity control **T7** Degree of compatibility
Physical Properties (P) **P1** Area requirement **P2** Indoor Appearance **P3** Outdoor Appearance **P4** Loss of usable floor space **P5** Noise level	**Flexibility (F)** **F1** Installation Flexibility **F2** Integration Flexibility **F3** Ease of Maintenance **F4** Future flexibility **F5** Energy Source Flexibility
Reliability (R) **R1** Lifetime **R2** Lead Time **R3** Repair Time **R4** Vendor Availability	**Environmental Aspects (En)** **En1** Carbon Emissions **En2** Water Consumption **En3** Type of Refrigerant **En4** Renewable Energy Sources **En5** Waste Management
Comfortability (C) **C1** Occupants' health and safety **C2** Thermal comfort **C3** Cleanliness	

Figure 1: Finalised evaluation criteria for selecting HVAC options

Experts highlighted that the key stakeholders' preferences in the retrofit process reflect a focus on cost-effectiveness, energy savings, and feasibility. R1 and R2 emphasized the importance of financial feasibility and quick returns on investment (ROI), with R3 highlighting the role of cost savings and brand value in driving decisions. Experts also noted that high energy costs often prompt retrofit initiatives. Further, the importance of regulatory compliance and environmental impact was also highlighted. These perspectives reveal that stakeholders prioritise solutions offering economic and environmental benefits, aiming for operational efficiency and sustainability in retrofit projects. Economic incentives, such as reduced operational costs and increased property values, play a crucial role in driving retrofit decisions. Environmental motivators are also significant, with a strong focus on reducing energy consumption and carbon emissions, aligning with global sustainability targets. Additionally, technical improvements through retrofitting can increase the functional performance and safety of buildings, addressing the growing concern over natural disasters in the region (Ranawaka & Mallawaarachchi, 2018). These key motivators collectively support a comprehensive approach to building retrofitting in Sri Lanka, emphasizing the importance of integrated strategies that cater to economic efficiency and environmental responsibility.

Thus, expert opinions converge on the critical role of retrofitting in enhancing the energy efficiency and operational performance of Sri Lanka's commercial buildings. The preference for package systems in light commercial buildings is driven by their cost-effectiveness and efficiency. Stakeholders' decisions are guided by a balance of financial feasibility, energy savings, and regulatory compliance, ensuring that retrofitting efforts yield both economic and environmental advantages. The comprehensive insights from these experts provide a robust understanding of the strategies and preferences that shape retrofitting initiatives in the region.

5. CONCLUSIONS

This paper identified a set of evaluation criteria relevant to the selection of HVAC retrofitting options for commercial buildings in Sri Lanka. Altogether, 35 sub-criteria were identified. These were categorised under 07 main criteria as Economic factors, Technical properties, Physical properties, Flexibility, Reliability, Comfortability and Environmental aspects. Findings highlighted that the stakeholders' decisions are often guided by a balance of financial feasibility, energy savings, and regulatory compliance, ensuring that retrofitting efforts yield both economic and environmental advantages. Further, research is required to assign weightages to the identified criteria so that a comprehensive decision support criterion could be developed for evaluating and selecting retrofit options. This will in turn streamline the decision-making processes, potentially leading to more efficient and cost-effective building upgrades.

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CROWDFUNDING FOR POST-DISASTER RECONSTRUCTION PROJECTS: A CONCEPTUAL FRAMEWORK

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ABSTRACT

Post-Disaster Reconstruction (PDR) projects are essential for rebuilding communities affected by natural disasters and conflicts. Despite the increasing global demand, their success is often hindered by economic, social, and physical challenges. Among the economic constraints, insufficient funding is a critical barrier due to the substantial financial requirements involved. Therefore, this study aimed to review available financial mechanisms for PDR projects and to explore the feasibility of crowdfunding for PDR projects. Accordingly, a comprehensive literature review was conducted on existing studies related to financial mechanisms and the application of crowdfunding for PDR projects. The content analysis method was used to analyse the collected data. The findings identified challenges in existing financial mechanisms such as inadequate funding, high transactional costs, time delays, upfront payments and bureaucratic processes. Overcoming these challenges, the study identified crowdfunding as a viable and innovative solution to attract additional financial resources. Crowdfunding enables the collection of small funds from a broader community, providing an inclusive and accessible financing option. Hence, this study contributes to academic and practical knowledge by bridging the concepts of crowdfunding and post-disaster reconstruction. Beyond its theoretical value, the study offers significant social and economic contributions by promoting inclusive, community-driven financing approaches that enhance resilience and recovery. Furthermore, it supports the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 9 (Industry, Innovation and Infrastructure), and SDG 17 (Partnerships for the Goals), by fostering sustainable, innovative, and collaborative reconstruction efforts.

Keywords: *Crowdfunding; Financial Architecture; Financing Methods; Funding Mechanisms; Post Disaster Reconstruction (PDR)*

1. INTRODUCTION

PDR projects play a critical role in restoring affected infrastructure and livelihood (Pamidimukkalla et al., 2020). According to Ismail et al. (2014), PDR projects refer to

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the modification or complete replacement of a facility that has been completely or partially destroyed due to a catastrophic incident or disaster. Key components of PDR projects include damage assessment, reconstruction planning, community engagement, funding acquisition, construction management, and the implementation of more robust structural designs. In the Sri Lankan context, Siriwardhana and Kulatunga (2023) note that the country has placed considerable emphasis on PDR programs in response to the growing incidence of disasters.

PDR projects differ significantly from conventional construction projects due to their complexity, dynamism, and context-specific sociocultural and economic demands (Shafique & Warren, 2016). Despite support from governments, NGOs, and aid agencies, their success rate remains low due to implementation challenges (Ismail et al., 2014). Key issues include cost overruns from project delays and inefficient material use (Syaputra & Rarasati, 2023), as well as limited financial resources (Pamidimukkalla et al., 2020). Predominantly donor-driven, PDR projects rely on loans and aid, with limited private investment due to their non-profitable nature. In Sri Lanka, Nissanka (2008) identify Donor-Driven and Owner-Driven approaches in housing reconstruction, noting that many non-profits lack structured financial mechanisms for sustainable funding.

Due to limited access to conventional external financing, many entrepreneurs have increasingly turned to alternative funding sources, with crowdfunding emerging as a prominent and effective method (Hoque, 2024; Schwienbacher & Larralde, 2010; Mollick, 2014). Crowdfunding enables individuals to raise capital through small contributions from a large number of supporters via online platforms, bypassing traditional investment channels (Syaputra & Rarasati, 2023). Latorre (2016) highlights the growing application of crowdfunding in the construction industry, particularly in housing and real estate development. While several studies have explored its potential in construction financing, the use of crowdfunding specifically for PDR projects remains under-researched, and evidence of its successful implementation is limited.

Despite the potential for growth, social crowdfunding platforms have seen limited development, primarily due to investment constraints and concerns regarding transparency, reliability, and trustworthiness (Mollick, 2014). Developing a dedicated crowdfunding platform for PDR projects requires a comprehensive understanding of crowdfunding models and the determinants of campaign success. However, existing research lacks analysis of the critical success factors necessary to adapt crowdfunding as an alternative financing mechanism for PDR. Unlike real estate or housing projects, no dedicated crowdfunding models for PDR have been identified in the literature. Addressing this gap necessitates a thorough evaluation of traditional crowdfunding limitations and the development of a hybrid model tailored to the specific challenges of PDR fundraising. Furthermore, existing literature does not provide practical recommendations or structured guidelines for establishing customised crowdfunding mechanisms in this context. As objectives, the study reviews the types of financing mechanisms in PDR and reviews the crowdfunding concepts, types and processes.

This study comprises a detailed research methodology, followed by a comprehensive literature review that examines different financial mechanisms and then explores the applicability of crowdfunding as an alternative source of funds for PDR projects. Subsequently, the literature findings are discussed with the aid of a proposed conceptual

model for financing PDR projects. Finally, the key conclusions of the study and recommendations for further research directions and practical application are presented.

2. METHODOLOGY

A literature review explores the historical development of the subject matter and studies the key themes by broadening the significance of the study (Saunders et al., 2023). Further, Green et al. (2023) elaborate that a narrative literature review provides a discussion on theory and context, aiming to provoke thought and stimulate controversy. Thus, to achieve the research aim, a narrative literature review was undertaken to explore existing studies on the various financing mechanisms employed in post-disaster reconstruction (PDR) projects, with particular attention to the concepts, types, and processes of crowdfunding. Accordingly, a background study was conducted to understand funding challenges associated with PDR projects and to identify the potential in crowdfunding. Afterwards, a comprehensive literature review was conducted to investigate the types of financing mechanisms employed in PDR projects, examine challenges associated with existing financing mechanisms and explore the potential of crowdfunding to address these challenges.

The existing knowledge obtained through secondary sources such as journal articles, conference papers, books and reports were used for this study. To compile a comprehensive literature synthesis, various keywords were searched with the aid of search engines, including “Google Scholar”, “Emerald Insight”, “Scopus”, and “Science Direct”. In addition, reports and research papers published by professional bodies such as the Cambridge Centre for Alternative Finance (CCAF), European Crowdfunding Network (ECN), World Bank and Crowdfunding Professional Association (CfPA) were reviewed and incorporated into the literature analysis. The selection of keywords was primarily based on the themes associated with the study. Thus, keywords such as “post disaster reconstruction”, “PDR”, “financing method”, “funding methods”, “financial architecture”, “crowdfunding”, “crowdfunding models and topologies”, “investment models in crowdfunding” and “non-investment models in crowdfunding” were selected considering their significance and relevance for the study. However, articles specifically related to the targeted topic were identified after carefully reading the abstract to check for relevance.

The study employed a content-based analysis to analyse the collected literature. This method is commonly used in qualitative research for identifying themes and patterns methodically within textual data (Kongaracki et al., 2002). In this study,content-based analysis was helpful to identify types of financing mechanisms and to analyse the crowdfunding concepts and processes. Subsequently, the study presents a conceptual framework by analysing the operational procedure of the crowdfunding mechanism for PDR projects. A conceptual framework acts as an important research element to assist further investigations in the subject areas (Martín et al., 2019).

3. FINDINGS

3.1 FINANCING ARRANGEMENTS FOR POST-DISASTER RECONSTRUCTION

Suarez and Linnerooth-Bayer (2011) define reconstruction finance as the allocation of funds for the rebuilding and advancement of the constructed environment. According to Ryu and Kim (2018), potential sources may include loans, grants, donations, investments

from partner agencies, and programmatic below-market loans. Current discussions among policymakers and practitioners highlight the difficulty in precisely distinguishing between funding and financing sources, especially when determining whether infrastructure is funded or financed (Strickland, 2016). Hence, project financing serves as an umbrella term encompassing both funding and financing mechanisms in PDR projects. Accordingly, Feather (2021) uses the term 'Financial Architecture for Reconstruction' to describe the holistic mechanism for securing financial resources for PDR, integrating both financing and funding.

Despite its importance, disaster management research lacks a structured understanding of reconstruction finance. Most academic studies emphasise governmental subsidies and risk transfer tools, while practitioner reports often focus on fund disbursement rather than acquisition, overlooking the high costs of rebuilding (Usta et al., 2019). This has resulted in limited insight into how PDR is financed. Although various case studies have attempted to classify financial approaches in different countries, there remains a need for a comprehensive framework in this field (Feather, 2021).

Researchers have developed several classifications to understand the financing architecture for Post-Disaster Reconstruction (PDR). Accordingly, Feather (2021) identifies two main categories: "Ex Ante" and "Ex Post," where the former refers to financial mechanisms established before a disaster occurs, while the latter involves mobilising resources after a disaster through channels like donor aid, government relief, and emergency loans. Accordingly, Table 1 illustrates the different financial mechanisms used to manage risk at different phases of PDR projects.

Table 1: Financing mechanisms for risk management of post-disaster reconstructions
Adapted from: (Feather, 2019; Hammett & Mixter, 2017)

Risk	Ex Ante	Ex Post
Risk Transfer	**Capital Market Instruments**	**Credit**
	Indemnity Insurance	Government Bank Loans
	Parametric insurance	Bank and Non-Bank Lending
	Reinsurance	**Co-Finance**
	Catastrophic bonds	Intergovernmental transfers
	Derivatives	Public-private partnerships
Risk-Retention	**Public finance for disaster budget**	**Government Recovery Program**
	Taxation revenues	Discretionary Aid
	Non-taxation proceeds	**Organisational Resources**
	Lines of contingent capital (Credit)	Household assets, including savings and remittances
		Business revenue
		Civil society grants
		In-kind contributions

Different financing mechanisms are used to manage risk in the form of transfer and retention across various phases of PDR projects. In the ex-ante phase, risk is transferred through capital market instruments, while public funds and contingent credit lines are allocated for risk retention. In the ex-post phase, risk transfer is facilitated through credit

and co-financing mechanisms, whereas government recovery programs and organisational or community resources are used to retain risk.

3.2 SOURCES OF TYPICAL FINANCIAL ARCHITECTURE FOR PDR PROJECTS

3.2.1 Major Capital Providers and Sources of Reconstruction Finance

The various types of financial architecture for reconstruction are built on key funding sources that form the foundation for post-disaster financing. Feather (2021) identifies four primary mechanisms commonly used by property owners: insurance, grants, loans, and capital assets. Insurance functions as a risk transfer tool, offering compensation for property damage and including instruments like government subsidies and catastrophe bonds as proactive financial strategies (Feather, 2019). Grants, provided by governmental and non-governmental organisations, play a key role in funding infrastructure repairs and housing reconstruction (Daly et al., 2020). Loans issued by state bodies or financial institutions are often used to finance rebuilding efforts. Lastly, capital assets and personal or organisational financial resources can also be mobilised by property owners to fund reconstruction. Collectively, these mechanisms form the foundation of post-disaster recovery and are often used in combination to address diverse reconstruction needs.

3.2.2 Challenges with the Capital Providers and Sources

The drawbacks associated with traditional sources of funding for PDR projects are extensively discussed in academic literature. Overall, many authors, including Feather (2021), Ptashchenko and Chechelashvili (2018), discuss the difficulties in achieving funding sources through typical methods for projects with the motive of social well-being. The major reason here is the reluctance of stakeholders to invest in non-profitable social facilities. Furthermore, the governments may also not prioritise the financing of social projects, leading to a gap in funding for the construction.

Table 2: Challenges associated with capital-providing sources

Capital providers and sources	Challenges	References
Insurance	Inadequate coverage, delayed payouts, and complex damage assessments.	(Cummins & Weiss, 2009),
	Government subsidies and catastrophe bonds may lack scalability and effectiveness in large-scale disaster contexts.	(Cebotari & Youssef, 2020)
Grants	The amount of grants is often insufficient for comprehensive reconstruction.	(Banomyong, 2001),
	Grants are affected by bureaucratic processes, uncertain availability and potential misallocation.	(Daly et al., 2020)
	Overreliance on grants may hinder timely and efficient reconstruction efforts.	
Loans	Loans pose challenges such as high interest rates, repayment burdens, and eligibility constraints, limiting access for some property owners.	(Sharma et al., 2018).
	Inadequate loan funding remains a barrier to reconstruction	

Capital providers and sources	Challenges	References
	Slow and bureaucratic application processes can delay fund disbursement, increase costs, and affect project timelines.	
Capital assets	Not readily available or sufficient for all property owners. Upfront fees in traditional financing models.	(Awodele et al., 2022).

In summary, the drawbacks associated with the major sources underscore the importance of considering an alternative effective mechanism. The involvement of multiple sources can be addressed as a problem since financial arrangements for reconstruction can be complex with multiple funding sources, all with their accounting requirements and allocation timeframes (McCawley, 2008).

3.3 CROWDFUNDING AS AN ALTERNATIVE SOURCE OF FUNDS FOR PDR PROJECTS

Crowdfunding can be considered a multifaceted solution for PDR financing, which provides not only financial support but also fosters community engagement. Crowdfunding is a way to collect money from a large group of people, where each person gives a small amount. Instead of getting big amounts from a small group of investors (Belleflamme et al., 2014). Usually, crowdfunding gathers contributions from many backers through the Internet (Short et al. 2017), often without traditional financial intermediaries (Mollick, 2014). This concept originates from applying crowdsourcing principles to fundraising, creating new channels for community-backed financing in various project areas such as business, culture, humanitarian efforts, social causes, politics, environment, and technology (Schwienbacher & Larralde, 2012). Initially, consisting of sporadic independent efforts, crowdfunding has evolved into numerous dedicated platforms that mediate between fundraisers and contributors within a trusted framework. According to data from various platforms, global alternative finance volumes, covering all crowdfunding types, reached USD 371 billion in 2017, growing by 42% from 2016 (Ziegler et al. 2019).

3.3.1 Crowdfunding as a Capital Source for Construction Projects

Crowdfunding is increasingly recognised as an effective financing tool across various industries, including construction (Hoque, 2024). In the real estate sector, crowdfunding helps bridge the funding gap left by traditional banks, as illustrated by Slesarev (2022), who explored how Finnish real estate developers leverage crowdfunding to finance development projects. Similarly, in Nigeria, crowdfunding offers solutions to the limitations of traditional financing, such as restricted fund access, lengthy processes, and high upfront fees, by enabling more inclusive and efficient funding (Awodele et al., 2022). Their research outlines a model where project developers launch campaigns to attract small equity or rewards-based investment and use the funds for construction, particularly beneficial for smaller projects. However, the model carries inherent risks, such as potential fraud and limited investor protection.

3.3.2 Current Status of Crowdfunding in PDR

Crowdfunding has demonstrated effectiveness in supporting immediate relief efforts (Behl and Dutta, 2019). However, research on its application in PDR projects remains limited, with less emphasis placed on long-term reconstruction activities. Ptashchenko and Chechelashvili (2018) advocate for the utilisation of crowdfunding as a means to finance social infrastructure, proposing that crowdfunding platforms can attract investment from socially engaged individuals. They argue that crowdfunding offers a viable solution to bridge financing gaps in the development of innovative ideas and social projects. Within this context, PDR projects can be viewed as a form of social empowerment, providing a meaningful opportunity to explore the potential of crowdfunding in supporting sustainable recovery and reconstruction efforts.

A key consideration in crowdfunding is selecting the most suitable model to achieve specific objectives, as success largely depends on the mechanism employed. Therefore, it is crucial to conceptualise the prominent models currently employed to construct an effective and specific mechanism for funding PDR projects through crowdfunding. Accordingly, reviewing the components and typologies of existing crowdfunding models is crucial.

3.3.3 Main Stakeholders and the Typical Process of Crowdfunding

The essence of crowdfunding revolves around a mutually beneficial dynamic involving three primary stakeholders: the fundraiser, the backer, and the platform. The fundraiser initiates funding campaigns, gaining not only capital but also market exposure, customer engagement, and product feedback (Ryu & Kim, 2018). As another major stakeholder, backers support projects financially and benefit from influencing innovations, improving personal consumption opportunities, and fostering community ties (Shneor & Munim, 2019). Platforms act as intermediaries, connecting fundraisers and backers through online systems, and generate income through success fees and service charges (Belleflamme et al., 2015). Each successful campaign boosts the reputation of the platform and expands its user base (Thies et al., 2018).

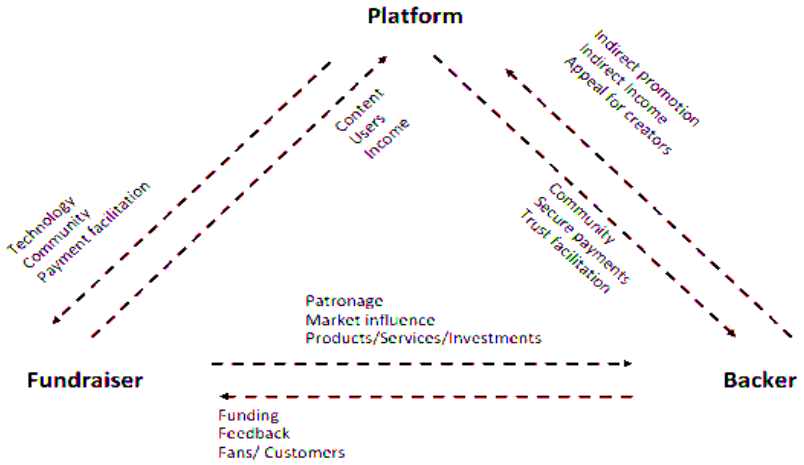


Figure 1: The win-win dynamics of crowdfunding
Source: (Shneor et al., 2020)

At the core of crowdfunding practice lies an expectation for a "win-win" game, where all parties enjoy various benefits from their involvement in the process, as highlighted in

Figure 1 (Shneor et al., 2020). In addition to the main stakeholders, public authorities play a significant role in influencing the crowdfunding industry's development and the interactions between its participants. Regulations, primarily focused on consumer and investor protection, establish the framework for different crowdfunding models. Furthermore, authorities aim to facilitate greater public contributions to civic, cultural, educational, and environmental initiatives, aligning with government policies.

3.3.4 Common Crowdfunding Models and Typologies

The literature categorises crowdfunding models and types according to varying value propositions, practice patterns, funder motivations, associated risks, and regulatory requirements of crowdfunding platforms (Shneor et al., 2020). Belleflamme et al. (2015) propose a basic distinction between 'investment models' and 'non-investment models,' focusing on the nature of compensation promised to funders. Non-investment models involve reward and donation crowdfunding, while investment models encompass lending and equity models, including royalty variations like profit or income sharing.

The CCAF provides a comprehensive categorisation of crowdfunding models in its annual industry reports (Ziegler et al., 2018; Zhang et al., 2018), clearly illustrating the relationships among various crowdfunding types. A simplified version of this categorisation is presented in Figure 02.

Investment based Models

Investment-based crowdfunding models include debt-based, equity-based, and emerging models like invoice trading. Debt-based models, such as peer-to-peer (P2P) and balance sheet lending, connect borrowers with investors or provide loans directly from the platform’s funds. A distinct form, pro-social lending, incorporates social impact goals, with microfinance focusing on small loans to the poor (Short et al., 2017). Equity-based models, including equity crowdfunding, enable investments in unlisted shares of SMEs, expanding into areas like real estate crowdfunding and community shares, where social return often outweighs financial gain (Zhang et al. 2017). Invoice trading allows SMEs to sell invoices at a discount for quick liquidity, aiding short-term cash flow (Dorfleitner et al., 2017).

Non-investment-based Models

Finally, the reward and donation crowdfunding models are arguably the models most commonly recognised by the public. These models typically involve individuals or businesses providing funding to projects without expecting monetary returns. In reward models, funders often receive pre-sales of products or services within a specified timeframe. In donation models, there are no tangible rewards, and funders derive satisfaction from contributing to something they deem important. An interesting variant is patronage, featuring subscription-like payments (rather than a one-time donation) to support ongoing occupations or careers, particularly relevant for artists (Swords, 2017), despite being relatively marginal in the overall crowdfunding sphere so far.

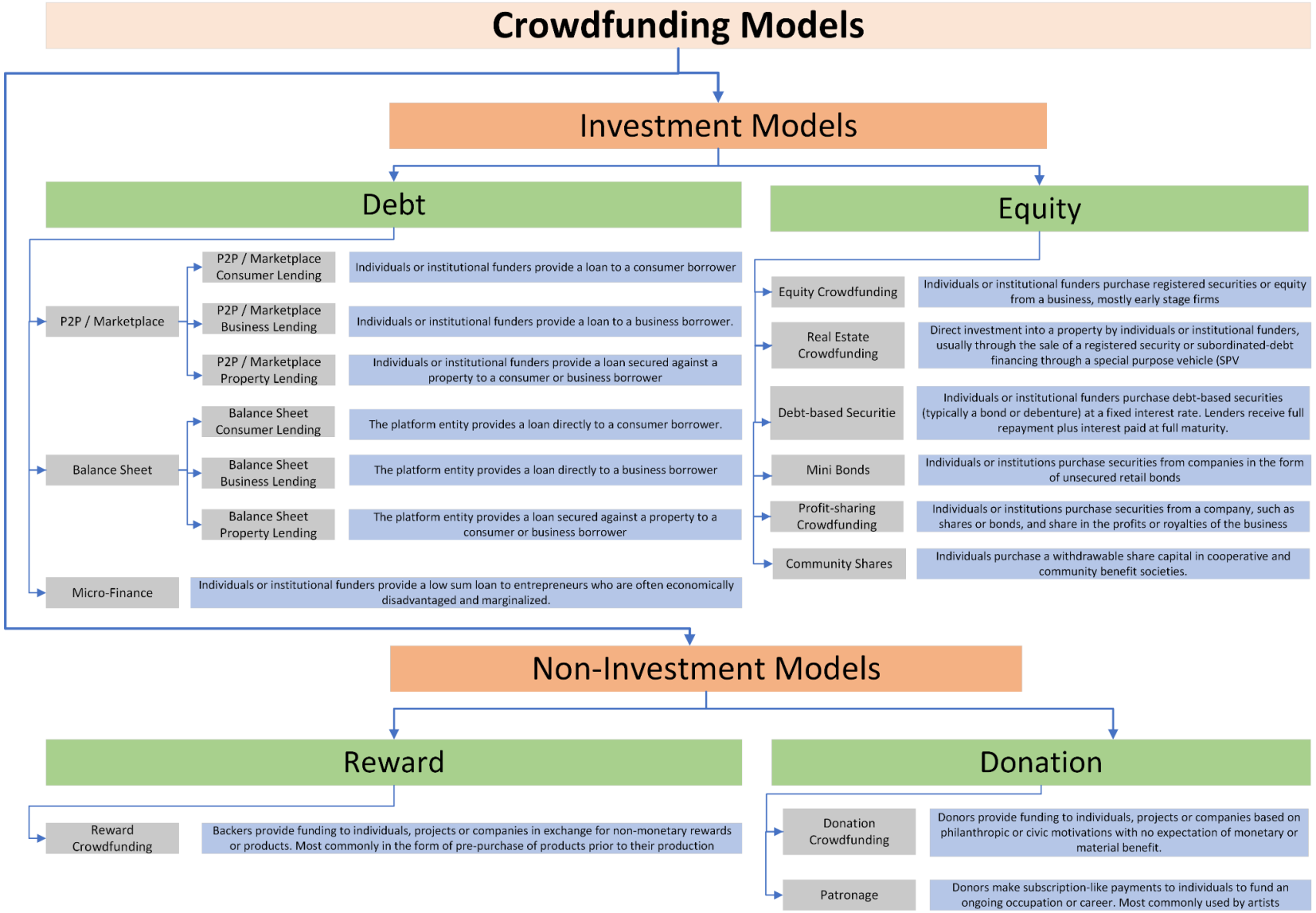


Figure 2: Summary of crowdfunding types/models
Adapted from: (Ziegler et al., 2018; Zhang et al., 2018)

4. DISCUSSION

The growing frequency of natural disasters and conflicts has significantly increased the demand for PRD, essential for restoring normalcy for affected populations. However, a key challenge in implementing these projects lies in securing adequate financing, as PDR projects often lack a standardised financing structure (Feather, 2021). Instead, various financing architectures are employed depending on the context, comparable to architectural designs where similar components are arranged differently. These architectures are built from core revenue streams such as insurance, grants, loans, and capital assets (Feather, 2021). Each of these sources has limitations, affecting the efficiency and success of PDR efforts. As a result, crowdfunding is emerging as a promising alternative, particularly suited for philanthropic causes like disaster recovery. While four primary crowdfunding models exist, the CCAF highlights the potential of developing hybrid models tailored to specific funding needs.

In contrast to traditional capital sources such as insurance, government subsidies, grants, loans, and capital assets, which often suffer from limitations such as inadequate coverage, bureaucratic delays, high interest rates, and limited accessibility (Cummins & Weiss, 2009; Banomyong, 2001; Awodele et al., 2022), crowdfunding offers a more flexible and inclusive financing alternative. Investment-based models, including debt and equity crowdfunding, enable direct engagement between funders and recipients, often with quicker disbursement and broader eligibility (Short et al., 2017). Non-investment-based models, such as donation and reward crowdfunding, foster community-driven support without repayment burdens, providing accessible funding especially in socially motivated contexts (Swords, 2017). Furthermore, crowdfunding platforms can rapidly mobilise dispersed capital, making them particularly suitable for post-disaster recovery or niche funding needs where traditional mechanisms fall short (Ziegler et al., 2018; Zhang et al., 2018).

This paper contributes to the field of PDR by reviewing alternative fundraising mechanisms and identifying the challenges associated with traditional sources such as insurance, grants, loans, and capital assets. It identified crowdfunding as an effective alternative to address persistent financing gaps in PDR projects, particularly due to its potential to mobilise resources efficiently, inclusively, and in support of philanthropic or community-driven initiatives. The study further explores the applicability of various crowdfunding models and the roles of key stakeholders in enhancing funding strategies for PDR. For future advancement, research should focus on empirically validating the proposed model, identifying critical success factors for its practical implementation, and addressing relevant regulatory considerations.

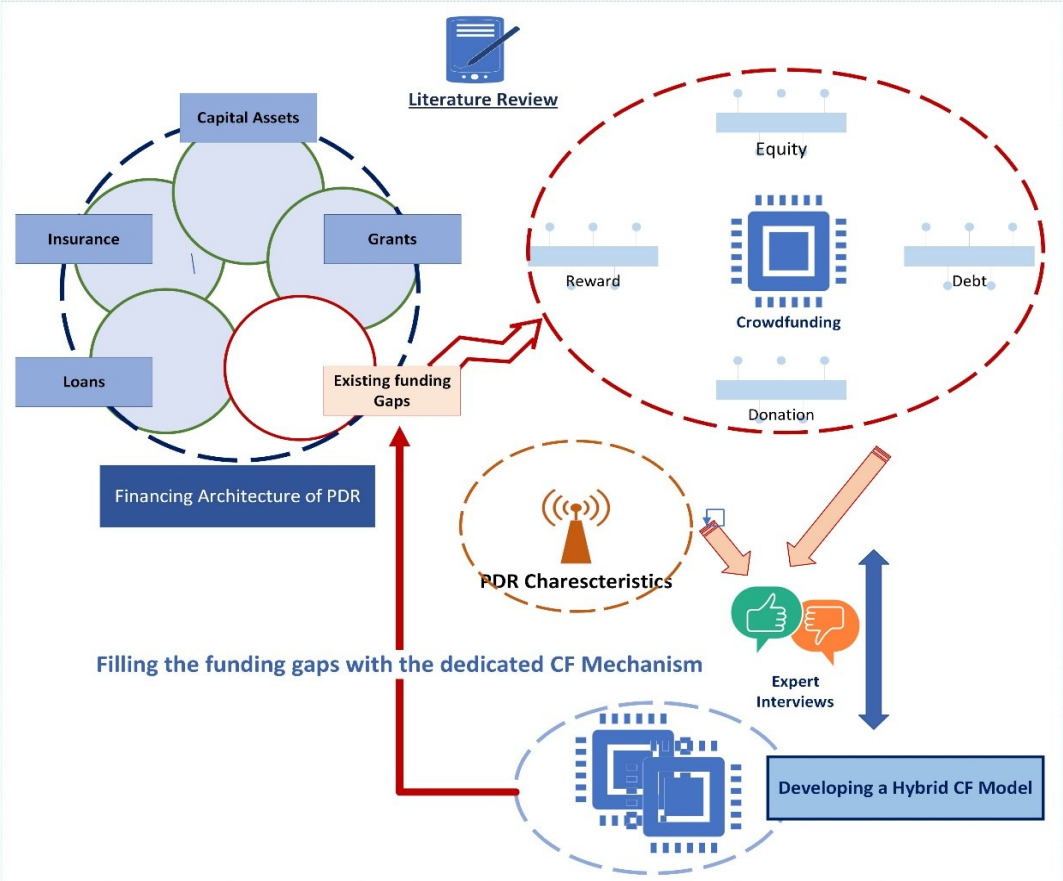


Figure 3: Conceptual framework

5. CONCLUSION AND RECOMMENDATIONS

In conclusion, the research focuses on the financial issues related to the PDR projects that significantly impact throughout the entire project lifecycle. Among the financial challenges, insufficient funding is a major issue due to huge funding requirements and limited funding availability because of the inherent nature of PDR projects. Therefore, the typical financing methods of PDR projects and the issues with sources of funds are analysed and evaluated through the literature findings. Crowdfunding, as an emerging funding tool, has proven to be a viable alternative source of capital for various types of projects, particularly in the construction sector, such as real estate and condominium developments. Its unique features, such as decentralised funding, community engagement, and flexibility, make it especially suitable for these project types. Similarly, PDR projects, which represent a distinct category of construction with urgent and socially driven objectives, can also benefit from the implementation of crowdfunding to attract necessary funds and bridge financing gaps often left by traditional mechanisms.

The study offers substantial contributions across multiple dimensions. Socially, it proposes an inclusive funding model that empowers affected communities and enhances participatory engagement. Economically, it introduces an alternative mechanism for the efficient mobilisation of capital for PDR projects. Academically, it addresses a notable gap in the literature by situating crowdfunding within the broader discourse of disaster recovery finance. Furthermore, research provides a conceptual guideline for industry practitioners to adopt crowdfunding as an alternative financing mechanism for attracting

funds. Moreover, the study aligns with and supports the advancement of several SDGs, specifically SDG 11 Sustainable Cities and Communities, SDG 9 Industry, Innovation and Infrastructure and SDG 17 Partnerships for the Goals.

Nonetheless, the research adopts a narrative literature review approach, which, while offering valuable thematic insights and conceptual clarity, inherently limits empirical generalizability. Therefore, future research should focus on evaluating the viability and effectiveness of the proposed crowdfunding framework for funding PDR projects. Moreover, as further research should explore the potential of integrating blockchain and Building Information Modelling (BIM) for developing crowdfunding platforms.

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DECENT WORK ENFORCEMENT GAPS: ADAPTING GLOBAL LESSONS INTO SRI LANKAN CONSTRUCTION INDUSTRY

Sathyami Dissanayake[1], D.N.L.S. Uduwage[2] and R.A.B.U.N. Perera[3]

ABSTRACT

The construction industry, while vital for economic development, faces significant challenges in achieving Sustainable Development Goal 8 (SDG 8), particularly Target 8.5, which emphasizes decent work, fair wages, and productive employment. This study investigates the barriers to SDG 8.5 implementation in Sri Lanka's construction sector through a mixed-methods approach, combining bibliometric analysis and qualitative literature review. Findings reveal critical gaps in awareness, with research predominantly focused on productivity metrics rather than worker welfare, as evidenced by weak co-occurrence of SDG 8.5-related keywords. Key barriers include gender disparities, market-driven exploitation, informal sector reliance, and stakeholder policy gaps, which hinder progress toward decent work. The study identifies three strategic interventions—promoting gender equality, strengthening labour rights, and formalizing informal work—as essential for aligning Sri Lanka's construction industry with global standards. These insights provide actionable recommendations for policymakers and industry leaders to foster a more equitable and sustainable workforce, ensuring the sector's contribution to inclusive economic growth by 2030.

Keywords: *Construction Industry; Decent Work; Sri Lanka; SDG 8; Sustainable Employment.*

1. INTRODUCTION

The construction industry is inherently labour-intensive, relying heavily on human resources to execute planning, design, building, and maintenance activities (Fei et al., 2021). Unlike many other sectors where automation and technology dominate, construction remains deeply dependent on manual labour for its operations (Buntara et al., 2018). Buntara et al. (2018) has mentioned that labour intensiveness underscores the critical importance of safeguarding worker rights and ensuring decent working conditions. Without adequate protections, the industry faces severe repercussions, including high turnover rates, reduced productivity, and increased occupational hazards (Fadhilah et al., 2023). Labour rights are not merely ethical imperatives but also economic necessities, as the stability and growth of the construction sector hinge on the well-being

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and motivation of its workforce (Fei et al., 2021). Failure to address these issues can lead to systemic inefficiencies, project delays, and diminished quality, ultimately undermining the industry's contribution to national development (Buntara et al., 2018).

Ensuring decent work is a globally recognized priority, particularly through Sustainable Development Goal 8.5 (SDG 8.5) under the United Nations (UN) agenda, which promotes safe, fair, and equitable employment. Despite the global recognition, many countries still face considerable challenges in fully realizing these objectives, especially in labour-intensive sectors such as construction (Chigbu & Nekhwevha, 2023). Even in developed nations, enforcement of decent work standards often requires continuous policy updates, workforce education, and strong institutional support (Islam, 2020). As a committed UN member state, Sri Lanka has committed to advancing the Sustainable Development Goals (SDGs), particularly Sustainable Development Goal 8 (SDG 8), which promotes sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. Target 8.5 of this goal explicitly calls for equal pay, safe working environments, and fair employment opportunities, principles that are especially relevant to the construction sector (Islam, 2020). Globally, many UN member states, such as the UK, Australia, and Germany, have made significant strides in aligning their construction industries with SDG 8.5 by enforcing stringent labour laws, promoting gender equality, and investing in worker training and safety programs (Chaha & Rani, 2024). Falk (2007) stated that these efforts have not only improved working conditions but also enhanced productivity and social equity within the industry. However, Sri Lanka lags in these advancements, with persistent challenges hindering progress. The absence of suitable strategies leaving the sector ill-equipped to meet international standards (Morton et al., 2017).

As a member of the United Nations, Sri Lanka is committed to achieving the SDG 8.5 by the year 2030. In line with this national commitment, it is essential for the Sri Lankan construction industry to adapt practices of SDG 8.5. However, prior to implementing such standards within the local construction sector, it is necessary to examine the existing body of literature to understand current research trends and the extent of awareness related to decent work in the Sri Lankan context. Identifying these patterns enables the recognition of knowledge gaps and informs the adaptation of international best practices. Furthermore, by analysing global strategies and challenges, context-specific barriers can be understood, thereby facilitating the development of appropriate interventions to support the integration of SDG 8.5 into the Sri Lankan construction industry. To achieve this aim, following objectives were formulated.

- To assess the current awareness and implementation of SDG 8.5 in Sri Lankan construction sector.
- To identify the key barriers impeding progress and propose actionable strategies to integrate decent work principles into the industry.

Through this research, policymakers, industry leaders, and stakeholders can gain insights to foster a more equitable, productive, and sustainable construction workforce in Sri Lanka. This study initially reviews existing academic literature to assess research trends related to SDG 8.5 in Sri Lanka, utilizing secondary sources such as peer-reviewed publications. A bibliometric analysis was then conducted to map these trends, followed by a manual content analysis to identify key barriers to achieving decent work in the construction industry.

2. LITERATURE REVIEW

The SDGs, adopted by all UN member states in 2015, represent a universal call to action to end poverty, protect the planet, and ensure prosperity for all by 2030 (Zulu et al., 2023). Comprising 17 interconnected goals, the SDGs address global challenges through a holistic framework that balances economic, social, and environmental dimensions (Morton et al., 2017). Among these, SDG 8 (Decent Work and Economic Growth) stands out as a critical driver of sustainable development, aiming to promote "sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all" (Ogunmakinde et al., 2022). This goal recognizes that economic progress must be equitable, creating opportunities for meaningful employment while safeguarding workers' rights and well-being.

Table 1 narrowing the focus, Target 8.5 of SDG 8 specifically emphasizes achieving "full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value" (Paksi et al., 2024).

Table 1: Targets and indicators of SDG 8.5

Target	Description	Indicators
8.5	By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value	8.5.1 - Average hourly earnings of female and male employees, by occupation, age and persons with disabilities. 8.5.2 - Unemployment rate, by sex, age and persons with disabilities.

Figure 1 shows the four pillars of decent work, and this target highlights the importance of fair wages, job security, and safe working conditions particularly relevant to labour-intensive industries (Morton et al., 2017). According to the researcher, the construction sector, as one of the largest global employers, plays a pivotal role in advancing SDG 8.5.

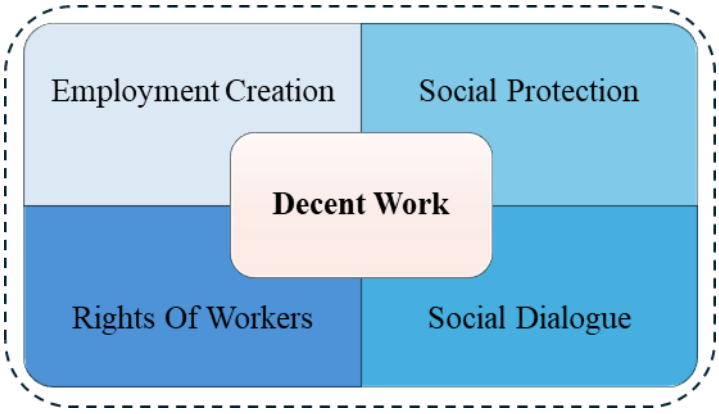


Figure 1: Four pillars of decent work

The construction industry in Sri Lanka is of key importance to the national economic development as it has a significant contribution to Gross Domestic Production and employment generation (Gnanothayan & Kauškale, 2022). However, though the sector is of key importance, it lags in adopting the principles of SDG 8.5, that is, to ensure full and productive employment and decent work for all by 2030 (Colombage et al., 2023). Informal employment, absence of social protection, weak occupational health and safety

standards, and limited occupational skill development are typical of labour conditions in the industry (Ranasinghe & Kumarasinghe, 2019). These affect especially the marginalized group like migrant workers, daily wage earners, women in construction.

Comparative studies point out that unlike Sri Lanka, developed countries like Australia and Germany have been much more successful in establishing decent work frameworks in their construction industries (Zulu et al., 2023). Strong labour regulation, stakeholder collaboration and worker protection, fair wages and job security have been enforced in these countries (Zulu et al., 2023). This gap is in the absence of similar structures and policies in Sri Lanka as a developing country. As Dissanayake et al. (2021) point out, this gap highlights the necessity of context-specific strategies that can adapt and localize successfully international practice to the socio-economic, and cultural setting in Sri Lanka. To meet global sustainability goals as well as to have a fairer, safer and more productive workforce in the Sri Lankan construction sector, these enforcement gaps need to be addressed.

3. RESEARCH METHODOLOGY

This study employs a mixed-methods approach to comprehensively address its dual research objectives. The combination of quantitative bibliometric analysis and qualitative literature review was deliberately chosen to provide both macro-level awareness patterns and micro-level contextual insights (Bornmann, 2022). While pure quantitative methods might overlook nuanced challenges, and purely qualitative approaches could lack measurable trends, this blended methodology offers complementary strengths that enhance the validity and applicability of findings.

The first objective is focusing on scrutinizing the current awareness and implementation of SDG 8.5 in Sri Lankan construction sector as Figure 2 illustration show. Thus, bibliometric analysis was used to achieve this objective, where quantitatively evaluate the academic literature to identify the trends of publication data such as, authorship, key words, citations, co-citation, affiliation and journals. Subsequently, study extract the critical barriers from literature using manual content analysis which gives qualitative information. The review covers publications from 2015 to 2024, aligning with the UN's adoption of the SDGs in 2015. As per Figure 2, the Scopus database was chosen for its comprehensive coverage of peer-reviewed construction literature, with the search string which mentioned below, specifically designed to capture SDG 8.5 related concepts while filtering for Sri Lankan context (Cantu-Ortiz, 2018). The subsequent co-occurrence and cluster analysis of 80 papers enables to quantify research gaps and knowledge concentrations that indicate national awareness levels.

Search string: TITLE-ABS-KEY (SDG8 OR decent OR work OR productive OR employ AND construction AND Sri AND Lanka) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ECON”) OR LIMIT-TO (SUBJAREA , "SOCI”)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp"))

The search query was developed based on following criteria; the key words should be SDG 8, decent work, productive employment, construction, and Sri Lanka. The articles should be published withing 2014-2025 and it should be a journal or conference written in English. VOSviewer was used to conduct the bibliometric analysis based on gathered data. This approach was preferred over traditional surveys or interviews because it: (1)

objectively measures existing scholarly attention through publication patterns, (2) reveals invisible networks between research themes, and (3) provides visualizable data trends across time.

Following three types of bibliometric analysing techniques were employed to achieve the first objective.

1. Co-Authorship Analysis

This is a method to study the collaborative relationships among researchers, institutions or countries, which are based on shared authorship in academic publications. This method demonstrates how knowledge is produced and shared across geographical and institutional boundaries. One of the most important advantages of co-authorship analysis is identifying influential researchers, research groups, and potential collaborators in each domain. It offers a quantifiable and objective view of collaborative patterns.

2. Co-occurrence Analysis

Academic articles are analysed to determine how often certain keywords occur together in them. It is a technique through which one acquires the subtle theme, topic and trend of an area of research. The major advantage of the keyword co-occurrence analysis is that it provides a visually and systematically mapped conceptual structure of the literature. It helps in identifying underexplored area and gives a better proposition for future research direction.

3. Co-Citation Analysis

This is the analysis of how often two documents are cited together by other publications, therefore suggesting that they are linked or similar in content. Co-citation analysis can be used to find tides in how knowledge about a concept is acquired over time, unlike expert opinion or qualitative assessment. It provides a historical view for the evolution of research topics, which is hard to achieve through interviews or manual literature reviews.

Figure 3 represent the research process of second objective, and it adopts a qualitative systematic review methodology to examine global barriers and strategies. It prioritized over meta-analysis or case study approaches because it: (1) allows for thematic synthesis of diverse international experiences, (2) captures policy and implementation nuances lost in statistical analyses, and (3) facilitates identification of transferable best practices. The content analysis process involved iterative coding of literature from multiple databases to ensure thematic saturation. This method was selected over automated text mining as it enables deeper interpretation of contextual factors and more accurate categorization of complex strategies. The qualitative findings are systematically organized to highlight both universal principles and culturally specific adaptations relevant to Sri Lanka's construction sector.

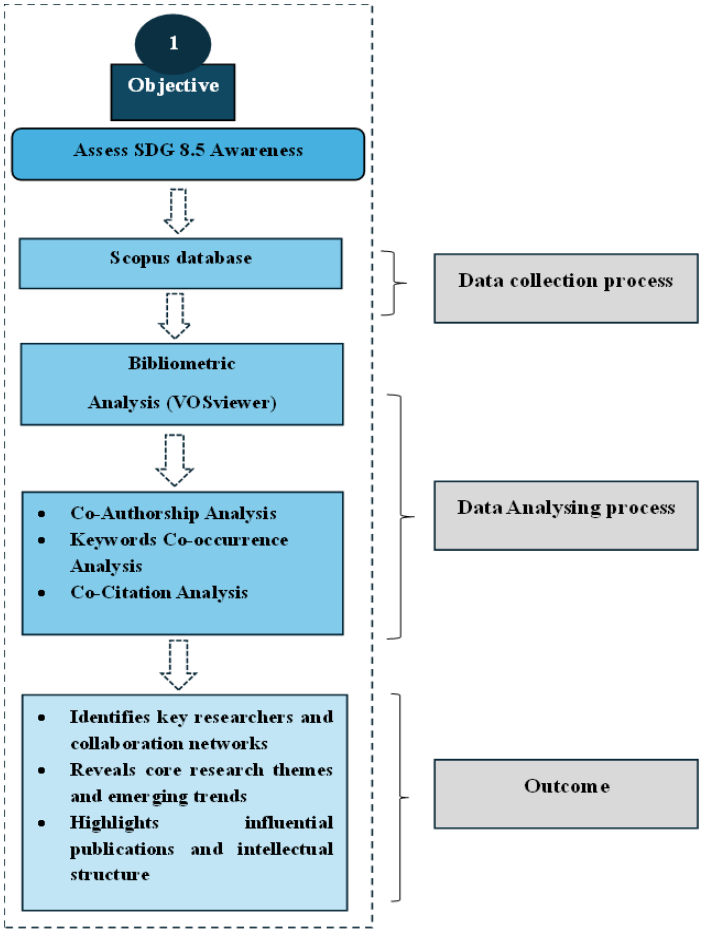


Figure 2: Methodology of objective 01

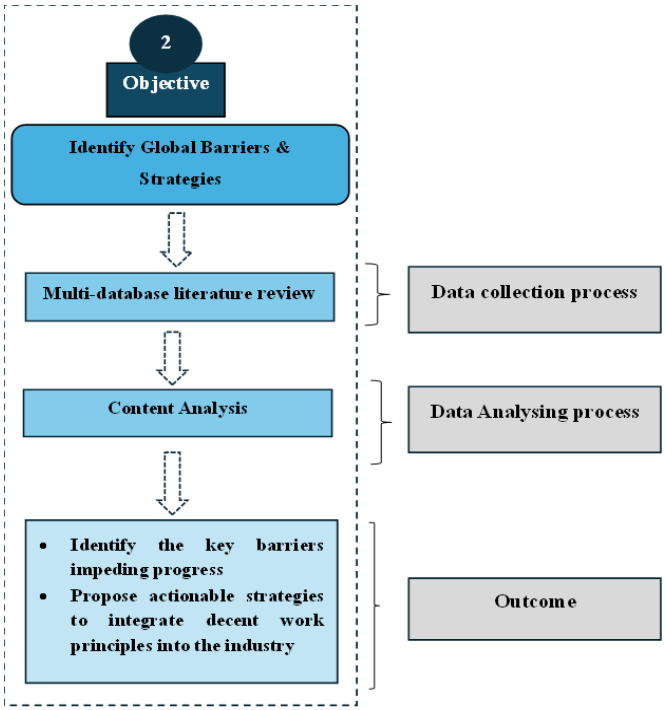


Figure 3: Methodology of objective 02

4. DATA ANALYSIS AND DISCUSSION

This section analysis the gathered data and discuss the results.

4.1 AWARENESS OF SRI LANKAN CONSTRUCTION INDUSTRY ABOUT SDG 8.5

This section examines the level of awareness among stakeholders in the Sri Lankan construction industry regarding SDG 8.5, which focuses on achieving full and productive employment and decent work for all by 2030. The analysis draws on data collected to assess how familiar industry professionals are with the goals, targets, and relevance of SDG 8.5 to their daily operations and strategic planning.

4.1.1 Co-authorship Mapping

Figure 4 shows the Co-authorship analysis of Sri Lankan construction research, and it reveals limited but strategic collaborations around SDG 8.5 themes, with key authors like Dissanayake and Manoharan (link strength:19) forming strong research clusters, while isolated high-producers like Perera (7 papers) and low-citation works (e.g., Waidyasekara:1 citation) indicate fragmented knowledge dissemination. The concentration of decent work research within small academic circles, combined with weak industry-policy linkages (evident in Dodanwala's 117 citations but minimal collaborations), highlights critical gaps in translating SDG 8.5 awareness into practical implementation. Strengthening interdisciplinary networks between technical experts (Ranadewa), policymakers (Senaratne), and institutional researchers could bridge this divide, transforming academic insights into actionable strategies for improving labour conditions, gender equity, and formal employment in Sri Lanka's construction sector.

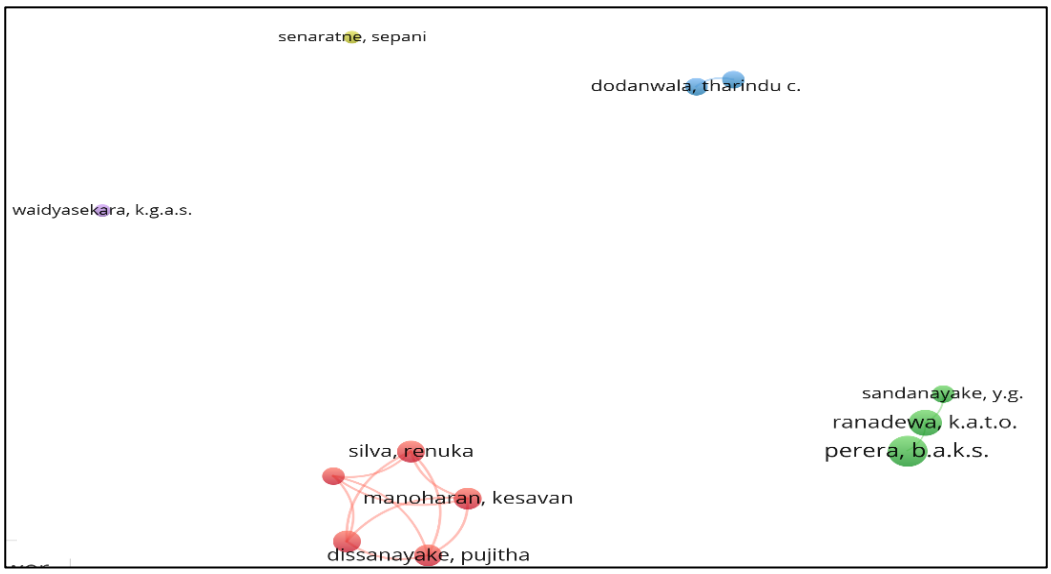


Figure 4: Bibliographic analysis co-authorship

4.1.2 Co-occurrence Analysis

The bibliographic analysis of co-occurrence of keywords of Sri Lankan construction research reveals a predominant focus on project management, cost reduction, and sustainable development, evidenced by large, interconnected nodes, while themes central to SDG 8.5 such as job stress, well-being, and role ambiguity appear as small, isolated

nodes, indicating severe neglect of decent work principles. As per the Figure 5, each node represents a keyword. The size of the nodes reflects the frequency of keyword appearance, and links between nodes indicate how often those keywords appear together in publications. Different colours represent thematic clusters, helping to identify major research areas and interrelated topics.

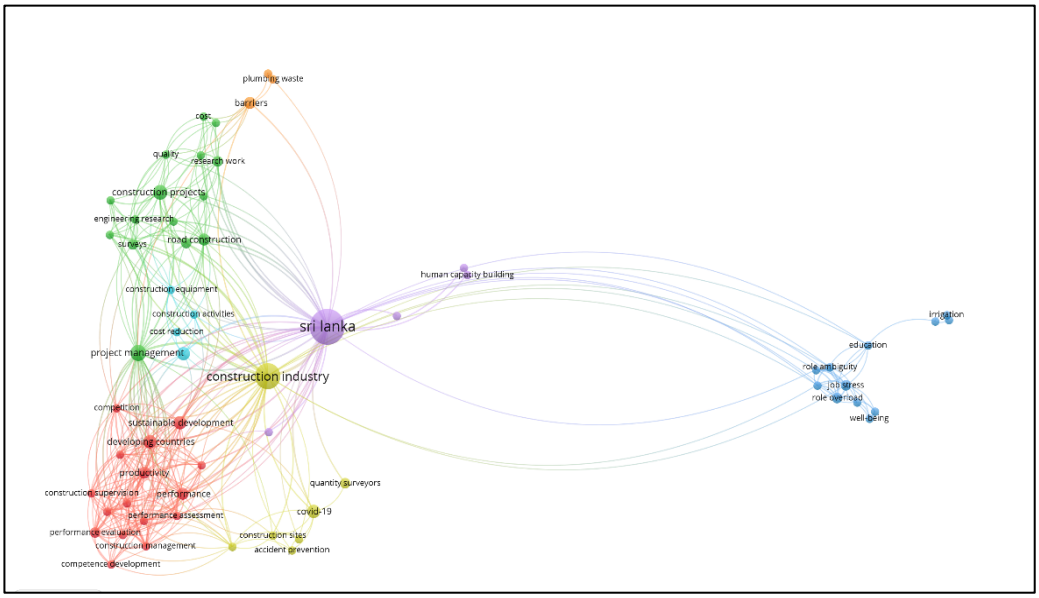


Figure 5: Bibliographic analysis of co-occurrence of keywords

This disparity highlights the industry's entrenched prioritization of productivity metrics over worker welfare, with critical gaps in research on employment conditions, psychological safety, and equitable opportunities. The weak co-occurrence of SDG 8.5-related keywords underscores an urgent need for rebalancing academic and policy attention toward human-centric studies, which could transform workplace practices and align Sri Lanka's construction sector with global sustainability targets through evidence-based interventions targeting worker empowerment and inclusive growth.

4.1.3 Co-Citation Analysis

The co-citation analysis reveals influential research relationships shaping SDG 8.5 discourse in Sri Lanka's construction sector, with *Dissanayake P.* (366 link strength) and *Deegahawature D.* (363) forming the dominant intellectual cluster, indicating their foundational role in decent work research. While local scholars demonstrate strong interconnectivity, the limited co-citation of international experts like *Lingard H.* (23) and *Ballard G.* (83) suggests weak integration of global decent work frameworks into local studies. This insular citation pattern reflects a disconnect *between Sri Lankan research and international SDG 8.5 advancements*, particularly in occupational health and gender equity. The high link strength among local authors (*Silva R.*, *Manoharan K.*) confirms concentrated expertise, but the sparse citations of labour sociology pioneers (*Koskela L.*, *Thornhill A.*) highlight a critical gap in applying cross-disciplinary insights to improve worker welfare. Strengthening co-citation networks with global decent work literature could accelerate policy-relevant research to address Sri Lanka's construction labour challenge.

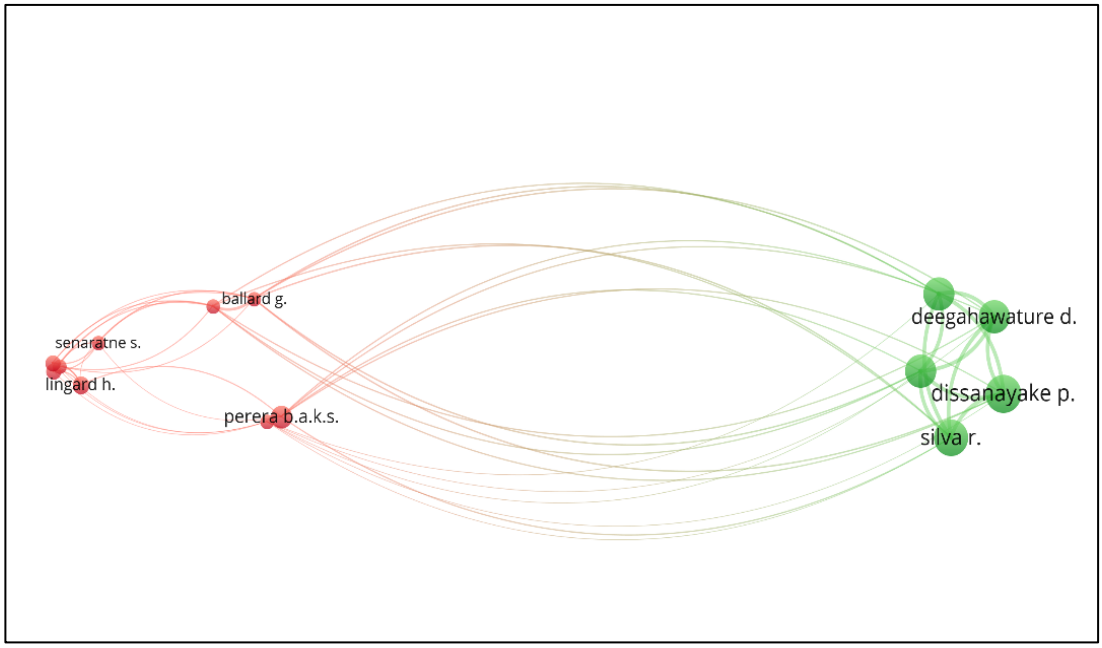


Figure 6: Bibliographic analysis of co-citation

Results of the bibliometric analysis of co-authorship, co-occurrence of keywords and co-citation mapping corroborate the fact that the construction research in Sri Lanka is specialized and yet limited in its engagement with SDG 8.5. Dissanayake-Manoharan is one of the small research clusters that demonstrate strong local influence, but the larger academic environment is characterized by fragmented collaboration, weak interdisciplinarity, and minimal international linkage. Analysis of keyword shows that cost and project performance dominate while themes of decent work like well-being and job security are sidelined. In addition, citation patterns indicate that there exists a lack of the use of literature on the global decent work to aid the sector to adopt inclusive labour strategies. These findings therefore directly meet Objective 01 by documenting the current level of awareness and research engagement regarding SDG 8.5 in Sri Lanka's construction industry and identify key areas that need academic and practical attention to promote productive and decent work in the Sri Lankan construction industry.

4.2 BARRIERS IN ACHIEVING DECENT WORK IN CONSTRUCTION INDUSTRY

The content analysis of global literature reveals six persistent barriers hindering SDG 8.5 implementation in the construction industry, categorized into four thematic areas: gender disparities, market economy pressures, informal sector reliance, and stakeholder gaps. Table 2 shows the summary of analysis of barriers. Gender inequality emerges as a cross-cutting challenge, with studies highlighting systemic discrimination, wage gaps, and limited leadership opportunities for women and persons with disabilities (Anojan & Siriwardana, 2021; Pourmazaherian M. & Musonda, 2022; Silva, 2018). Maqbool et al. (2023) states, market-driven exploitation manifests through cost-cutting practices that depress wages and weaken labour rights enforcement, while Anaman & Amponsah (2007) mentioned informal employment exacerbates vulnerabilities through absent legal protections and social security. Critically, stakeholder failures particularly inadequate policies and awareness perpetuate these issues (Anaman & Amponsah 2007; Maqbool et al., 2023). The Table 2 demonstrates how these barriers intersect globally, with

developing nations facing acute informalization and developed economies struggling with equitable growth, underscoring the need for context-specific strategies to achieve decent work.

Table 2: Barriers in achieving decent work in construction industry

	Barrier	A	B	C	D	E	F
Gender Disparities	Systemic discrimination	✓			✓		
	Wage gaps		✓			✓	
	Limited leadership opportunities for women	✓	✓	✓			
	Limits job opportunities (Women and Persons with Disabilities)	✓					
	Inadequate training opportunities		✓		✓		✓
Market Economy Pressures	Cost-driven exploitation	✓					
	Low wages						
	Lack of labour rights enforcement		✓		✓		✓
Informal Sector Reliance	Lack of legal protections	✓					
	Lack of social security				✓		✓
	Lack of safe conditions for informal workers		✓				
Stakeholders	Lack of awareness and understanding		✓			✓	
	Lack of effective policies that promote decent work			✓			✓

A- (Pourmazaherian M. & Musonda, 2022), B- (Anojan & Siriwardana, 2021), C- (Silva, 2018). D- (Bruno & Oliveira, 2024), E- (Anaman & Amponsah, 2007), F- (Maqbool et al., 2023)

4.3 STRATEGIES TO OVERCOME FROM BARRIERS IN ACHIEVING DECENT WORK IN CONSTRUCTION

Table 3 indicates the analysis which identifies three key strategic approaches to advance SDG 8.5 in the construction sector: promoting gender equality, strengthening labour rights, and formalizing informal work. As per the Islam (2020), gender-focused strategies emphasize equal pay laws, leadership representation, and targeted training programs to address systemic disparities. Labor rights reinforcement highlights stricter law enforcement, union support, and worker complaint mechanisms to combat exploitation (Chaha & Rani, 2024; Islam, 2020). For informal sector challenges, solutions centre on accessible registration, social benefits, and skills development to transition workers into formal employment (Chaha & Rani, 2024; Chigbu & Nekhwevha, 2023). These strategies directly counter the identified barriers with gender initiatives tackling discrimination, labour policies addressing market pressures, and formalization measures reducing

informal sector vulnerabilities demonstrating a targeted, multi-pronged framework for achieving decent work globally.

Table 3: Strategies to overcome from barriers

	Strategy	A	B	C	D	E	F
Promoting Gender Equality	Enforcing equal pay laws	✓					
	Improving fair representation of women in leadership and technical roles		✓		✓		✓
	Providing mentorship and vocational training			✓			
	Conducting Pursuing programs that encourage women and PWD	✓			✓		
Strengthening Labor Rights	Implement stricter enforcement of labour laws	✓	✓				
	Supporting unions	✓					✓
	Ensuring complaint mechanisms for workers.						
	Ensure legal protections for workers	✓		✓			
Formalizing Informal Work	Establish accessible registration processes			✓			✓
	Provide financial and social benefits to encourage formalization		✓				
	Expanding vocational training and skills development opportunities	✓			✓		✓

A-(Islam, 2020), B-(Chaha & Rani, 2024), C-(Chigbu & Nekhwevha, 2023), D-(Zulu et al., 2023), E-(Khalique et al., 2021), F-(Fei et al., 2021)

The synthesis of barriers and strategies based on global literature offer a holistic view of the challenges and their solutions associated with the achievement of SDG 8.5 in the construction industry. The analysis identifies systemic gender disparities, market pressures, informal sector dependence and stakeholder failures as key barriers which strategic pathways of promoting gender equality, strengthening labour rights and formalising informal work can help overcome. The findings are consistent with Objective 02 since they provide a comprehensive appraisal of current global approaches and identify feasible tactics that can be adopted to Sri Lanka's construction context. The analysis makes a significant contribution to formulating a context sensitive roadmap for decent and productive work in the industry by linking the root causes with appropriate interventions.

5. CONCLUSIONS AND RECOMMENDATIONS

This research examined the enforcement gaps in the achievement of SDG 8.5, which aims to achieve full and productive employment and decent work for all in the construction industry of Sri Lanka. The study is important because although the construction sector contributes a great deal to the national GDP and employment, it lags in adopting fair labour practices, equal opportunity policies and worker welfare standards. The study

utilized a mixed methods approach, whereby bibliometric analysis was used to assess national awareness, identify key barriers, propose strategies that were globally informed and pertinent to the Sri Lankan context from a qualitative systematic review.

The findings suggest that the awareness of SDG 8.5 is not very high, and that research is mainly concentrated on productivity and project management, rather than employment conditions and workers' rights. Co-occurrence and co-authorship mapping of the keywords showed fragmented scientific attempts, poor participation of expert stakeholder and minimal global best practice integration. Gender disparity, market driven exploitation, reliance on informal sector and policy gaps were identified as key barriers. To that effect, three strategic recommendations were provided: the promotion of gender equality; the strengthening of labour rights; and formalising informal work, all aimed at making progress towards decent work.

Nevertheless, this study has a few limitations. This study used only Scopus indexed literatures yet, there are literature which are not indexed in the Scopus but have appeared in other databases. Although rich in context, the qualitative analysis relied purely on secondary data and did not include direct stakeholder interview or field-level feedback. Empirical surveys or interviews with industry practitioners, labour unions and policymakers, should be conducted to validate and refine the proposed strategies in the future research.

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DEFINING GREEN BUILDING CRITERIA FOR BUILDING INFORMATION MODELING-BASED RATING SYSTEMS

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ABSTRACT

As sustainability becomes increasingly central to architectural and construction practices, robust frameworks are needed to evaluate and guide the implementation of green building (GB) standards. Integrating Building Information Modelling (BIM) with GB criteria presents a promising approach to advancing sustainable construction. BIM provides a comprehensive digital representation of a building's physical and functional characteristics and has the potential to streamline sustainability assessments by aligning traditional GB standards with data-driven design and evaluation processes. In Indonesia, the adoption of GB principles remains limited due to the complexity of building design and evaluation. This paper explores GB criteria tailored for BIM-based rating systems based on the Regulation of the Minister of Public Works and Public Housing No. 21 of 2021. Data were collected through a literature study and analyzed using expert judgment. The findings classify the criteria into two categories: (1) those that can be directly integrated with BIM and (2) those that require manual assessment. The study identifies 18 criteria suitable for BIM integration and 11 that depend on manual processes. These results illustrate the opportunities and constraints of using BIM to support GB assessments.

Keywords: *Building Information Modelling; Green Building; Rating System.*

1. INTRODUCTION

The growing urgency of climate change and rapid urbanization has increased the pressure on the building and construction sector to adopt sustainable practices. This sector is

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responsible for nearly 40% of energy-related carbon emissions worldwide. As a response, many governments now promote the use of green building (GB) standards to reduce environmental impacts. In Southeast Asia, GB initiatives have become more prominent part of national strategies for sustainable development. GBs not only provide environmental benefits but also reduce life-cycle costs (Zuo & Zhao, 2014). GBs help conserve natural resources, enhance occupant well-being, and improve building performance (Sari et al., 2022). Various GB technologies have been developed to suit local construction contexts, although most research still focuses on isolated components rather than integrated solutions.

To achieve long-term sustainability in building projects, stakeholders need a comprehensive understanding of how to design, construct, operate, and manage buildings responsibly. As a result, sustainability assessment has become an essential approach in the development process (Reed et al., 2017). Green Building Rating Systems (GBRSs) support this goal by providing structured tools that evaluate building performance against defined sustainability criteria. These systems help ensure that sustainable design requirements are met and that environmental objectives are achieved (Romano & Riediger, 2020). In Indonesia, however, the use of GBRS remains limited by challenges in adapting frameworks to national regulations and local conditions. Addressing these constraints is necessary to accelerate the adoption of sustainable construction practices.

While GBRS provide a strong foundation for sustainability evaluation, their effectiveness can be improved through digital tools such as Building Information Modelling (BIM) (Seghier et al., 2018). BIM provides a centralized platform for visualizing and managing building data. It supports sustainability assessment by enabling automation, improving accuracy, and simplifying the certification process (Doan et al., 2023). BIM is also capable of supporting detailed modelling and simulation at every building's life cycle.

Over the past two decades, BIM has transformed the architecture, engineering, and construction (AEC) industry, and has been widely used for communication and coordination in design, construction, and facility management (Wong & Kuan, 2014). The main benefits of BIM include better decision-making, faster access to information, improved performance analysis, and more efficient GB certification (Ilhan & Yaman, 2016). Studies show that BIM-based GB evaluations can enhance building performance by 31.5%, reduce energy use, and improve indoor comfort (Guo et al., 2021). BIM has already supported green certification frameworks in several countries. In New Zealand, BIM is used for 75% of the Green Star Certification Tool (GhaffarianHoseini et al., 2017). In Australia, it contributes to 66% of credits under the Green Star system (Gandhi & Jupp, 2014). It has also been used in Canada (Jalaei & Jrade, 2014), Portugal (Carvalho et al., 2021), and Malaysia (Solla et al., 2022) to support national GB certifications.

Although these developments show clear progress, most studies still focus on limited aspects of integration between BIM and GBRS. Researchers have primarily explored energy efficiency, material selection, or partial system automation. For example, the BIM-based GBRS developed by Romano and Riediger (2020) emphasizes energy-related features. The framework developed by Rahman et al. (2021) includes only Energy and Atmosphere (EA) and Material Resources (MR) in alignment with LEED. Additional studies have examined the use of BIM for automatic assessments (Motamedi et al., 2017), green certification support (Seyis et al., 2021), and verification of sustainability goals

(Alwan et al., 2015). However, few studies have offered a complete view of how national GB criteria can be fully embedded within BIM-based systems.

This research focuses on Indonesia's Regulation of the Minister of Public Works and Public Housing No. 21 of 2021, which aims to identify which of these criteria are relevant to BIM-based evaluation and to classify them based on their compatibility with BIM tools through expert validation. The goal is to support the development of a more structured and technology-enabled approach to GB evaluation in Indonesia. The findings are expected to provide practical guidance for BIM practitioners, researchers, and policymakers in strengthening GB practices within the Indonesian context.

2. GREEN BUILDING RATING SYSTEM CATEGORIES

GB refers to a structured approach that minimizes the negative environmental impact of construction activities while preserving natural resources across a building's life cycle (Sari et al., 2022). Indonesia is one of the developing countries that attempts to massively adopt GB concept. Indonesia's GB assessment framework, outlined in the Regulation of the Minister of Public Works and Public Housing, organizes criteria into six main categories: Appropriate Site Development (ASD), Energy Efficiency and Conservation (EEC), Water Conservation (WAC), Use of Material Resources and Cycle (MRC), Indoor Health and Comfort (IHC), and Building Environment Management (BEM). These categories align with global GBRSs such as LEED and BREEAM (Surya et al., 2024).

ASD focuses on minimizing environmental disruption through site planning, with indicators include building orientation, accessibility, land remediation, green spaces, and infrastructure alignment. LEED addresses these under Location and Transportation (LT) and Sustainable Sites (SS) (Ismaeel & Elsayed, 2022), while BREEAM emphasize more on pollution control and soil protection during construction (Telichenko et al., 2019).

EEC addresses the optimization of a building's energy performance across its systems. EEC emphasizes efficient energy use across building systems, including envelopes, HVAC, lighting, and power distribution. LEED assesses these elements through the Energy and Atmosphere (EA) category (Pushkar, 2021), while BREEAM highlights performance tracking, metering, and low-carbon sourcing (Pritchard & Kelly, 2017).

WAC supports water efficiency through reliable sourcing, low-consumption fixtures, and reuse systems. LEED's Water Efficiency (WE) category includes indoor and outdoor water strategies (Poon, 2021). BREEAM assesses water use from a broader operational perspective that includes user behaviour (Zegarra, 2021).

MRC encourages reduced material impact through responsible selection, waste prevention, and life cycle thinking. LEED promotes certified materials and transparency in sourcing and embodied carbon (Zegarra, 2021). BREEAM expands this by rewarding efficient design, reuse, and supply chain oversight (Shukla et al., 2015).

IHC addresses occupant health and comfort through air quality, thermal performance, and refrigerant safety. LEED captures these under Indoor Environmental Quality (EQ) and emphasizes measurable indicators such as ventilation and lighting (Lee & Kim, 2008). BREEAM includes additional factors such as ergonomics and access to views, with both systems emphasize the importance of using non-toxic and well-commissioned systems (United States Green Building Council, 2021).

BEM encompasses waste and wastewater management. Indicators include the 3R principles, monitoring systems, and on-site treatment. LEED promotes construction waste diversion and landfill reduction (Chi et al., 2020), while BREEAM stresses end-use waste and water recovery infrastructure (Luangcharoenrat & Intrachooto, 2018).

3. METHODS

This study was structured around two research objectives and conducted in two stages, each involving different data collection and analysis approaches.

3.1 IDENTIFICATION OF GREEN BUILDING CRITERIA

To address the first objective, data were sourced from Indonesia's Regulation of the Minister of Public Works and Public Housing No. 21 of 2021 on Green Building Performance Assessment and from previous studies related to GB certification and BIM applications. Data collection was conducted through document analysis and a literature study. Relevant criteria were extracted and grouped under categories such as site management, energy efficiency, water conservation, and others. These criteria were examined using content analysis to determine their structure and assess whether they matched the characteristics of information stored and processed within BIM models.

3.2 CLASSIFICATION OF BIM-COMPATIBLE CRITERIA

The second objective was addressed through expert validation. Five experts participated in the study, including a BIM consultant, two BIM practitioners, one government regulator, and one academic researcher. All were selected based on their professional experience in BIM implementation and GB evaluation. Data were collected through structured interviews using a validation form that listed all criteria identified in the first stage. Experts assessed whether each criterion could be integrated into BIM or required manual input. Closed-ended questions were used to maintain consistency and clarity throughout the process (Creswell, 2018; Woodhead & Berawi, 2008).

4. RESULTS AND DISCUSSION

4.1 IDENTIFICATION OF GREEN BUILDING CRITERIA

This subsection addresses the first research objective: identifying GB assessment criteria from Indonesia's Regulation of the Minister of Public Works and Public Housing No. 21 of 2021 on Green Building Performance Assessment that align with BIM functionalities. The analysis was conducted by extracting criteria from the regulation and organizing them into six main categories (Kamath et al., 2019; Wardhana et al., 2023).

Each criterion was examined through document analysis and supported by a literature review to determine its alignment with data types and modelling outputs typically found in BIM environments. Prior studies such as Akhanova et al. (2021), Jalaei & Jrade (2014), and Alwan et al. (2015) served as key references in associating regulatory requirements with BIM functionalities, including parametric modelling, spatial coordination, energy simulation, and material tracking.

The result of this process is summarized in Table 1, which lists 29 GB criteria drawn from the regulation along with relevant references that indicate prior studies that support the technical feasibility of assessing each criterion using BIM. These sources were used to

validate the relevance of each criterion to BIM functionalities such as modelling, simulation, or automated data extraction. These criteria form the foundation for the classification of BIM compatibility.

Table 1: Green building assessment criteria identified from national regulation

Category		Criteria	References
1. ASD	1.1	Building Orientation	Alwan et al. (2015)
	1.2	Site management including accessibility or circulation	Jalaei & Jrade (2014), Seyis et al. (2021), Akhanova et al. (2021)
	1.3	Management of land contaminated with hazardous & toxic waste (B3)	Akhanova et al. (2021)
	1.4	Private green open space plan	Akhanova et al. (2021), Seyis et al. (2021)
	1.5	Provision of walkways	Akhanova et al. (2021)
	1.6	Basement tread management	
	1.7	Parking Lot Provision	Jalaei & Jrade (2014)
	1.8	Outdoor lighting system	
	1.9	Construction of Building above and/or under Land, Water, and/or Public Infrastructure/Supplies	Akhanova et al. (2021)
2. EEC	2.1	Building envelope	Xu & He (2019), Fan et al. (2023)
	2.2	Ventilation system	Seyis et al. (2021)
	2.3	Air conditioning system	Xu & He (2019), Fan et al. (2023)
	2.4	Lighting system	Jalaei & Jrade (2014), Akhanova et al. (2021)
	2.5	Transportation System in Building	Jalaei & Jrade (2014)
	2.6	Energy efficiency calculation	Seyis et al. (2021)
	2.7	Electrical system	Jalaei & Jrade (2014), Alwan et al. (2015)
3. WAC	3.1	Water Source	
	3.2	Water usage	Jalaei & Jrade (2014), Seyis et al. (2021)
	3.3	Use of water efficiency sanitary equipment	
4. IHC	4.1	Smoking Ban	Jalaei & Jrade (2014)
	4.2	Carbon dioxide (CO2) and carbon monoxide (CO) control	Jalaei & Jrade (2014), Alwan et al. (2015)
	4.3	Refrigerant Usage Control	Akhanova et al. (2021)
5. MRC	5.1	Controlling the Use of Hazardous Materials	Alwan et al. (2015), Jalaei & Jrade (2014), Seyis et al. (2021)
	5.2	Use of Eco - Labelling Certified Materials	

Category		Criteria	References
6. BEM	6.1	Application of the 3R Principle (Reduce, Reuse, Recycle)	Olanrewaju et al. (2022)
	6.2	Implementation of Waste Management System	
	6.3	Implementation of Waste Generation Recording System	
	6.4	Provision of Wastewater Treatment Facilities Before Discharge to City Sewers	Jalaei & Jrade (2014)

4.2 CLASSIFICATION OF CRITERIA BASED ON BIM COMPATIBILITY

This subsection presents the results of the second research objective, which aims to classify the identified GB criteria based on their compatibility with BIM. The classification was carried out through expert validation using a structured form that listed all 29 criteria extracted from Indonesia's Regulation of the Minister of Public Works and Public Housing No. 21 of 2021 on Green Building Performance Assessment. Five experts that participated in the validation process each had over ten years of professional experience in GB certification or BIM implementation.

The experts assessed whether each criterion could be evaluated using BIM authoring tools or whether manual assessment was necessary. The instrument included binary response options (BIM-based / Manual) and provided space for additional comments. Responses were analyzed to identify which criteria aligned with quantifiable or spatial parameters available in BIM environments, like Autodesk Revit or Green Building Studio (GBS).

The results confirmed that 18 criteria could be evaluated using BIM. These criteria correspond to parameters that can be modelled, simulated, or extracted from BIM platforms. For example, building orientation and lighting systems can be assessed through spatial modelling and daylight simulation, while energy systems such as HVAC and electrical loads are compatible with BIM-integrated performance tools.

CO_2 and CO control can be addressed through space scheduling and pollutant tracking features in Autodesk Revit, which allow simulation of indoor air exchange and monitoring of emissions based on room occupancy and mechanical system configurations (Akhanova et al., 2021). Lighting systems are assessable through daylight simulation and artificial lighting analysis, where BIM tools simulate natural light penetration and optimize lighting layout in accordance with building codes and sustainability standards Jalaei & Jrade (2014). Ventilation and HVAC systems can be modelled using tools such as GBS, which supports airflow simulation, thermal zoning, and mechanical load distribution for performance evaluation.

Energy efficiency calculations are also supported by BIM through dashboards that simulate building energy use and estimate contributions from renewable sources. For water use efficiency, BIM enables water consumption modelling and plumbing fixture representation to estimate total demand and potential savings. Lastly, environmentally friendly materials can be managed in BIM through tagging, quantity take-off, and data exports that support verification of material sources and compliance with eco-labelling or low-impact material requirements (Alwan et al., 2015; Seyis et al., 2021).

The remaining 11 criteria require manual evaluation due to the absence of direct digital representation in BIM or because they involve qualitative elements. These include criteria such as construction above public infrastructure, implementation of waste management systems, and smoking bans. Evaluation of such elements often depends on regulatory interpretation, post-occupancy monitoring, or documentation that must be verified externally. This classification is detailed in Table 3, which categorizes each criterion by its compatibility with BIM-based assessment.

Table 2: Green Building Criteria that can be evaluated using BIM

No.	Category	BIM-integrated	Manual Entry
1	ASD	1.1 Building Orientation	1.3 Management of land contaminated with hazardous & toxic waste (B3)
		1.2 Site management including accessibility or circulation	1.5 Provision of walkways
		1.4 Private green open space plan	1.7 Parking Lot Provision
		1.6 Basement tread management	1.9 Construction of Building above and/or under Land, Water, and/or Public Infrastructure/Supplies
		1.8 Outdoor lighting system	
2	EEC	2.1 Building envelope	
		2.2 Ventilation system	
		2.3 Air conditioning system	
		2.4 Lighting system	
		2.6 Energy efficiency calculation	
		2.7 Electrical system	
3	WAC	3.1 Water Source	
		3.2 Water usage	
		3.3 Use of water efficiency sanitary equipment	
4	IHC	4.2 Carbon dioxide (CO2) and carbon monoxide (CO) control	4.1 Smoking Ban
		4.3 Refrigerant Usage Control	
5	MRC	5.1 Controlling the Use of Hazardous Materials	
		5.2 Use of Eco – Labelling Certified Materials	
6	BEM		6.1 Application of the 3R Principle (Reduce, Reuse, Recycle)
			6.2 Implementation of Waste Management System
			6.3 Implementation of Waste Generation Recording System
			6.4 Provision of Wastewater Treatment Facilities Before Discharge to City Sewers

The results of this study confirm that BIM can support a substantial portion of Indonesia's GB assessment framework, particularly in categories that rely on quantifiable and spatial data. EEC, WAC, and IHC show high levels of integration with BIM tools and offer strong potential for automation in energy simulation, water efficiency analysis, and indoor environmental monitoring (See Figure 1). In contrast, ASD and MRC include both BIM-integrated and manual-entry criteria, which reflects the need for hybrid approaches in areas involving site-specific design or material documentation. BEM emerges as the least compatible category since all indicators require manual assessment due to their dependence on post-construction operations, waste handling, or regulatory documentation. These findings suggest that while BIM can digitalize sustainability evaluations in many areas, full automation across all GB criteria remains limited.

Integrating BIM into the certification process provides benefits beyond data assessment. BIM centralizes project information, improves visual clarity for reviewers, and reduces duplication in documentation. This allows certification teams to generate compliant submissions more efficiently using model-based outputs. For criteria that cannot be assessed through BIM, supporting materials such as technical reports, annotated plans, or regulatory checklists should be prepared separately and submitted alongside BIM outputs. A hybrid approach that combines digital automation with manual verification ensures that both quantifiable and qualitative criteria are addressed consistently during certification.

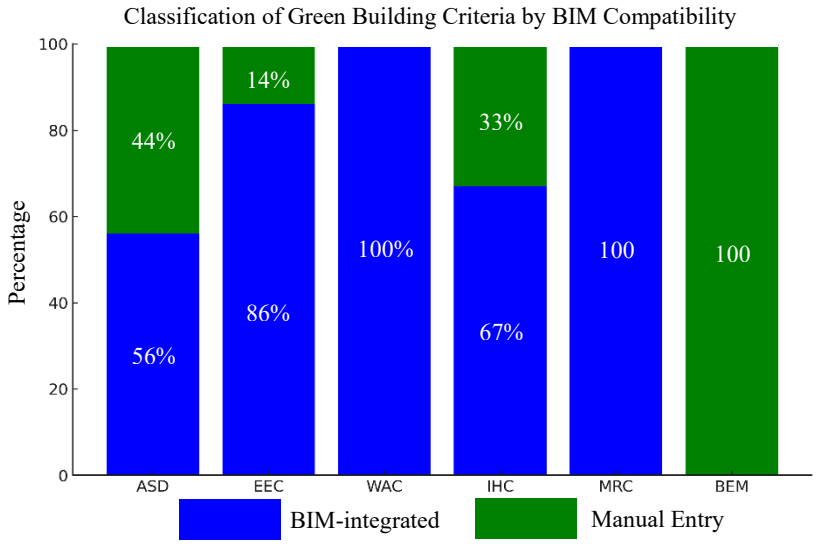


Figure 1: Classification of green building criteria by BIM compatibility

4.3 COMPARISON WITH PREVIOUS STUDIES

The findings of this study are consistent with previous research that confirms BIM's ability to support automated assessments across various GBRSs. Prior studies confirm that core criteria, such as EEC, WAC, IHC, ASD, and MRC, are suitable for integration into BIM-based workflows. Lim et al. (2021) introduced a computational BIM workflow built on Dynamo that enabled automation of assessments for EEC, IHC, ASD, and MRC under Malaysia's GBI. Khoshdelnezamiha et al. (2020) created the AGBIA tool, which combined Revit and Dynamo to address five major evaluation categories: EEC, MRC, WAC, IHC, and ASD. Nguyen et al. (2016) enhanced LEED assessments through a BIM-enabled framework that supported multiple green design metrics. Lai et al. (2023) conducted a comprehensive review that showed BIM frequently supports evaluation of

EEC, WAC, ASD, and MRC criteria, especially when integrated with plug-ins or visual scripting tools like Dynamo. Seghier et al. (2017) demonstrated a more technical application by developing a BIM-based method to evaluate ETTV, aligned with energy requirements in the Green Mark and GreenRE certification systems. These studies affirm the results of this research by highlighting BIM's strength in managing quantifiable and performance-driven indicators through modelling and simulation. At the same time, they also identify limitations in BIM's ability to address qualitative or regulation-specific indicators, such as waste management and construction restrictions, which often require manual input or external review.

Although this study focuses on criteria drawn from Indonesia's Regulation No. 21 of 2021, it is necessary to compare these criteria with the rating systems widely used in practice, such as LEED and GBCI. The categories across these systems are broadly similar, particularly in their inclusion of energy, water, materials, and indoor environmental quality. However, the methods of assessment show important differences. The Indonesian regulation primarily adopts a compliance-based structure, where each criterion must be fulfilled in a binary fashion. The Indonesian framework follows a binary compliance model, while LEED and GBCI apply point-based scoring that recognizes partial achievements. This flexibility supports project customization and encourages continuous improvement through higher-level goals.

Beyond structure, international systems often incorporate elements absent from the national regulation. LEED includes innovation credits, lifecycle assessments, and post-occupancy evaluations. These allow project teams to demonstrate ongoing performance, which is not yet part of the Indonesian system. Enhancing the regulation with adaptive scoring and performance monitoring would improve alignment with global practices and strengthen long-term sustainability outcomes.

5. CONCLUSIONS

This study defines a set of green building (GB) assessment criteria based on their potential for integration with Building Information Modelling (BIM). From a total of 29 regulatory criteria outlined in Indonesia's Ministerial Regulation No. 21 of 2021, 18 were identified as suitable for BIM-based evaluation. These include elements that rely on quantifiable data and spatial modelling, particularly in the categories of energy efficiency, water conservation, and indoor health. The remaining 11 criteria require manual assessment due to their qualitative nature or lack of representation in BIM environments.

The main contribution of this study is the development of a regulatory-specific classification framework that links national GB assessment criteria with BIM functionalities. This study offers a localized and practical approach to integrating BIM into Indonesia's sustainability assessment framework. The results provide actionable insights for policymakers, professionals, and stakeholders seeking to adopt digital methods for green building certification.

There are limitations that should be noted. The scope of this study is confined to Indonesia's Regulation No. 21 of 2021 and does not extend to other certification frameworks. Criteria that involve regulatory interpretation, post-construction documentation, or behavioural outcomes remain beyond the current capacity of BIM-based evaluation. Future research should explore ways to address these gaps by

integrating BIM with post-occupancy monitoring systems and by comparing the alignment of national GB regulations with BIM across different countries.

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DETECTION OF MOBILE PHONE USE BY LABOURERS ON CONSTRUCTION SITES USING YOLOV11-S

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ABSTRACT

Mobile phone distractions among construction labourers pose significant productivity challenges. This study presents a YOLOv11-s-based model to detect and classify construction labourers who use mobile phones during work. The system was trained using a person dataset, a helmet dataset and a mobile phone dataset, obtained from an online database and custom images collected from Sri Lankan construction sites. The proposed system followed a four-stage approach, beginning with person detection, followed by helmet detection and classification. Then, through image preprocessing, the model analysed the helmet colour using histogram analysis and the Hue Saturation Value colour scale to detect labourers with yellow helmets. Subsequently, the performance evaluation metrics, such as precision-recall curve, mAP@0.5 and inference time, indicate that the trained model performs better on the testing data in detecting construction labourers who are using mobile phones during work. Finally, mobile phone detection is carried out. Images from Sri Lankan construction sites were used for deployment validation and to check for model overfitting. The system can be further developed by using motion detection through IoT to detect the continuous use of mobile phones through timeframe analysis. This study contributes to improving workplace productivity through the automated detection of distractions in construction.

Keywords: *Construction; Helmet Detection; Mobile Phone Detection; Productivity; Yolov11,*

1. INTRODUCTION

Construction labour productivity is defined as the amount of work completed per unit of labour input, typically measured in output per labour hour (Assaad et al., 2023). According to Hamza et al. (2022), it is a crucial factor in the construction industry, as it directly influences project efficiency and cost-effectiveness. However, distractions on-site can decrease productivity and lead to delays, inefficiencies, and increased operational costs. Distractions can arise from various sources (Ke et al., 2021), one of which is mobile phone usage on construction sites. Although mobile phones facilitate instant

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communication and coordination (Hasan et al., 2019), their unregulated use can become a major source of distraction due to the constant flow of notifications, messages and calls, which can easily become a source of distraction (Merchán et al., 2024).

To mitigate these issues, tighter supervision of labourers' mobile phone usage on construction sites is necessary. According to Hamza et al. (2022), supervision significantly enhances productivity. However, Raoofi et al. (2024) found that traditional supervision methods in construction can be time-consuming and costly. A case study conducted by Kim et al. (2023) in Korea highlighted that digital technologies can significantly enhance the efficiency of construction supervision. Automated systems utilising cameras and computer vision can detect, localise and classify mobile phones. The use of Artificial Intelligence (AI) in construction management can improve efficiency and reduce costs (Ruchit & Olivia, 2024).

One effective way to distinguish construction labourers from other personnel is through helmet colour detection. Studies have shown the feasibility of computer vision models in detecting labourers wearing construction helmets (Cheng, 2024; Hayat & Morgado-Dias, 2022; Li et al., 2023). Merchán et al. (2024) conducted a study to detect the use of mobile phones through an inertial measurement unit for safety monitoring. However, this approach relied on sensors embedded in helmets focusing on detections in indoor scenarios. Therefore, there is still a gap between the detection of mobile phone use in the external environment of the construction site.

This paper introduces a mobile phone detection model that uses the YOLOv11-s architecture to enhance productivity on construction sites. The model achieves this by (1) detecting persons, (2) detecting and classifying safety helmets (3) detecting the colour of helmets to differentiate labourers with yellow helmets, and (4) detecting their use of mobile phones. By integrating computer vision into construction supervision, this approach provides a solution to enhance productivity at construction sites. The paper is structured as follows. First, it provides a comprehensive review of labour productivity and computer vision for enhancing productivity. Next, the research method, including data collection and analysis techniques, is elaborated. This is followed by the findings and conclusions.

2. LITERATURE REVIEW

2.1 SIGNIFICANCE OF LABOUR PRODUCTIVITY ON CONSTRUCTION SITES

Construction productivity plays a vital role in the growth of a nation's economy (Naoum, 2016). Productivity in construction refers to the maximisation of output while optimising input utilisation, ensuring efficiency and cost-effectiveness (Hamza et al., 2022). According to Muqeem et al. (2011), construction labour is the most crucial resource in the industry, directly impacting overall construction productivity. However, low productivity levels remain one of the major challenges faced by the construction sector, leading to delays, increased costs, and inefficiencies. Dixit et al. (2019) further emphasised that low productivity can create inflationary pressure on a nation's economy, affecting overall economic stability.

One of the contributors to reduced labour productivity is mobile phone distractions among labourers (Sattineni & Schmidt, 2015). Labourers who divide their attention between critical tasks and mobile phone use are more likely to exhibit decreased efficiency, leading to lower work output and increased errors (Merchán et al., 2024).

Traditional supervision methods for maintaining productivity rely on manual monitoring, which is often time-consuming and costly (Raoofi et al., 2024). As a result, researchers are increasingly exploring technology-driven solutions to enhance productivity and automate site supervision (Adamu et al., 2024; Bai et al., 2023; Yuan et al., 2023).

2.2 COMPUTER VISION FOR ENHANCING PRODUCTIVITY AT CONSTRUCTION SITES

With the rapid growth of Artificial Intelligence (AI), computer vision has emerged as a significant tool for information perception and automated detection in various applications. In construction safety, helmet detection has been significantly enhanced using computer vision algorithms, enabling real-time monitoring of compliance on construction sites (Cheng, 2024). Numerous studies have utilised Convolutional Neural Networks (CNNs) to detect helmet usage, improving labour productivity and site supervision. Fang et al. (2018), utilised faster regional-based CNN to detect helmet use on construction sites, while Wu et al. (2019) and Han and Zeng (2022) developed deep learning-based systems that detected helmet usage and classified its colour.

CNN-based object detection models are categorised into single-stage and multi-stage detectors (Sumit et al., 2020) . Single-stage detectors, such as You Only Look Once (YOLO), perform object classification and localisation in a single step, making them significantly faster in object detection (Pham et al., 2020). In contrast, multi-stage detectors, such as Faster R-CNN and Mask R-CNN, use a two-step process, which results in higher accuracy but slower processing (Sumit et al., 2020)The primary advantage of single-stage detectors is their real-time capability, making them ideal for applications that require fast object detection. Therefore, YOLO models are an optimal choice for automated construction site supervision, which prioritises speed while maintaining a satisfactory level of accuracy.

The architecture of YOLO consists of three major components: (1) Backbone, (2) Neck, and (3) Head (He et al., 2024). The backbone is responsible for feature extraction within an image, identifying key visual patterns necessary for object detection. The neck enhances multi-scale feature fusion, enabling the model to detect objects of different sizes with improved accuracy. Finally, the head is responsible for final object classification, bounding box regression and refining detection accuracy (Alif, 2024).

2.3 YOLOV11 ARCHITECTURE

Among the YOLO series, YOLOv11 represents the latest iteration, offering significant improvements in real-time object detection (Khanam & Hussain, 2024). It incorporates a range of architectural enhancements designed to improve speed, accuracy, and adaptability. Lin (2024) proposed a YOLOv8-based algorithm designed to enhance helmet detection in complex backgrounds, including instances with small or distant objects. Furthermore, other studies have also used various YOLO models for safety helmet detection on construction sites (Wan et al., 2024; Yang et al., 2024). According to He et al. (2024), YOLOv11 demonstrated the highest accuracy and recall rate compared to previous YOLO versions. A comparison of key performance metrics of the YOLO series is provided in Table 1.

Table 1: Comparison of YOLO series
Source: (He et al. 2024)

Method	mAP/%	Precision/%	Recall/%
YOLOv5	54.4	64.5	62.6
YOLOv8	55.5	71.1	60.9
YOLOv9	43.8	55.2	50.7
YOLOv10	48.0	79.3	56.2
YOLOv11	57.2	66.4	64.8

The YOLOv11 series includes multiple variants designed for different application requirements. These variants, such as YOLOv11-n (nano), YOLOv11-s (small), YOLOv11-m (medium), YOLOv11-I (intermediate), and YOLOv11-x (extreme), offer a balance between accuracy, speed, and computational efficiency (Kishor, 2024). YOLOv11-s is particularly suitable for medium-scale applications, providing a balance between detection speed and accuracy.

2.4 SIGNIFICANCE OF THE STUDY

This study introduces a computer vision system using YOLOv11-s architecture to detect mobile phone use among construction labourers, which is a critical yet underexplored factor in construction productivity. Some studies have focused on helmet detection (Cheng, 2024; Hayat & Morgado-Dias, 2022) and indoor mobile use using sensors (Merchán et al., 2024). However, no studies have integrated person detection, helmet detection and mobile phone detection for alternative manual supervision for enhancing construction productivity. The system aims to offer a scalable, real-time alternative to manual supervision with implications for improving the productivity of labourers at construction sites.

3. METHODOLOGY

3.1 DATASET COLLECTION

Three datasets were used to train the model: (1) for person detection, (2) for "helmet" referred to as "hard hat" detection and (3) for mobile phone detection. These datasets were obtained from an online platform called RoboFlow, which provides a collection of images and associated annotations, specifically designed for training computer vision models. RoboFlow was chosen due to its high-quality and annotated datasets. The dataset consisted of construction images taken from different locations for the model development. Custom images from Sri Lankan construction sites were also incorporated for deployment validation and to identify overfitting. The images were standardised to a resolution of 640×640×3 (RGB scale) to ensure the consistency of the dataset throughout the model training, testing and validation processes.

The person dataset consisted of 5,483 images, with 80% allocated for training, 19% for validation, and 1% for testing. The hard hat dataset contained images of construction labourers with helmets (labelled as "hard hats") and no helmets (labelled as "no hard hats"). The hard hat dataset consisted of a total of 19,745 annotated images, with 70% allocated for training, 20% for validation, and 10% for testing. The mobile phone dataset consisted of 10,768 annotated images, capturing various instances of mobile phone usage by people. The dataset was divided into 82% for training, 14% for validation, and 4% for

testing. These splits ensured that the model had a large enough dataset for learning, testing and validation. For this study, it was assumed that wearing a yellow hard hat is mandatory for construction labourers in Sri Lanka.

3.2 MODEL TRAINING

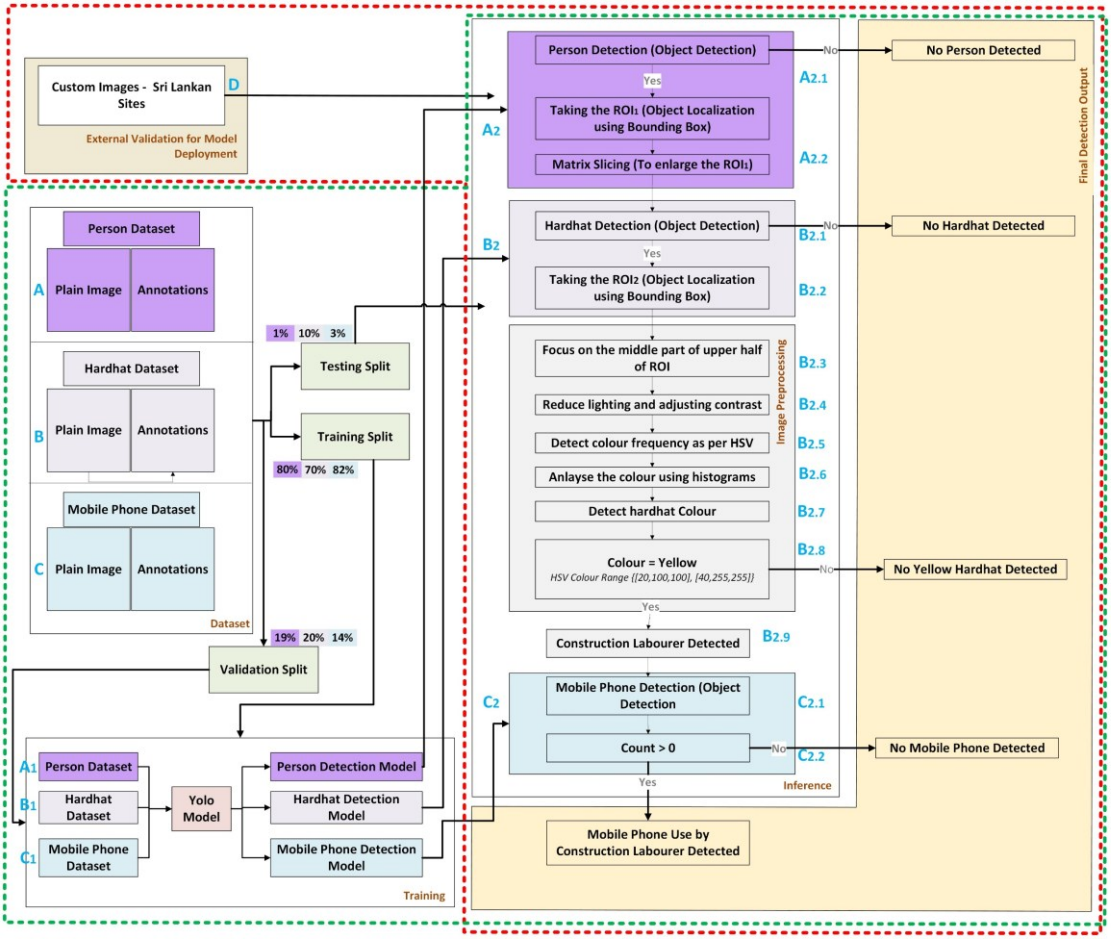


Figure 1: Overall architectural diagram of YOLOv11-s model for detection of mobile phone use by construction labourers

3.2.1 Hyperparameters

Before training, various hyperparameters are utilised to balance the model performance and computational efficiency. These hyperparameters are configuration variables that control the training process by determining the complexity, learning rate, batch size and other variables (Andonie, 2019). According to Alif (2024), key hyperparameters of the YOLOv11 models are learning rate, momentum, weight decay, batch size and the number of epochs. The learning rate of a model indicates how quickly a model learns based on the dataset, whereas momentum accelerates the training process by smoothing out updates of the model. Weight decay is a regularisation technique that prevents the model from overfitting. Batch size represents the number of training datasets processed at once. The number of epochs refers to the number of times the model processed the entire dataset.

In the model, all the hyperparameters, apart from the epochs number were preset with the values in Table 2. In this study, the model was trained for 100 epochs, allowing it to refine the internal parameters based on error calculations.

Table 2: Key parameters for YOLOv11-s training

Hyperparameter	Value
Learning Rate	0.01
Momentum	0.937
Weight decay	0.0005
Batch Size	16 images

3.2.2 Training Process

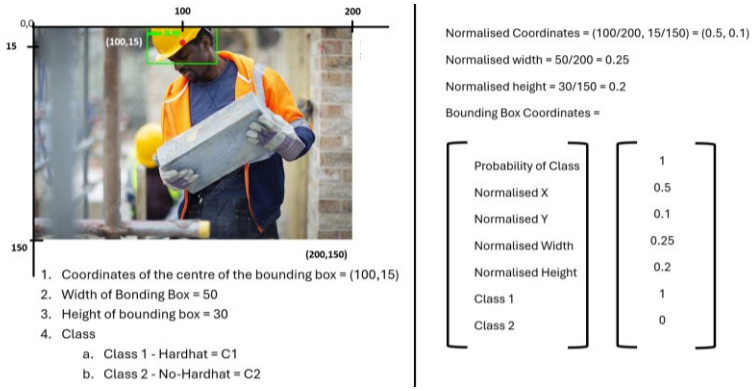


Figure 2: Bounding box coordinates

After splitting each dataset into training, validation, and testing sets, the YOLOv11-s architecture was trained in three phases, as illustrated in Figure 1. The steps have been labelled as "A" for person detection, "B" for hard hat detection, and "C" for mobile phone detection. Additionally, the model development and deployment processes are represented using two types of dotted boxes: the green-coloured dotted box indicates training, internal validation, and testing, while the red-coloured dotted box represents external validation using custom Sri Lankan images. The first phase (A1) involved identifying the region of interest (ROI) by detecting people in the image and applying matrix slicing to separate the ROI area while storing the original coordinates of the ROI within the image. During this stage, the model performed object localisation by generating bounding box coordinates, assigning a confidence score, and classifying detections as person or no-person. The bounding box coordinates were determined as shown in Figure 2. Here, if a person was detected in the image, the model was trained to process only the selected region of interest (ROI) to the next phases. The total training time of the person detection model was 2.416 hours.

Similarly, in the second phase (B1), the model was trained to detect construction hard hats and accurately localise their positions within the image, where detected objects were classified as either hard hat or no-hard hat. The total training time for the hard hat detection model was 6.827 hours. In the third phase (C1), the model was trained using the mobile phone dataset to detect and localise mobile phones. Unlike the person detection model and hard hat detection model, C1 focused solely on detection, where the model was trained to determine whether a mobile phone was present in an image, without further classification. The total training time for the mobile phone detection model was 5.192 hours.

3.3 MODEL VALIDATION (INTERNAL)

During each training epoch, the model underwent an internal validation process to assess its performance and generalisation ability. The validity of the model was determined using several metrics such as precision, recall, mean average precision (mAP), and inference time.

3.4 MODEL INFERENCE

After training, the inference process (A2 to C2) was conducted to evaluate each model's performance. As illustrated in Figure 1, the inference pipeline consists of four key components: to detect people, the presence of hard hats, the colour of hard hats and the use of mobile phones. The first component of the pipeline is the YOLOv11-s person detection model, which detects (A2.1), localises (A2.2), and slices the matrix (A2.3) to isolate ROI1 (the detected person) from the full image. This step provided the subsequent detections with enlarged ROI focusing only on relevant regions.

The sliced matrix is passed through the hard hat detection model, which detects (B2.1) and localises (B2.2) hard hats within the ROI. After localisation, the hard hat region undergoes image preprocessing (B2.3 to B2.8) to determine its colour accurately. Due to varying lighting conditions, detecting a fixed hard hat colour was challenging, as some areas of the hard hat appeared shinier or darker than others. The Red-Green-Blue (RGB) colour scale relies on fixed values, which are suitable for consistent lighting conditions. However, inconsistent lighting caused by environmental factors made the RGB-based colour scale unsuitable for this model. To overcome this limitation, this study used the Hue-Saturation-Value (HSV), which employs a range of values to define colours. By applying histogram analysis, the primary colour of the hard hat was determined based on the HSV range it belonged to. As shown in Figure 3, the central part of the upper half of the ROI was focused (B2.3), lighting and contrast were adjusted (B2.4), and its HSV values were extracted (B2.5). A histogram analysis (B2.6) was then performed to detect the colour (B2.7) and classify the hard hat as either "yellow hard hat" or "no yellow hard hat" (B2.8).

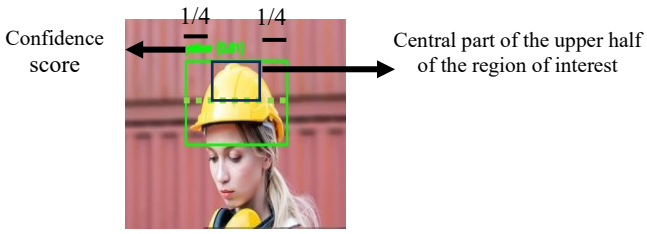


Figure 3:Region of interest

After the hard hat detection, the processed image was passed through the YOLOv11-s mobile phone detection model (C2). This model detects the presence or absence of a mobile phone (C2.1), highlighting whether a labourer is using a mobile phone in the image. Finally, the pixels in the original image were replaced with the processed image containing the detected elements. Here, the original image is displayed with the detections made.

3.5 MODEL DEPLOYMENT VALIDATION

The model was validated using images obtained from Sri Lankan construction sites (D) to assess its applicability within the Sri Lankan context and to check for potential overfitting.

4. RESULTS AND PERFORMANCE EVALUATION

4.1 CONFUSION MATRIX

A confusion matrix of 2x2 classifiers determines the predicted and actual classification. Table 3 provides the details of a 2x2 confusion matrix, which provides the relationship between true positives, false positives, true negatives and false negatives. As shown in Figure 2, the model provides a confidence score for the certainty of its detection, which plays a crucial role in identifying the false negative and false positive labels (Wenkel et al., 2021). In this study, a confusion matrix was generated only for the hard hat detection model, which performed detection and classification.

Table 3: Standard Confusion Matrix

	Actual Positive	**Actual Negative**
Predicted Positive	True Positive (TP)	False Positive (FP)
Predicted Negative	False Negative (FN)	True Negative (TN)

Figure 4 provides the normalised confusion matrix of the hard hat detection model, which detects two classes: hard hat and no hard hat. The values are normalised to represent the proportion of the outcome instead of raw counts, which undergoe object detection and classification. The values are normalised to represent the proportion of the outcome instead of raw counts. The matrix indicates 95% accuracy for hard hat detection and 90% accuracy for no-hard hat detection, with significantly low false positive and false negative rates.

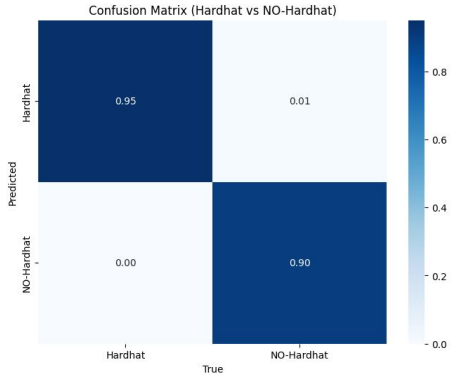


Figure 4: Normalised confusion matrix for hard hat classification

4.2 PRECISION-RECALL CURVE

Precision measures the ratio of true positive detections to the total positive detections made (see Equation 1). This reflects the ability of the model to accurately classify “hard hat” or “no-hard hat” without generating false detections. A high precision score indicates a lower rate of false detection. Meanwhile, recall measures the ratio of true positive detection to the total actual positive labels (see equation 2). It indicates how well positives

are recalled. A high recall score indicates that the model is effective in detecting the relevant instances.

$$Precision = \frac{TP}{TP+FP} \quad Equation\ (1) \qquad Recall = \frac{TP}{TP+FN} \quad Equation\ (2)$$

To achieve high prediction accuracy, it is crucial to maintain a balance between precision and recall. A model with high precision but low recall is very accurate in its positive predictions but misses a significant number of actual positive labels, while high recall but low precision may lead to excessive false positives. Therefore, a precision-recall (PR) curve for each detection task illustrates how well the model trades off these values.

The PR curve in Figure 5 shows the balance between precision and recall for the person detection model. Accordingly, the model achieved a high precision at a lower recall value, indicating a high probability of correct positive prediction. As the recall value increases, the false positive prediction also increases. The PR score for the person detection model was 0.826, indicating that the model correctly detects 82.6% of the actual instances. Similarly, the PR curve for hard hat detection in Figure 6 demonstrates high precision-recall scores, with 0.933 for hard hat detection and 0.927 for no-hard hat detection. The model maintains high precision across most recall values. This indicates the model can correctly classify hard hats while minimising false positives. Finally, Figure 7 presents the precision-recall curve for mobile phone detection, which also indicates a high PR value of 0.916, indicating that the model correctly detects 91.6% of the actual instances.

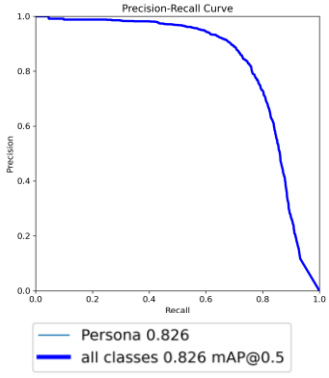


Figure 5: Precision-Recall curve for person detection

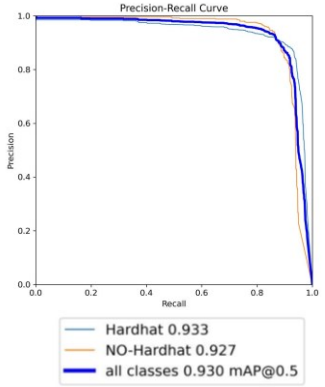


Figure 6: Precision-Recall curve for hard hat detection model

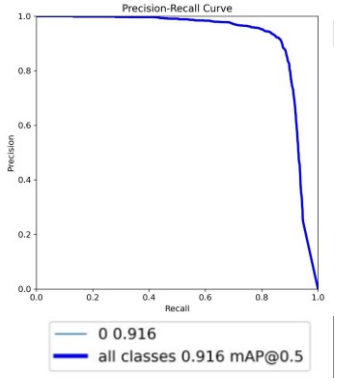


Figure 7: Precision-Recall curve for mobile phone detection

4.3 MEAN AVERAGE PRECISION (MAP)

The mAP calculates the average precision across multiple Intersections over Union (IoU) thresholds. Here, mAP@0.5 was calculated, where the average precision was calculated at a threshold of 0.5. This evaluated the accuracy of the classification.

$$mAP@0.5 = \frac{1}{number\ of\ classes\ (n)} \sum_{i=1}^{n.} Average\ Precision \quad Equation\ (3)$$

According to Figures 5, 6, and 7, the mAP@0.5 of the person detection model, hard hat detection model, and mobile phone detection model were 0.826, 0.930, and 0.916, respectively. These results indicate that each model achieved a high detection accuracy, with scores exceeding the identified threshold values. The hard hat detection model showed the highest performance among the trained models. These results infer that the trained models can provide accurate detection in construction site environments.

4.4 INFERENCE TIME

Inference refers to the process of using a trained model to make predictions on new, unseen data by processing an image and generating detection results. The inference time of the model measures the average time taken by the YOLOv11-s model to process a single image and generate the detection results. The YOLOv11-s model demonstrated fast inference times, with the person detection model achieving the quickest processing of 4.9ms. The hard hat detection model took 8.5ms, which is slightly longer due to the added classification of hard hat and no-hard hat classes. Similarly, the mobile phone detection model had an inference time of 8.4ms, due to the additional processing required for detecting smaller objects. All three models demonstrated a fast-processing time which indicated that the model is suitable for real-time application.

4.5 TRAINING AND VALIDATION LOSS

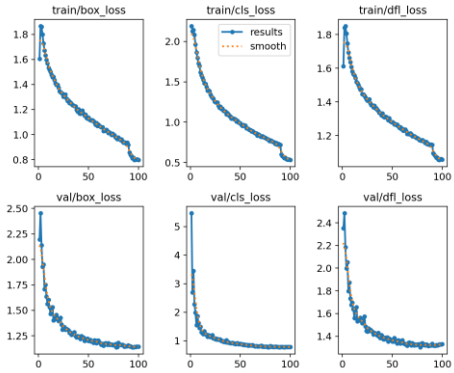


Figure 8: Training and validation loss curve for person detection

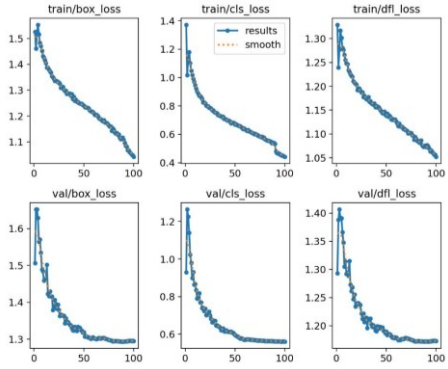


Figure 9: Training and validation loss curve for hard hat classification

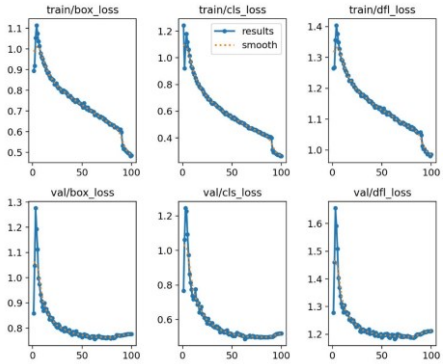


Figure 10: Training and validation loss curve for mobile phone detection

Furthermore, the loss function, also referred to as the error function, quantifies the error between the algorithm's predicted output and the actual output. The YOLOv11-s model uses a unified loss function, which is a combination of three loss components. This includes Complete Intersection over Union loss (CioU), Binary Cross Entropy Loss (BCE) and Distribution Focal Loss (DFL). CioU is used for the bounding box regression (box_loss) (Zheng et al., 2021), BCE is used for the classification (cls_loss) (Li et al., 2024)and DFL is used for better localisation accuracy by refining the predicted bounding box coordination (dfl_loss) (Wang et al., 2023).

Figures 8, 9 and 10 provide the training and validation loss curves recorded during the model's training in person detection, hard hat classification and mobile phone detection. As the number of epochs increased, the loss function steadily decreased indicating an

effective learning and optimisation by the model. Similarly, the precision, recall and mAP metrics exhibited a steady increase over epochs, reinforcing the model's improving performance. The model's stable performance suggests high reliability in classifying hard hat and no-hard hat cases.

4.6 MODEL DETECTIONS

Figure 11 presents the detections performed by the model across various conditions during the testing phase. Here the detection is indicated with a bounding box and a confidence score which demonstrates the level of certainty of the model in making the detection.

4.7 MODEL DEPLOYMENT IN THE SRI LANKAN CONTEXT

The model was tested with custom images obtained from Sri Lankan construction sites, captured with cameras and mobile phones to validate its deployment performance and to check for model overfitting. The Sri Lankan construction site dataset included images taken from distant locations, where the person detection model and matrix slicing played a crucial role in enlarging the ROI for subsequent detections. After detecting the mobile phone, the processed image was refitted to the original image using its initial coordinates with detection results as shown in Figure 12 to Figure 14.



Figure 11: Construction labourers with mobile phones



Figure 12: Construction labourer with mobile phone



Figure 13: Construction labourer with blue helmet



Figure 14: Construction labourer without helmet and with mobile phone

5. CONCLUSIONS AND RECOMMENDATIONS

This study presented an analysis of the YOLOv11-s model in the detection of mobile phone use by construction labourers. The use of YOLOv11-s has demonstrated faster processing by structuring detection into four components: (1) detection of people, (2) detection and classification of hard hats, (3) image processing to detect hard hat colour and (4) mobile phone detection. Training, internal validation and testing of the model were done using datasets obtained from an online database. The model was externally validated for deployment using custom images obtained from Sri Lankan construction sites and checked for potential overfitting. With high inference speed and accuracy, the model indicated a satisfactory level of applicability to the Sri Lankan context and proved to be a solution for construction projects concerned with productivity challenges caused by mobile phone distractions among labourers. While the system was tested on Sri Lankan site images for the deployment, the methodology and model architecture are universally applicable across global construction environments. Even though the model demonstrated a satisfactory level of accuracy, the detection accuracy may vary depending on external factors such as dust levels in surroundings, weather conditions, detection

distance, and the quality of captured photos, which is a limitation of this study. Therefore, future research can focus on enhancing the proposed model by training it with a large set of Sri Lankan images captured under diverse environmental conditions and lighting variations to improve its reliability. Additionally, the model can be developed to detect continuous mobile phone usage among site labourers through motion detection and timeframe analysis using the Internet of Things (IoT). This would enable the model to monitor frequent and prolonged mobile phone usage from CCTV footage, providing real-time alerts to supervisors to enhance productivity on construction sites.

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DEVELOPING A KNOWLEDGE VALUE CHAIN FRAMEWORK FOR TENDERING IN SRI LANKAN CONSTRUCTION ORGANIZATIONS

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ABSTRACT

The construction industry in Sri Lanka, like many in developing nations, faces persistent inefficiencies in tendering processes due to fragmented knowledge practices and inadequate knowledge management systems. This study presents the preliminary findings of a broader research project aimed at developing an advanced Knowledge Value Chain Management (KVCM) framework to address these challenges. Drawing on both theoretical underpinnings and empirical insights, the research critiques the limitations of existing tendering models for the purpose of developing a KVCM framework to structure, process, and leverage organizational knowledge. Preliminary insights suggest that successful integration of the KVC approach requires not only process-level adjustments but also a cultural and infrastructural shift toward strategic knowledge sharing and ICT-enabled systems. This paper forms part of an ongoing research initiative that culminates in the formulation of a comprehensive, context-sensitive KVCM model for the Sri Lankan construction sector. By bridging knowledge management principles with tendering strategy, this study contributes to the emerging discourse on knowledge-based competitiveness in project-driven industries. It underscores the strategic potential of KVC integration to foster institutional memory, improve tendering efficiency, and support sustainable organizational learning in developing construction markets. This contribution advances the discourse on knowledge management in project-based industries and underscores the strategic role of knowledge as an asset in competitive tendering environments.

Keywords: *Knowledge Value Chain Management; Quantity Surveyors'; Construction; Sri Lanka; Tendering.*

1. INTRODUCTION

Knowledge Management (KM) has evolved as a critical discipline within organizational theory, particularly since the 1990s, emphasizing the strategic role of knowledge as a core asset for competitive advantage (Nonaka & Takeuchi, 2023). In construction, where

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projects are unique and temporally bound, KM is especially important for capturing, codifying, and transferring valuable project knowledge to enhance future project outcomes. The development of Knowledge Value Chain Models (KVCMs), such as those building on Porter's foundational Value Chain framework (Porter, 2008), has further advanced the structured management of knowledge. Many studies (De Bem Machado et al., 2022; Di Vaio et al., 2021; Gallupe, 2001) have investigated the concepts of knowledge, KM, and KVCMs from an organizational perspective. KVCMs in construction are tailored frameworks that map the flow of knowledge across project stages, ensuring that valuable insights gained are not only retained but systematically used to optimize performance and improve tendering processes (Baia et al., 2020). However, existing KVCMs are generally designed with a broad organizational focus, leaving a gap in literature regarding their application to the specific knowledge value creation within the tendering process of construction organizations, particularly in relation to quantity surveying.

The construction industry, particularly in developing economies such as Sri Lanka, is knowledge-intensive and increasingly reliant on the effective mobilization of intellectual capital for competitive advantage. Among key professionals, Quantity Surveyors (QSs) play a central role in cost control, tender evaluation, and contract administration, functions that depend heavily on the systematic creation, sharing, and utilization of knowledge. As construction projects become more complex and time-bound, the ability to manage this knowledge efficiently across the tendering phase has become critical. This shift underscores the growing relevance of KVCM frameworks which aim to optimize knowledge flows to enhance organizational performance and strategic positioning. Globally, research has demonstrated the utility of KVCM in refining construction processes, particularly tendering, through structured knowledge governance. Dewagoda et al. (2021) proposed a KVCM framework explicitly for contractor organizations, emphasizing how knowledge processes can increase the probability of winning tenders and improve decision-making efficacy. However, such frameworks are typically conceptualized in broader corporate or regional contexts, with minimal focus on the nuanced operational roles played by QSs in emerging economies.

In the Sri Lankan context, knowledge management among QSs has largely been limited to ad hoc practices. Senaratne and Sabesan (2010) found that while QSs in Sri Lanka are competent in applying experiential knowledge, systemic barriers such as poor institutional support, time constraints, and limited professional recognition hinder knowledge acquisition and dissemination. Moreover, existing research have not addressed how structural and cultural constraints unique to Sri Lanka impede the implementation of formal KVCM approaches during tendering. While Perera and Gunatilake (2022) discussed the broader inefficiencies in Sri Lanka's construction value chains, their work did not explore tendering-specific dynamics or the QS's knowledge role therein.

This paper aims to explore the preliminary conditions necessary for the development of a Knowledge Value Chain Management framework tailored to the tendering processes of Sri Lankan construction organizations. As a foundational phase of a broader research project, the study seeks to critically examine current knowledge practices, identify barriers to effective knowledge management, and assess the applicability of existing KVC models within the local tendering context. Specifically, the objectives are: (1) to investigate how knowledge is created, shared, and utilized by Quantity Surveyors and

other professionals during tendering; (2) to evaluate the strategic role of knowledge in achieving competitive advantage in construction tendering; and (3) to identify structural, cultural, and operational constraints that influence the integration of KVC principles in practice. These insights serve as the empirical and conceptual groundwork for the subsequent development of a comprehensive, context-sensitive KVCM framework aimed at enhancing organizational learning and decision-making in Sri Lanka's construction sector.

2. LITERATURE REVIEW

2.1 EVOLUTION OF KM IN CONSTRUCTION

KM has evolved through three distinct generations, reflecting a shift from information-centric systems to strategic, value-driven frameworks. In the first generation, KM was primarily technical, focusing on the codification and storage of explicit knowledge through databases and intranets. However, this approach inadequately addressed the tacit, experience-based knowledge crucial in project-based industries like construction (Rezgui et al., 2010). The second-generation approaches emphasized social interaction and knowledge sharing, introducing mechanisms such as communities of practice and mentoring. In construction, this generation aligned more closely with the industry's collaborative nature, where cross-functional teams must exchange expertise across fragmented project cycles (Anumba & Pulsifer, 2010). The third generation of KM focuses on strategic alignment and value creation, positioning knowledge as a dynamic capability rather than a static resource. It integrates KM into innovation, performance improvement, and organizational competitiveness, critical in today's complex construction environments (Chen & Fong, 2013).

Despite these advances, the construction sector remains one of the more challenging environments for KM implementation. The fragmented supply chains, short-term contractual relationships, and diversity of stakeholders pose systemic barriers to KM maturity (Egwunatum & Oboreh, 2022). These barriers are especially pronounced in small to medium-sized firms, which lack the resources to implement sophisticated KM systems. Furthermore, the emphasis on project delivery over organizational learning continues to marginalize KM in many construction enterprises. The evolution of KM has laid a conceptual and operational foundation for the emergence of KVCM models. As KM transitioned from static knowledge repositories to dynamic, value-oriented systems, scholars recognized the need to map knowledge processes directly to organizational performance outcomes (Rezgui et al., 2010). This realization gave rise to the KVCM approach, which integrates KM activities into a chain of interrelated processes that collectively generate measurable business value (Boamah et al., 2022). In project-based industries like construction, where knowledge must be continuously created, contextualized, and applied across shifting teams and time-bound deliverables, KVCM offers a structured methodology to convert intellectual capital into strategic advantage (Dewagoda et al., 2021). Thus, KVCM can be understood as an advanced extension of KM, bridging the gap between knowledge practice and value realization in complex, knowledge-intensive sectors.

2.2 KNOWLEDGE VALUE CHAIN MODELS

KVCMs are structured frameworks that outline the processes through which knowledge is created, shared, and applied within organizations. One of the foundational models was introduced by Porter (1985) in his Value Chain framework, which highlighted how value is created through a series of primary and support activities. Adapted for KM, KVCMs emphasize the flow and transformation of knowledge across different stages, such as knowledge creation, storage, sharing, and utilization. These stages are essential for capturing both explicit and tacit knowledge, ensuring that valuable insights from past projects or organizational experiences are effectively leveraged. The application of KVCMs in KM practices can foster better decision-making, innovation, and overall organizational learning, particularly in knowledge-intensive industries like construction (Rezgui, 2001). However, the effectiveness of KVCMs depends on their integration into organizational structures and the willingness of individuals to contribute their knowledge to these systems.

A key aspect of KVCMs is their focus on knowledge creation and dissemination, often facilitated by advanced technologies such as knowledge management systems (KMS). Dalmarco et al. (2017) argue that effective KVCMs not only capture knowledge but also enhance knowledge sharing across departments, reducing silos and promoting organizational cohesion. By structuring knowledge flows, KVCMs ensure that both tacit and explicit knowledge are accessible for decision-making processes, contributing to competitive advantage. However, despite their benefits, the challenge often lies in the codification of tacit knowledge, experiential, often unspoken insights that are difficult to formalize (Nonaka & Takeuchi, 2007). Construction organizations, for instance, struggle with capturing the vast amounts of tacit knowledge generated through project experiences, which is critical for maintaining continuity between projects (Carrillo et al., 2013). KVCMs have evolved significantly since Porter's seminal work in 1985, which introduced a framework for analysing competitive advantage by examining primary and support activities within organizations. Over time, these models have adapted to include critical aspects of KM and digital transformation, which are increasingly important in today's data-driven business environments. Table 1 provides a summary of five key KVCMs that have been recognized through the literature. These models have played a key role in the evolvement of knowledge management in the construction industry.

Table 1: KVCMs developed over the years

	Reference	Model summary
1	(Porter, 1985)	This model identifies primary (inbound logistics, operations, outbound logistics, marketing and sales, and service) and support activities (firm infrastructure, human resource management, technology development, and procurement) to analyse competitive advantage.
2	(Alavi & Leidner, 2001)	This model applies value chain logic to knowledge, focusing on stages such as acquisition, codification, transfer, and application to optimize the creation and utilization of knowledge within organizations.
3	(Stankosky, 2005)	This model extends KM principles by focusing on knowledge flow and transformation within organizations,

	Reference	Model summary
		advancing from data to information, knowledge, and wisdom to support strategic decision-making.
4	(Lambert & Cooper, 2000)	This model adds customer and supplier relationship management to traditional value chain analysis, reflecting modern supply chain complexities.
5	(Bharadwaj et al., 2013)	This model adapts value chain concepts for digital business, emphasizing data-driven processes and digital resources, enhancing efficiency and responsiveness in real-time market dynamics.

In developed economies, the application of KVCMs has been linked to enhanced project integration, transparency, and innovation. Organizations benefit from ICT-enabled knowledge flows, organizational learning cultures, and institutional incentives. In contrast, the implementation of KVCs in developing countries often suffers from significant structural deficiencies. These include limited digital infrastructure, fragmented project teams, and the absence of formal knowledge-sharing mechanisms. Such inefficiencies constrain the conversion of knowledge into actionable project outcomes, contributing to cost overruns and tendering inefficiencies (Senaratne & Sabesan, 2010). Sri Lanka exemplifies this disparity. Despite the growing strategic role of Quantity Surveyors in managing cost and risk, KVCM adoption remains embryonic. Studies reveal knowledge-sharing mechanisms are informal, often limited to individual initiative, with minimal institutional support or sector-wide frameworks (Perera & Gunatilake, 2022). These systemic gaps highlight a pressing need for a context-specific KVC model tailored to Sri Lanka's construction environment. This study addresses that lacuna by critically exploring the preconditions necessary for meaningful KVC integration in tendering processes.

3. RESEARCH METHODOLOGY

This study adopts a qualitative, interpretivist (constructivist) research paradigm to investigate how knowledge is generated, shared, and applied in tendering processes within Sri Lankan construction organizations. The interpretivist approach, which focuses on understanding subjective meanings and contextualized practices, is well-suited for exploring the complex, tacit nature of knowledge in construction tendering settings (Creswell & Creswell, 2017).

3.1 RESEARCH DESIGN AND RATIONALE

Given the exploratory nature of the study and the limited literature on KVCM in construction tendering, a qualitative approach was selected. This design enables deep engagement with the perspectives of QSs, and other professionals involved in the tendering process. The study specifically focuses on the contractor-side perspective, as contractors are primarily responsible for operationalizing knowledge in competitive bidding and pricing strategies. Two qualitative methods were employed: semi-structured expert interviews and multiple case studies. The combination enhances methodological triangulation and allows for both depth (through interviews) and context (through organizational case analysis) as recommended in exploratory construction research (Yin, 2009).

3.1.1 Phase I: Expert Interviews

Semi-structured interviews were conducted with ten purposefully selected professionals (Table 2). Participants were selected using purposive sampling based on three criteria:

- Minimum of 10 years of experience in tendering/contract management.
- Chartered status or senior executive position.
- Involvement in contractor-side tendering decisions.

This selection ensured that participants possessed in-depth practical knowledge of tendering knowledge practices. The semi-structured format enabled consistent inquiry while allowing exploration of emergent themes (Adeoye-Olatunde & Olenik, 2021).

Table 2: Expert interviewee profiles

Code	Designation	Experience	
		Years	Key Experience
PI.01	Claims Consultant	20	Tendering, Claims Management, Project Management
PI.02	Freelancer QS	30	Tendering, Tender Negotiation, Project Administration
PI.03	Chief QS	20	Tendering, Contract Management, Project Administration
PI.04	Director	43	Tendering, Tender Evaluation, Contract Management
PI.05	Assistant General Manager	11	Tendering, Tender Negotiation, Project Administration
PI.06	Senior Lecturer	26	Tendering, Claims Management, Commercial Management, Forensic Delay Analysis
PI.07	Senior QS	20	Tender Evaluation, Consulting, Project Administration
PI.08	Managing Director	35	Tendering, Tender Negotiation, Contract Management
PI.09	Chairman	20	Tendering, Project Administration, Contract Management
PI.10	Senior QS	20	Tender Evaluation, Consulting, Project Administration

3.1.2 Data Analysis and Validation

Interview transcripts were analysed using manual content analysis, allowing for inductive theme identification with attention to contextual meaning (Mayring, 2021; Salmona & Kaczynski, 2024). Key themes included knowledge creation, sharing mechanisms, barriers, and perceived value across the tendering lifecycle.

To ensure rigor, the following validation strategies were implemented:

- Construct Validity: Achieved through triangulation of interviews and document reviews (Yin, 2009)
- Internal Validity: Enhanced via pattern matching between expected and emergent themes (Takada et al., 2021)

- Reliability: Ensured through standardized interview protocols and systematic transcript archiving (Wong et al., 2023)

4. FINDINGS AND DISCUSSION

This section presents and critically analyses the findings from Phase I of the research, which involved expert interviews aimed at informing the development of a Knowledge Value Chain Management framework for tendering in Sri Lankan construction organizations. Data were obtained from ten semi-structured interviews with Chartered Quantity Surveyors and senior professionals (see Table 2). The themes discussed here are directly derived from interview data and interpreted in relation to the research objectives. Quotations from participants are coded as PI.01 to PI.10.

4.1 THE KNOWLEDGE-INTENSIVE NATURE OF CONSTRUCTION

Participants unanimously agreed that the construction industry is inherently knowledge-intensive due to its complex and dynamic nature. PI.03 noted, "Every tendering decision we make depends on how well we understand the site, client, and contractual environment." The fast pace of technological change and the multifaceted nature of projects demand continuous learning and information flow. This finding reinforces the notion that effective knowledge practices are vital to navigating risk and uncertainty in project environments. Unlike prior literature that generalizes the importance of KM (Nonaka & Takeuchi, 2007), this study emphasizes that the demand for knowledge specificity is especially acute in tendering contexts.

4.2 STRATEGIC USE OF TENDERING APPROACHES

Interviewees highlighted two dominant strategies in tendering: cost leadership and differentiation. Cost leadership is more prevalent in public-sector projects, while differentiation is pursued in private-sector tenders. However, PI.06 emphasized that "real differentiation comes not just from price, but from how we propose to execute and manage the job." These findings nuance Carrillo et al.'s (2013) framework by indicating that strategic deployment is often bid-phase specific and shaped by institutional expectations. Moreover, the interviews revealed a lack of formal integration between strategic intent and knowledge processes, which creates inefficiencies in adapting tendering strategies.

4.3 ROLE OF TACIT KNOWLEDGE IN COMPETITIVE ADVANTAGE

Interviewees consistently emphasized the significance of tacit knowledge in enhancing organizational competitiveness. PI.01 stated, "You can't teach someone how to price intuition, you learn it on the job." The data revealed that practical experience, intuition, and context-sensitive knowledge play a dominant role in shaping tender outcomes. This insight echoes Hanisch et al. (2009), but the study adds granularity by showing how tacit knowledge is often internalized by senior QSs and not effectively transferred within teams. This knowledge asymmetry creates strategic vulnerabilities for firms.

4.4 ORGANIZATIONAL LEARNING AND KNOWLEDGE REUSE

Participants strongly supported the idea that construction organizations function as learning entities. PI.08 observed, "Each project teaches us something new, but we often fail to document or apply that knowledge." The absence of formalized feedback loops leads to repeated mistakes and lost insights. While Darwin (2017) advocates for structured learning in project cycles, the data here suggest that although professionals value learning, organizations lack mechanisms to operationalize it. This presents a critical area where KVCM could improve tendering performance.

4.5 STRATEGIC ROLE OF QUANTITY SURVEYORS

QSs were unanimously acknowledged as central to the competitive success of construction firms. According to PI.02, "The QS is the one who converts the project vision into numbers, it's both an art and a science." Their dual role in cost control and value optimization underscores their importance as knowledge brokers. This supports Mbachu (2015), but the present study contributes further by highlighting how QSs must navigate between managerial and knowledge-intensive roles, making them pivotal in KVC deployment.

4.6 QSS AS KNOWLEDGE WORKERS AND DECISION MAKERS

Interviewees offered nuanced perspectives on classifying QSs as Knowledge Workers (KW) or Decision Makers (DM). PI.09 stated, "Even junior QSs make decisions, maybe not strategic ones, but operationally critical ones." This suggests a fluid continuum where roles shift based on context and experience. This challenges Powell's (2001) rigid categorization and emphasizes the need for adaptable role definitions in KVCM models tailored for construction.

4.7 APPLICABILITY OF THE KVCM IN TENDERING

Participants expressed strong support for the KVCM concept. PI.04 stated, "We badly need a model that helps us align our experience, lessons learned, and market understanding with each new bid." The model was seen as a practical tool for minimizing redundancy, improving pricing strategies, and fostering learning. While Alavi and Leidner (2001) underscore the benefits of structured KM systems, this study provides empirical validation from a Sri Lankan context, highlighting both the necessity and feasibility of KVCM in enhancing tendering effectiveness.

4.8 BARRIERS TO KVCM IMPLEMENTATION

Several barriers to KVCM implementation emerged from the interviews. While these challenges are situated within the Sri Lankan construction context, they are emblematic of broader trends observed across developing and transitional economies in the construction sector, suggesting that the findings are both context-specific and generalizable to comparable settings. A recurrent theme is the misalignment between formal knowledge systems and existing organizational structures. Specifically, the fragmentation of KVCs and the marginalization of enabling systems reflect a structural rigidity commonly observed in project-based industries. Dewagoda et al. (2021) identified this lack of integration as a barrier to optimizing knowledge as a competitive asset in contractor organizations, underscoring the importance of cohesive systems that facilitate knowledge continuity across the tendering lifecycle.

Behavioural and cultural resistance emerges as another critical barrier. This includes scepticism toward knowledge outputs, disregard for feedback mechanisms, and an entrenched focus on traditional roles. These cultural barriers are not unique to Sri Lanka but are well documented in global construction knowledge management studies. As noted by Senaratne and Sabesan (2010), there exists a strong reluctance to share knowledge due to professional insecurities and a lack of systemic incentives, resulting in poor dissemination and underutilization of institutional knowledge. Furthermore, Mahinkanda et al. (2019) highlight the difficulty of bridging the theory-practice gap in value management frameworks due to resistance to new ideas, inadequate training, and minimal support for professional development in knowledge-based roles.

Operational constraints, namely time and cost limitations, were universally acknowledged across all data sources. These are symptomatic of the fast-paced, budget-restricted nature of construction tendering worldwide. The literature emphasizes that KWs, such as quantity surveyors, are often "running against time," which inhibits the adoption of reflective and systematic knowledge practices (Senaratne & Sabesan, 2010). These conditions are mirrored in other studies that link tight project cycles with poor uptake of long-term knowledge strategies. Human resource constraints also appear to have wide relevance. The shortage of skilled professionals with dual competencies in construction and knowledge management has been highlighted as a structural gap, both in Sri Lanka and in other developing regions. Senaratne and Sabesan (2010) emphasized that the emigration of experienced quantity surveyors and the undervaluation of their roles within local firms leads to a weakened knowledge base and diminished opportunities for mentoring and skill transmission.

Finally, the delayed realization of KVCM benefits reflects a broader industry challenge regarding innovation adoption. Without short-term measurable outcomes, organizations may lack the strategic foresight and patience to nurture knowledge ecosystems. This impatience is compounded by a narrow definition of "value" that favours immediate cost or time savings over intangible gains like learning, adaptability, or collaborative capacity. These findings, while grounded in Sri Lankan case studies, point to broader, cross-contextual insights. They underscore the need for an integrative approach to KVCM that encompasses not just technological enablers and formal processes, but also human, cultural, and institutional readiness. As such, the barriers presented are not anomalies but are reflective of deeper structural and behavioural tendencies within the global construction sector. Addressing them requires more than technical adjustments, it calls for a paradigmatic shift in how organizations perceive and operationalize knowledge.

5. CONCLUSION

This This study explored the preliminary conditions necessary for developing a KVCM framework tailored to the tendering processes of Sri Lankan construction organizations. Grounded in qualitative insights from expert interviews with senior Quantity Surveyors and construction professionals, the research examined how knowledge is created, shared, and utilized during tendering, and identified the structural, cultural, and operational factors that influence these practices.

The findings highlight that construction tendering in Sri Lanka is heavily reliant on tacit knowledge, with limited formal mechanisms for capturing and institutionalizing experiential learning. Despite recognition of the strategic value of knowledge in gaining

competitive advantage, organizations lack structured systems for knowledge reuse, resulting in inefficiencies and recurring errors. The study also reveals the dual role of QSs as both Knowledge Workers and Decision Makers, underscoring their pivotal function in shaping tender outcomes. Furthermore, interviewees affirmed the relevance and potential of the KVCM concept for enhancing knowledge-driven competitiveness, even though its practical adoption remains minimal.

This research contributes original, context-specific insights into the intersection of knowledge management and tendering strategy in a developing country context. It advances the understanding of QSs' evolving roles and provides empirical evidence supporting the applicability of KVCM principles in contractor-led tendering environments.

5.1 LIMITATIONS AND FUTURE RESEARCH

This paper represents Phase I of a broader research project. Phase II will involve in-depth case studies with C1-graded construction organizations to examine organizational-level practices and validate the findings. The future phase will culminate in the development of a conceptual KVCM framework specifically adapted to Sri Lankan contractor organizations, linking knowledge processes with decision-making across the tendering lifecycle.

This study is limited by its exclusive reliance on interview data, which, while rich in insight, may not fully capture organizational systems or informal practices across diverse firm sizes. Additionally, the sample was restricted to contractor-side professionals, limiting perspectives from consultants or clients. Future research should incorporate multi-stakeholder viewpoints and mixed methods to triangulate findings and generalize the model across different construction contexts.

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DEVELOPING A SATELLITE-ENABLED DIGITAL TWIN ECOSYSTEM FRAMEWORK FOR ENERGY MONITORING IN SMART CITIES IN SRI LANKA: A LITERATURE REVIEW

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ABSTRACT

Smart cities are at the forefront of sustainable urban development, yet energy monitoring remains a critical challenge for achieving efficiency and environmental goals. Current technologies, such as Internet of Things (IoT) and building management systems, often lack the city-wide perspective needed for comprehensive energy optimization. Similarly in Sri Lanka, energy consumption in smart cities presents a complex challenge, as urban areas account for a significant portion of global energy demand and contribute heavily to carbon emissions. Hence, effective real time energy monitoring is essential to enhance energy efficiency and reduce carbon emissions in smart cities. Among emerging technologies, the satellite-enabled digital twin ecosystem (SEDTE), powered by real-time satellite data, offers a transformative approach to energy monitoring. This study aimed proposing a satellite-enabled digital twin ecosystems (SEDTE) to enhance energy monitoring in smart cities in Sri Lanka. Accordingly, key peer-reviewed journal articles, conference papers, and reports published on satellite technology, digital twins, smart cities, energy monitoring and energy efficiency between 2015 and 2025 were comprehensively reviewed. As derived through literature review, data acquisition, real-time energy optimization, grid resilience, load balancing, demand response, renewable energy integration, and disaster preparedness of energy systems are the key applications of SEDTE in the context of smart city energy monitoring. Finally, a framework was proposed to adopt this advanced technology in the development of smart cities in Sri Lanka and similar settings as the key implication of the study.

Keywords: *Digital Twin Ecosystems; Energy Monitoring; Satellite Technology; Smart Cities; Urban Sustainability.*

1. INTRODUCTION

With cities growing rapidly, smart cities use advanced tech to boost efficiency and sustainability. Energy management is a key challenge, critical for cutting emissions and meeting climate goals. Smart cities rely on interconnected systems to manage energy across residential, commercial, and industrial sectors. Urban areas consume about 70%

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of global energy and produce 75% of carbon emissions. Rising populations, electric vehicles, and tech like IoT devices drive complex energy demands. Consumption varies by area and time—think business districts peaking daytime versus homes at night. This variability, plus the shift to renewables like solar, demands precise monitoring to avoid waste and ensure grid stability (Batty, 2018).

Monitoring energy use is vital for sustainable smart cities. It helps spot inefficiencies, balance supply and demand, and cut emissions. Real-time data supports strategies like dynamic pricing, easing grid stress (Mohammadi & Taylor, 2017). It also aligns with UN Sustainable Development Goals (SDGs 7 and 11) and aids renewable energy integration, like rooftop solar. At present, smart meters, building management systems (BMS) and graphic information systems (GIS) are applied for monitoring energy consumption in buildings and urban infrastructure, while ground-based remote sensing and IoT sensors have become increasingly popular (Alahakoon & Yu, 2016; Ejaz et al., 2017; Yamagata & Seya, 2013). However, these tools work well in isolation but lack the integration needed for city-wide, real-time monitoring, highlighting the need for solutions like digital twins (Qi et al., 2021). Satellite-enabled digital twins' virtual representations of urban systems enhanced by real-time satellite data which provide a revolutionary approach to monitor energy consumption. These systems provide city-wide insights and predictive tools (Tao et al., 2019; Sharma et al., 2024). The satellite-enabled digital twins system combines satellite imagery and virtual modelling to track city energy systems. Further, this technology can be used to monitor the entire city, detecting heat losses and solar efficiency. Possibility of integrating real-time data to predict energy demand or failures, cost effective use for diverse cities application of dashboard-aided planning can be highlighted as key benefits of the satellite-enabled digital twins ecosystem (SEDTE) which signifies the use of satellite-enabled digital twins for monitoring performance of building and infrastructure (Qi et al., 2021). Although several studies have been conducted on artificial intelligence, digital twins, energy monitoring and smart cities (Sghiri et al., 2025; Sayed et al., 2025; Noori et al., 2025), it is seldom in prevailing research studies that applying satellite-enabled digital twins for energy monitoring in smart cities. Similarly, the smart city in Sri Lanka also lacks modern energy monitoring mechanisms, thus exclaim the need of integrating with SDETE. Hence, the need to investigate how SEDTE can be applied for energy monitoring in smart cities was considered as the point of departure for this research. Hence, this study aims at developing a satellite-enabled digital twin ecosystem (conceptual) model for energy monitoring in smart cities in Sri Lanka. As the initial step, this paper aimed at achieving two (02) objectives as: (i) Review the concept of satellite-enabled digital twin ecosystem, its applications for energy monitoring in smart cities, (ii) Propose a conceptual framework of SEDTE for energy monitoring in smart cities in Sri Lanka.

The methodology adapted is explained subsequently.

2. RESEARCH METHODOLOGY

This research aims at developing a satellite-enabled digital twin ecosystem (conceptual) model for energy monitoring in smart cities in Sri Lanka answering the research question "how SEDTE can be applied for energy monitoring in smart cities in Sri Lanka?". Hence, qualitative approach was adopted. Accordingly, a non-systematic literature review was adopted as the methodological foundation for the present study. Non-systematic reviews are often referred to as narrative reviews in academic literature. These reviews aim to

identify, synthesise, and summarise existing published work while also highlighting potential research gaps for future investigation (Ferrari, 2015). Further to the author, non-systematic reviews provide a theoretical and conceptual overview of the state of knowledge in a particular research area.

Hence, a non-systematic literature review was conducted on the satellite-enabled digital twin ecosystems (SEDTE) and its application for energy monitoring in smart cities. As this is new technology, due to limited literature, available key research papers were selected and reviewed to synthesise key insights, highlighting the research gap. Accordingly, key peer-reviewed journal articles, conference papers, and reports published on satellite technology, digital twins, smart cities, energy monitoring and energy efficiency between 2015 and 2025 in databases such as IEEE Xplore, ScienceDirect, Scopus, and Google Scholar and written in English were comprehensively reviewed. The search string was developed using the key words, such as Satellite-enabled digital twin ecosystems or SEDTE; Applications, Strategies, Energy monitoring and Smart cities. Themes were developed iteratively, guided by the review's objectives: understanding technological capabilities, applications and benefits. The review is limited by its reliance on published literature, which may exclude emerging but unpublished SEDTE applications.

3. SATELLITE-ENABLED DIGITAL TWIN ECOSYSTEM

A satellite-enabled digital twin ecosystem (SEDTE) is a sophisticated framework that integrates real-time satellite data with digital twins which can be used to enhance energy monitoring in smart cities. Digital twins are dynamic models that could mirror physical assets, such as buildings, energy grids etc, using data to simulate and optimise performance (Tao et al., 2019). SEDTE encompasses this concept by integrating satellite-driven data, such as weather, solar radiation, and air quality to provide a city-wide analysis on energy consumption. Unlike traditional systems, such as BMS, which focus on localised data, SEDTE provides a holistic view enabling predictive energy management and reducing carbon emissions (Deren et al., 2021). This ecosystem is essential for smart cities, where complex energy demands require scalable, real-time solutions to achieve efficiency and resilience (Ketzler et al., 2020).

3.1 SYSTEM INPUTS AND OPERATION

The SEDTE operates by processing diverse data inputs through advanced analytics to monitor and optimise building performance including energy consumption. According to key literature (Alahakoon & Yu, 2016; Yamagata & Seya, 2013), the key inputs of SEDTE include:

- Satellite data: This incorporates real-time data from low-earth orbit satellites, including high-resolution imagery, weather patterns, solar radiation, and air quality metrices. These data enable city-wide monitoring of energy related factors including heat losses and solar panel efficiency.
- Terrestrial data: This includes IoT sensors, smart meters and BMS, which provide building level insights, such as HVAC usage, lighting demands, occupancy patters etc.

- Contextual data: This considers urban planning data, energy grid performance and socio-economic factors (population density etc) which contextualise the energy needs across cities.

Operationally, SEDTE integrates these inputs into a unified digital twin platform, often powered by machine learning algorithms like Neural Networks or Random Forest. These algorithms analyse patterns to predict demand spikes, identify inefficiencies, and recommend optimizations, such as adjusting HVAC based on solar data or stabilizing grids with renewable energy inputs (Qi et al., 2021). Key functional capabilities include:

Real-Time Monitoring: Dashboards visualize energy trends, aiding stakeholders in decision-making (Deren et al., 2021), Predictive Analytics, such as forecasts energy needs and equipment failures, reducing waste by 15-25% (Sharma et al., 2024), and Scalability that covers entire cities cost-effectively, unlike localized systems (Ketzler et al., 2020).

4. SATELLITE-ENABLED DIGITAL TWIN ECOSYSTEM FOR ENERGY MONITORING

4.1 ENERGY CONSUMPTION AND MONITORING IN SMART CITIES

Energy consumption in smart cities poses a complex challenge, with urban areas accounting for approximately 70% of global energy demand and contributing to 75% of carbon emissions (International Energy Agency [IEA], 2023). This significant energy footprint stems from diverse sectors, including residential, commercial, industrial, and transportation activities.

Rapid urbanisation, and the widespread use of IoT-enabled devices further amplify energy needs (Batty, 2018). These factors create dynamic consumption patterns, with commercial districts peaking during the day and residential areas consuming more at night (Batty, 2018). The shift to renewable energy sources, such as solar and wind, adds complexity due to their weather-dependent and intermittent nature, requiring advanced systems to balance supply and demand in real time (Taylor et al., 2021). Effective energy monitoring is vital to identify inefficiencies, reduce waste, and achieve sustainability goals, such as those outlined in the United Nations Sustainable Development Goals (SDGs), specifically SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) (United Nations, 2015). Without robust monitoring, smart cities risk grid instability, higher emissions, and weakened resilience, undermining efforts to build sustainable urban environments (Taylor et al., 2021). The adoption of SEDTE brings substantial advantages to smart city energy management. Through predictive analytics, it reduces energy waste by 15-25% by optimizing systems like HVAC and lighting, as well as improving grid operations. Unlike terrestrial systems, SEDTE scales cost-effectively across entire cities, making it adaptable to diverse urban settings (Ketzler et al., 2020). It also enhances decision-making by providing stakeholders with real-time insights through interactive dashboards, facilitating evidence-based policies and investments. Another key benefit is its support for renewable energy integration, as it aligns supply with demand to reduce reliance on fossil fuels, thereby strengthening grid stability (Yamagata & Seya, 2013). By minimizing inefficiencies and emissions, SEDTE contributes to urban resilience and aligns with global sustainability goals (Mohammadi & Taylor, 2017).

4.2 APPLICATIONS OF SEDTE FOR ENERGY MONITORING IN SMART CITIES

The SEDTE plays a crucial role in transform the energy monitoring process by giving real time access via digital Twin for Smart Cities. With thermal information and Satellite image over selected city area, SEDTE maps the Energy usage and detect building inefficiencies such as heat losses and poor infrastructure. It also optimizes the systems of renewable energy using solar radiation and weather data to maximize solar panel outputs or wind turbine operations for next level integration into city grids (Sharma et al., 2024). In addition, SEDTE utilizes machine learning to process satellite and ground data, including IoT sensor feeds, to forecast demand peaks and facilitate dynamic pricing or load shifting measures. It also adjusts to the environment by utilizing air quality and urban heat island information to modulate ventilation or cooling systems, improving energy efficiency while making cities more liveable (Deren et al., 2021).

As reviewed in key literature, 11 key applications of SEDTE for energy monitoring were identified as summarised in table 1.

Table 1: Applications of SEDTE for energy monitoring

Applications of SEDTE	Source of Reference
Using satellites to obtain energy monitoring data	[1], [2], [3], [4]
Facilitating real-time energy optimization and predictive analytics	[5], [6]
Increasing grid sustainability and resilience	[7], [8], [9]
Solar energy monitoring	[2], [4], [5], [6]
Facilitating dynamic load balancing and demand response	[2], [4], [5], [7]
Maximising the integration of renewable energy	[2], [6], [8], [10]
Providing an energy-efficient approach to urban planning	[4], [11], [12], [13]
Effective planning for energy systems	[2], [6], [9]
Providing electric vehicle (EV) support	[5], [6], [8]
Ensuring climate resilience and disaster preparedness	[2], [7], [9]
Reducing carbon footprint and reporting sustainability	[4], [8]

Reference: [1] Mayer & Gróf, 2021; [2] Boccalatte, 2023; [3] Tian et al., 2021; [4] Zhou et al., 2022; [5] Alola et al., 2023; [6] Gao & Huang, 2023; [7] Sghiri et al., 2025; [8] IEA, 2023; [9] Batty, 2018; [10] Taylor et al., 2021; [11] Li et al., 2020; [12] Hosseini Haghighi et al., 2023; [13] Tian et al., 2021

These applications show that SEDTE can offer a complete view of the whole city, going beyond what local systems like Building Management Systems can do. The applications showed in Table 1 in the context of energy monitoring in smart cities are described subsequently.

4.2.1 Using Satellites to Obtain Energy Monitoring Data

Satellites that carry sophisticated sensors, for instance, multispectral and hyperspectral imaging systems, gather useful environmental data which has an impact on energy use in smart cities (Mayer & Gróf, 2021). For example, satellites monitor solar conditions like solar irradiance, cloud cover, and atmospheric aerosol load directly impacting photovoltaic (PV) electricity generation at specific geographic sites (Boccalatte, 2023).

These tools are used to display the amount of solar energy available at any given time on buildings, cities, or solar farms. And satellites track weather data like wind direction and speed. Thermal imaging can also identify energy waste or building heat loss. Satellites can map out city roads and buildings using technologies like LiDAR and Synthetic Aperture Radar. These maps' details offer a clear picture of energy consumption (Tian et al., 2021). Satellite data is used to monitor energy use. S The information is transmitted to a digital twin system and analysed using machine learning and big data techniques. The digital twin integrates satellite information with information from smart meters, building management systems, and EV charging stations to provide a real-time overview of the city's energy environment (Zhou et al., 2022). According to the authors, a digital twin can illustrate the interplay between solar energy production, grid demand, and storage capacity. It considers fluctuations in sunlight as tracked by satellites (Zhou et al., 2022). This lets energy operators and urban planners predict changes in renewable energy supply and modify system operations in advance.

4.2.2 Real-Time Energy Optimization and Predictive Analytics

Satellite information used via digital twins streamlines energy usage in real time by creating an ongoing feedback loop between the physical city and virtual twin. (Alola et al., 2023). Satellites can see when solar energy drops and watch clouds. So, the digital twin can plan other ways to send out energy, like charging batteries or using backup power. The authors say that deep learning helps predict this by showing how energy is used and made. It does this by using old and new satellite data. (Alola et al., 2023). These models can identify when rare events occur, such as sudden bursts of energy usage or problems with building insulation, so early action can be taken to prevent waste. Also, digital twins use satellite data on land use to maximize where renewable energy installations are placed. (Gao & Huang, 2023). A digital twin can recommend the optimum locations for solar panels s based on a city's layout, population, and solar energy potential. This ensures that you get maximum energy without land use issues. Space needs to be considered in crowded cities because there is little land, and the energy infrastructure must be fitted into the city without causing issues.

4.2.3 Increasing Grid Sustainability and Resilience

The digital twin system backed by satellites helps keep our power grid strong by showing how energy moves through the city. Satellites can check how microgrids are working in real-time and spot problems or overloads before they affect the bigger grid. This system uses that info to run simulations for balancing energy use, making sure power stays reliable and outages are avoided. (Sghiri et al., 2025). By tracking energy consumption that produces high carbon emissions, the system helps shift towards cleaner energy, which is in line with the world's desire to limit carbon emissions. (IEA, 2023). Satellite-enabled digital twins are a good fit for smart cities, where energy systems are complicated and connected. Unlike regular monitoring systems that tend to zoom in on local data, satellites give us a wide view of the entire city, showing how energy works together and how different areas are affected by the environment. (Batty, 2018). This view helps city leaders create energy management plans that can handle local and regional needs, making the city more resilient and sustainable.

4.2.4 Solar Energy Monitoring

Satellites continuously monitor solar conditions, such as irradiance values and cloud cover, over the geographic spread of the city (Boccalatte,2023). This information is sent to the digital twin. The digital twin has a virtual representation of the city's energy system. This includes rooftop solar systems, big solar farms, and grid-connected storage devices (Zhou et al., 2022). The digital twin, as described by the authors, combines satellite images with real-time weather station and smart meter data to come up with an estimate of how much solar energy each building and zone will produce. (Zhou et al., 2022). The digital twin predicts a small drop in solar energy output and figures out how that might impact grid stability when satellite images show clouds coming in. It might also recommend increasing battery storage or adjusting energy use in less important areas. (Alola et al., 2023). Also, it can recommend increasing energy draw from battery storage or activating demand-response programs to reduce consumption in non-essential loads. Conversely, during peak irradiance times of the day, the digital twin modifies the energy supply to prioritize EV fleet charging or storing excess energy for nighttime use (Gao & Huang, 2023). The adaptive interaction between satellite data and digital twin analytics optimizes energy use, reduces losses, and enables the city to achieve its sustainability goals (United Nations, 2015).

4.2.5 Dynamic Load Balancing and Demand Response

SEDTE balances energy consumption by depicting real-time energy demand and supply (Sghiri et al., 2025). Satellites monitor weather, such as sunshine and windspeed, that impacts how much renewable energy is generated (Boccalatte, 2023). The digital twin combines this with data from smart meters to forecast busy hours and potential shortages in energy (Zhou et al., 2022). If there is an unexpected decrease in solar energy due to clouds, SEDTE can initiate software to automatically decrease energy consumption in less crucial areas such as commercial lighting or HVAC systems (Alola et al., 2023). This stabilizes the grid and enhances energy consumption at peak hours.

4.2.6 Maximizing the Integration of Renewable Energy

The varying levels of renewable energy such as sun and winds pose challenges for smart cities (Taylor et al., 2021). SEDTE utilizes satellite data to monitor weather to forecast how much energy will be generated from renewables (Boccalatte, 2023). By observing solar radiation in locations, digital twin optimizes roof-top solar systems as well as massive installations to generate maximum amounts of energy. During more energy is generated, SEDTE stores additional energy in storage units or targets high-priority needs, such as car chargers. (Gao & Huang, 2023). This application develops the efficiency of renewable energy systems and reduces reliance on backup power based on fossil fuel, aligning with the city's standards for decarbonization (IEA, 2023).

4.2.7 An Energy-Efficient Approach to Urban Planning

SEDTE helps lower energy use in buildings and other structures by spotting problems through thermal satellite images that show heat patterns. (Tian et al., 2021). Satellites have thermal sensors that can spot where heat is escaping from buildings. This helps identify spots with bad insulation or heating and cooling systems that aren't working well, as mentioned by Li et al. (2020). A digital twin uses real-time data from building management systems to give energy-saving advice, like adjusting the heating or recommending upgrades. (Zhou et al., 2022). In cities, SEDTE shows how energy is used

in different neighbourhoods. This helps urban planners spot areas that use a lot of energy and kick off projects to improve efficiency, like upgrading buildings or putting in better streetlights. (Hosseini Haghighi et al., 2023).

4.2.8 Effective Planning for Energy Systems

SEDTE is working on energy infrastructure by using land data from satellites and keeping an eye on urban building projects. Their digital twin helps identify the best spots for setting up new renewable energy sources, like solar farms or wind turbines, ensuring they generate plenty of energy while causing less impact on the land and environment. (Gao & Huang, 2023). The system can spot good roofs for solar panels or find open areas with steady winds for putting up turbines. (Boccalatte, 2023). The system can spot the best roofs for solar panels or areas with steady winds for wind turbines. It also predicts how new buildings will affect the city's energy grid, letting planners check for reliability and sustainability in the long run before they start building. (Batty, 2018).

4.2.9 Electric Vehicle (EV) Support

More electric vehicles in smart cities means we need smarter energy solutions for EV charging stations. (IEA, 2023). SEDTE makes it easy to share energy for EV charging by providing real-time info on renewable energy availability. When the sun's out, the system makes sure that energy goes to the EV chargers first before anything else, helping to make the most of clean energy. (Gao & Huang, 2023). When energy levels are low, SEDTE plans charging during off-peak hours or uses stored energy to reduce stress on the grid. (Alola et al., 2023). This helps make transportation greener and keeps the grid stable when a lot of people are using electric vehicles. (IEA, 2023).

4.2.10 Climate Resilience and Disaster Preparedness

SEDTE helps with climate resilience by spotting early signs of energy system issues caused by extreme weather. (Sghiri et al., 2025). Satellites check out weather patterns like heatwaves or storms that could affect the electricity supply or increase demand. (Boccalatte, 2023). The digital twin simulates how the city's energy system works, looking for weak spots like overloaded microgrids or broken solar panels. (Sghiri et al., 2025). By planning for options like using advanced battery storage or adjusting energy flows, SEDTE makes sure there's a steady energy supply during disasters. This is key to staying strong against climate issues. (Batty, 2018).

4.2.11 Reducing Carbon Footprint and Reporting Sustainability

SEDTE helps smart cities reach their sustainability goals by giving them real-time data on energy use and carbon output. (IEA, 2023). The digital twin keeps an eye on how well renewable energy systems are working and spots any energy waste, allowing for real-time management of the city’s carbon footprint. (Zhou et al., 2022). SEDTE makes it simple for cities to report on sustainability by providing a complete look at energy use, renewable energy sources, and cuts in emissions. This helps cities show how they are doing with global agreements like the SDGs and their own local climate plans. (United Nations, 2015).

4.3 THE PROPOSED FRAMEWORK

Based on the literature reviewed, a framework was proposed to adopt the SEDTE for energy monitoring in smart cities. As shown in Figure 1, satellites continuously monitor

solar conditions, such as irradiance levels and cloud cover, across the city's geographical area. These data are relayed to the digital twin, which maintains a virtual model of the city's energy infrastructure, including rooftop solar panels, utility-scale PV farms, and grid-connected storage systems. The digital twin integrates satellite data with real-time inputs from smart meters and weather stations to calculate expected solar energy output for each building and district. If satellite data indicate an approaching cloud cover event, the digital twin predicts a temporary drop in solar generation and simulates its impact on grid stability. It may recommend increasing energy draw from battery storage or activating demand-response programs to reduce consumption in non-critical sectors. Conversely, during periods of high solar irradiance, the digital twin optimizes energy distribution to prioritize charging EV fleets or storing excess energy for nighttime use. This dynamic interplay between satellite data and digital twin analytics ensures efficient energy utilization, reduces waste, and supports the city's sustainability goals.

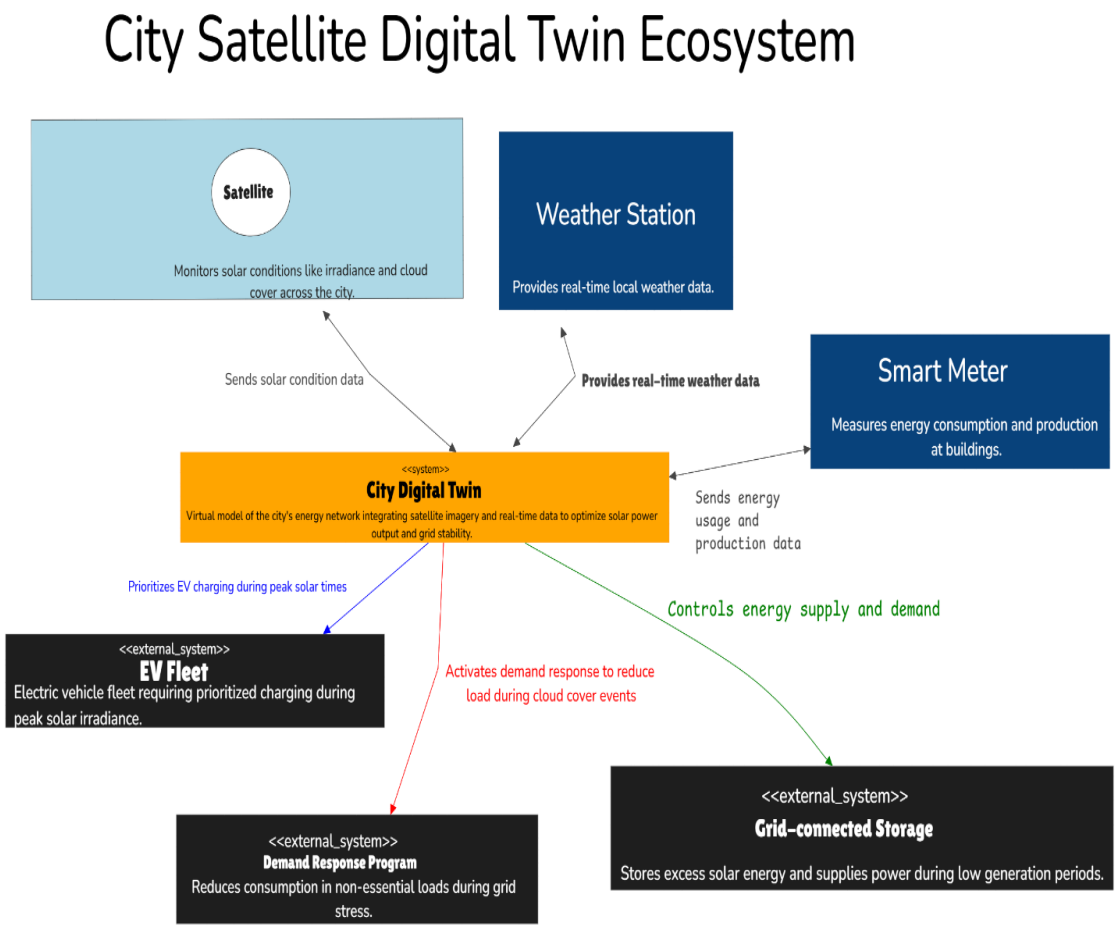


Figure 1: Proposed CITY satellite digital twin ecosystem framework (Author constructed)

In the proposed framework, sensors on satellites can capture solar irradiance, cloud cover movements, atmospheric moisture, and temperature gradients. The data received aids in forecasting solar photovoltaics (PV) energy production and estimating times during which the grid may require power or have excess supply potential. This allows smart cities to accurately forecast the need and supply. Sentinel-2 provides images pertinent to cloud cover and reflectance as well as MODIS onboard Terra/Aqua for aerosol data.

GOES and Himawari also provide real-time cloud and moisture profiles. Both satellites are equipped with global coverage and have a timely temporal resolution, making them ideal for monitoring solar potential over cities like Colombo, Kandy and Galle. Then, the data collected from satellites is integrated into a City Digital Twin, which is essentially a virtual model of the smart city integrated with GIS (Geographic Information Systems). This twin aids in monitoring the solar energy availability and forecasting its impact on the electricity grid, hence optimizing the management of the city's energy systems. Other than satellite data, weather stations and smart meters along with IoT devices installed in buildings provide essential information to fuel this digital twin. The forecasts provided by the digital twin along with other real-time data-driven decisions are sent to Building Management Systems (BMS) for automatic adjustments to energy consumption. Overall, this dual approach enhances the eco-friendliness and sustainability of cities while reducing waste. Following energy simulations, the digital twin forwards control signals to a building's BMS. These systems communicate through industry standards such as BACnet for real-time energy modification. Scheduled optimizations include pre-emptive cooling of buildings during photovoltaic downtimes, demand throttling on elevators, optimistic charging from batteries during peak solar times, and A/C sparing. This enables continuous sky feedback driven optimization of citywide energy economical building operation coordination.

5. CONCLUSIONS AND A WAY FORWARD

Energy consumption in smart cities poses a complex challenge, with urban areas accounting for high energy demand and contributing to excessive carbon emissions. Effective energy monitoring is vital to identify inefficiencies, reduce waste, and achieve sustainable development goals. Hence, monitoring energy use is vital for sustainable smart cities. Real-time monitoring has gained momentum in decision making related to building and infrastructure performance, especially for achieving energy saving and carbon emission reduction targets. Among the other technologies, satellite-enabled digital twins ecosystem powered by real-time satellite data offer a game-changing way to monitor energy use. The SEDTE revolutionizes energy monitoring by integrating real-time satellite data with digital twin technology, enabling innovative applications for smart cities. As a pathway for this newest technology adaptation, this study aimed at identifying the applications of SEDTE for energy monitoring in smart cities by reviewing key literature. Key applications of SEDTE in the context of smart city energy monitoring include data acquisition, real-time energy optimization, grid resilience, load balancing, demand responding, renewable energy integration, resilience and disaster preparedness of energy systems. The proposed framework also provides a basis for building and infrastructure professionals, policy makers towards facilitating this uphold technology adaptation in smart city development in Sri Lanka and similar contexts. However, challenges, such as data privacy concerns and high initial setup costs remain, underscoring the need for further research to ensure broader implementation. Thus, the next stage of the research will investigate the practical implementation of SEDTE in smart city development in Sri Lanka, focusing on its technological capabilities, socio-economic challenges, and strategies for successful technology adaptation.

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DISASTER-RESILIENT CITIES: TEMPORAL ANALYSIS OF URBAN LAND USE LAND COVER CHANGES AND URBAN FLOODS FROM 1999 TO 2022: CASE STUDY OF COLOMBO, SRI LANKA

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ABSTRACT

This study examines the land use land cover (LULC) changes in Colombo City from 1999 to 2022, focusing on the effects of rapid urbanization on urban flood frequency and severity in the Colombo Municipal Council (CMC) area. Using high-resolution satellite imagery from Landsat 5-8, the study tracks and classifies land use over three decades, revealing significant urban expansion, a reduction in green spaces, and the loss of natural water retention zones. These changes have led to increased surface runoff, exacerbating the risk of urban floods. The research highlights that urbanization, coupled with the inadequacy of drainage infrastructure, especially in informal settlements, has contributed to the growing flood vulnerability in the city. LULC maps generated through maximum likelihood classification were validated with high accuracy, confirming the reliability of the data. Correlation analysis suggests a moderate relationship between certain land cover types (e.g., water bodies) and flood impacts, though other factors such as drainage efficiency and urban planning are more critical in determining flood risks. The study underscores the need for improved drainage systems, preservation of green spaces, and comprehensive urban planning to mitigate flood hazards. The findings emphasize the importance of integrating climate adaptation measures into urban planning, with a focus on sustainable land management and infrastructure development. The research concludes that a holistic, resilience-based approach is crucial for building a climate-resilient city capable of adapting to ongoing urbanization and climate change impacts.

Keywords: *Land Use Land Cover; Remote Sensing; Urban Floods; Urbanization.*

1. INTRODUCTION

Over the past three decades, the Colombo city area has undergone significant economic, environmental, and social changes driven by political and administrative shifts, rural-to-urban migration, and climate-induced natural disasters, which have all led to notable alterations in land use patterns (Senanayake et al., 2013; Wickramasinghe et al., 2016;).

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Particularly after the civil war (post-2014), several government-funded city remodelling initiatives, donor-funded wastewater management projects (such as the Greater Colombo Wastewater Management Plan), and infrastructure developments (like the Port City project and the Kelani Valley Highway extension) were implemented. The city remodelling program, in particular, caused significant land use transformations, including the resettlement of underserved communities into high-rise buildings, the clearance of slum areas for real estate development, the creation of new green spaces (such as pocket gardens), the establishment of tree-lined streets, and the introduction of jogging and walking paths, with many modifications to existing green spaces aimed at catering to the real estate market (Hettiarachchi, 2014). The Colombo Port City project, funded by the Chinese government, further impacted the city's land use by expanding its area. However, the economic crisis triggered by the COVID-19 pandemic and subsequent political decisions resulted in major setbacks for many of these development and beautification projects. Several were temporarily or permanently halted, and others were rolled back. (Subasinghe et al., 2021).

Rapid urbanization, a trend observed globally, has also transformed major cities in Sri Lanka, significantly altering environmental and hydrological systems. Colombo, in particular, has seen a dramatic increase in infrastructure development such as roads and buildings, reducing rainwater infiltration and amplifying surface runoff, key contributors to the rising frequency and severity of urban floods, Notable flood events in 1999, 2005, 2020, 2014, and 2022 have caused extensive disruptions, including road inundation, transportation paralysis, prolonged waterlogging, and health crises such as dengue outbreaks. In 2017, Sri Lanka ranked second in the Climate Risk Index, with Colombo highlighted as one of the most climate vulnerable cities in the developing cities. This study addresses that gap by analysing land use and land cover (LULC) changes over time in Colombo, assessing their correlation with rainfall intensity and flood impacts. Through this approach, the research offers original insights into urban planning strategies for enhancing climate resilience and sustainable development.

2. LITERATURE REVIEW

In South Asia, cities like Dhaka in Bangladesh and Mumbai in India has undergone a significant urban growth, leading to a land use changes (Hassan & Southworth., 2018). As use refers to the human activities or socio-economic functions associated with a specific land area such as residential, industrial, or agricultural use. Land cover, in contrast, denotes the physical and biological cover of the Earth's surface, such as vegetation, water, bare soil, or built-up areas (Lambin et al., 2003). Changes in the urban atmosphere, particularly the reduction of green spaces and natural drainage systems, exacerbate flood risks by reducing water infiltration and increasing surface runoff (Ahmed et al., 2013). Colombo, the commercial capital of Sri Lanka has also experienced rapid urbanization, especially since the 1990s, with the construction of new infrastructure, expansion of residential areas, and an increase in population (Dissanayake, 2021). This urban sprawl has significantly altered Colombo's natural drainage system and land cover, leading to the increase in urban flood events (Dahanayake & Wickramasinghe, 2022).

Urbanization leads to increased runoff, as more areas become impervious, with limited space for natural water absorption. This reduction in permeable surfaces results in quicker and higher-volume storm water flow, overwhelming drainage systems and causing urban floods (Jiang & Zhang., 2010). In Colombo, the combination of increased built-up areas,

encroachment on floodplains, and poorly maintained drainage systems has increased the incidence of urban floods (Dissanayake, 2021).

According to Pelling (2010), the modification of land cover, particularly the expansion of impervious surfaces such as roads, parking lots, and buildings, directly correlates with increased risk of floods in urban areas. In Colombo, the conversion of wetlands and agriculture areas to urban zones has disrupted natural water retention and flood control mechanisms (Dona, 2025). Studies have shown that flood frequency and intensity in Colombo have increased over the past few decades. In particular, Colombo faces recurrent flooding during monsoon periods (Dahanayake & Wickramasinghe, 2022). These floods are often attributed to poor urban planning, unregulated construction in flood-prone areas, and the loss of natural flood mitigation systems like wetlands (Dona, 2025). Climate adaptation measures: Studies emphasize the need for climate adaptation planning in cities to reduce the impacts of flooding. Colombo has initiated some adaptation measures, such as the expansion of its drainage system and the implementation of flood mitigation strategies, but challenges remain, particularly in informal settlements and peri-urban areas (Wagenaar et al., 2019).

Satellite imagery has been widely used for land cover classification and monitoring urban growth. Landsat imagery, for instance, provides continuous coverage since the 1970s and has been used in numerous studies on urbanization and land cover change. In Sri Lanka, remote sensing has been used to monitor urban sprawl, land use changes, and their environment impacts (Manesha et al., 2021). In urban planning, LULC change reflects the spatial and temporal dynamics of urban expansion, infrastructure development, and the conversion of natural or agricultural lands into built environments (Seto et al., 2012; Liu et al., 2010).

GIS-based flood modelling is essential for understanding how land use changes influences flood risk. Temporal analysis refers to the examination of changes in LULC over time. This involves comparing spatial data from different time periods to identify trends, rates, and patterns of changes (Herold et al., 2003). In Colombo, studies have use GIS to analyse flood-prone areas and assess the impacts of urbanization on flood vulnerability. Intense rainfall over a short period, combined with inadequate infrastructure and the reduction of green spaces, causes urban floods in urban areas. This study focus is the urban flash floods that occurred in the CMC area.

The occurrence of these disasters can be attributed to two main factors: extreme weather events resulting from climate change and poor urban planning that fails to mitigate their adverse impacts. To date, there has been no scientific analysis of urban flash floods or urban riverine floods conducted in the CMC area.

3. METHODOLOGY

This study presents a case analysis of the Colombo Municipal Council area, focusing on land use and flood risk dynamics using medium-resolution satellite imagery with a 30 m resolution, the United States Geological Survey (USGS). The images spanned a timeline from 1999 to 2022 and were captured by the Landsat 5-8 satellites. The satellite images were selected from the year of 1999, 2005, 2010, 2014 and 2022 considering the flooding events happened those respective years. We specifically downloaded Level 2 products, which are atmospherically and radio-metrically corrected to ensure high data reliability. The Level of the satellite image indicates the degree to which the raw satellite data has

been corrected and made ready for utilized. To maximize uninterrupted coverage, satellite imagery with minimal cloud cover was selected. and cloud cover were masked out using Fmask, following the approach of by Sedano et al. (2011). This process ensured the integrity of land cover classification and change detection across time. In addition to satellite based quantitative analysis, rainfall data, population density, and flood incidents recorded were assessed correlation with land use changes. Qualitative insights were gathered through referring the DesIntenver database of the Disaster Management Centre. Table 1 presents detailed metadata for each satellite images used, including sensor specifics (sensor ID refers the specific imaging instrument used on board the satellites), acquisition date, path/row (path/ row of a satellite used to identify specific geographic locations on Earth as they are captured by satellite sensors), and the percentage of land area covered by clouds.

Table 1: Details of satellite images

Year	Satellite sensor	Sensor ID	Date	Path/ Row	Land Cloud cover
1999	Landsat 5 Level 2	TM	1999-12-05	142/055	9%
2005	Landsat 7 Level 2	ETM	2005-02-05	141/055	12%
2010	Landsat 7 Level 2	ETM	2010-10-01	141/055	25%
2014	Landsat 8 Level 2	OLI-TRIS	2014-01-21	141/55	11.36%
2022	Landsat 8 Level 2	OLI-TRIS	2022-02-04	141/55	15.72%

**Time range – January 23 to March 28*

3.1 STUDY AREA

In 2023, the Western Province, including Colombo, contributed 43.7% of the national GDP, highlighting its central role in the country's economy (Central Bank of Sri Lanka[CBSL], 2024). The CMC governs the western part of Colombo, playing a key role in managing its growth and development. This highlights the strategic significance of the study area. A map of the study area us shown in Figure 1.

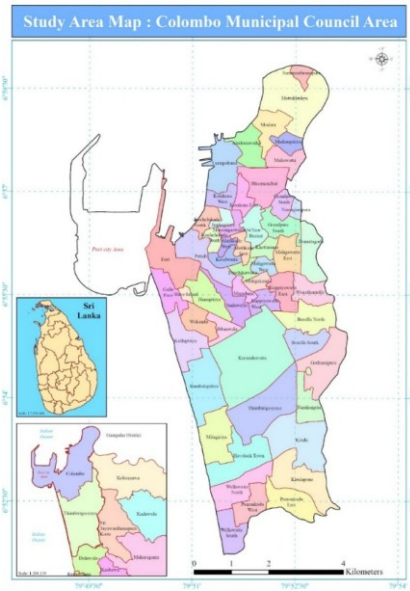


Figure 1: Colombo municipal council area

3.2 LAND USE LAND COVER CHANGE DETECTION

In this study, five LULC classes were identified within the study area: built-up areas, water bodies, barren lands, lawns & grasslands (sparse vegetation), and trees & shrubs (dense vegetation). To ensure accurate classification, we selected the highest possible number of training samples for each class, carefully considering the consistency and distribution of the satellite images over time. The land use/land cover classification was performed using the maximum likelihood classification technique, a supervised method where each image pixel is assigned to the category that most closely matches its spectral signature, corresponding to the recognized land cover types. This classification process was carried out using the ArcGIS pro 3.3 software package. To assess the accuracy of the classification, 100 random spatial points were selected for each satellite image. For historical datasets, Google Earth images (spanning from 1996 to 2023) and past land use maps available on the Google Earth platform were utilized for accuracy verification. Finally, to maintain consistency across all datasets, the classified images were resampled to a uniform spatial resolution of 30m x 30m. Following are the description of five land use classes.

- **Built-up areas**: Areas covered by man-made structures such as buildings, roads, and other infrastructure; characterized by impervious surfaces and high density.
- **Water bodies**: Includes rivers, lakes, ponds, canals, and other surface water.
- **Barren lands**: Land with little to no vegetation cover, including exposed soil, rocks, construction sites, and degraded areas.
- **Lawns and Grasslands** Areas with sparse or low-lying vegetation, including parks, fields, and recreational lawns
- **Trees and Shrubs**: Regions dominated by dense vegetation such as forests, woodlands, and plantations; typically, rich in biomass and ecological value

3.3 FLOOD IMPACT DETENTION

Flood inundation level maps, or data are not available for the study area (except for some specific locations like Kelani Valley River basin). However, the data on the area impacted (names of locations), and the number of people affected by each flood event are available from the open access DesInventar database, managed by Disaster Management Center (Disaster Management Center[DMC], 2025). These data were used as proxies for flood damage to determine the flood impact over the past 30 years in the study area, Table 2.

Table 2: Flood data used for the analysis

Data	Data type	Data source
Area impacted	Name of locations impacted	DesInventar Database
Number of people impacted	Number	DesInventar Database

3.4 CORRELATION ANALYSIS OF LAND USE LAND COVER CHANGES AND FLOODING

Correlation analysis was performed using Minitab version 20.2 to explore the relationships between key variables in the study. Specifically, the analysis aimed to identify the nature and direction of the relationships between flood locations, the number of people affected by floods, and the percentage of land use change (measured as the temporal variation in land use classes). Through this analysis, we sought to determine

whether the relationships were positive or negative, providing insights into how these factors interrelate. Additionally, the strength of these relationships was evaluated, allowing us to assess whether the associations between the variables were strong or weak. By conducting this correlation analysis, we were able to gain a deeper understanding of the dynamics between flooding events and changes in land use within the study area.

4. RESULTS AND DISCUSSION

4.1 LAND USE LAND COVER MAPS AND ACCURACY ASSESSMENT

The LULC maps were developed for 1999, 2005, 2010, 2014, and 2022 year, are presented in Figure 2. The maps clearly indicate the significant land use changes the CMC area has undergone during past three decades.

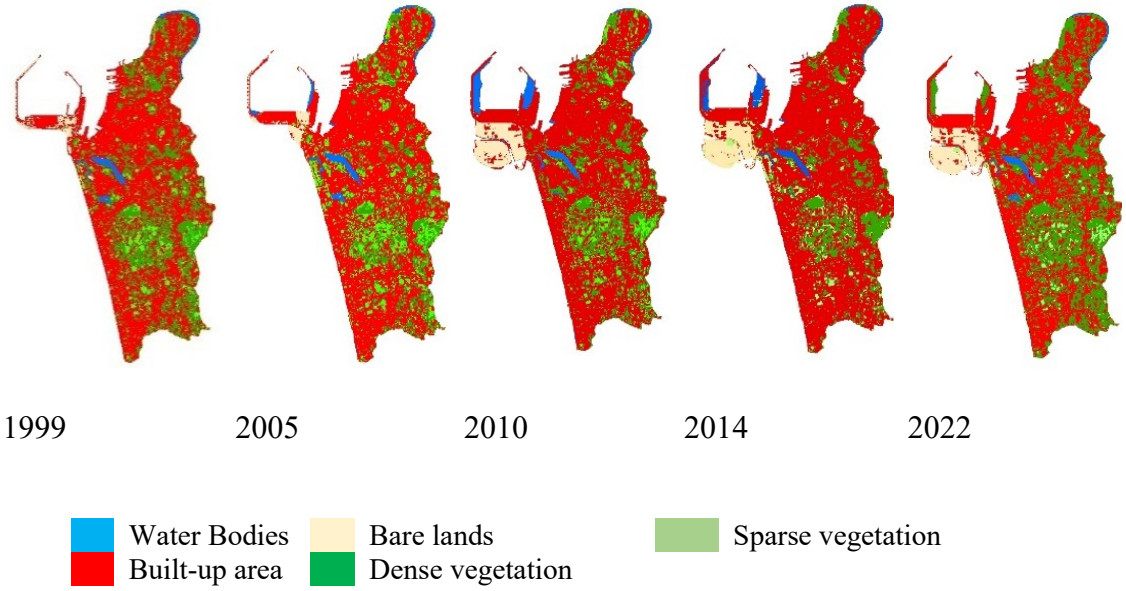


Figure 2: LULC Maps of 1999, 2005, 2010, 2014, and 2022

Table 3 presents the user accuracy, which is the is the probability that a pixel classified into a certain category on the map actually represents that category on the ground, and kappa coefficient which quantifies the agreement between the classified map and reference (ground truth) data values for each LULC map generated.

Table 3: Accuracy assessment of Land Use Land Cover maps

Year	U_Accuracy	Kappa
2022	0.930	0.855
2014	0.910	0.827
2010	0.930	0.867
2005	0.940	0.885
1999	0.910	0.817

The land use areas under five different land use categories, water bodies, built-up areas, bare lands, dense vegetation, and sparse vegetation were presented in Table 4. There is a

significant increase of the urban greenery in the CMC area due to the city remodelling programs undertaken during the past war period (Abeysinghe et al., 2024).

Table 4:Land use areas under different land use categories

Year	Water bodies	Built up area	Bare lands	Dense vegetation	Sparse vegetation
2022	2.80	72.44	5.21	14.26	5.28
2014	1.43	56.65	5.18	33.20	3.54
2010	3.05	67.68	5.27	17.00	6.99
2005	2.36	67.61	1.81	14.59	13.62
1999	1.78	63.32	2.02	26.35	6.51

4.2 TEMPORAL ANALYSIS OF URBAN FLOODS IN COLOMBO MUNICIPAL COUNCIL AREA

During the period between 1999 and 2022, the CMC area experienced several major flood events, each of which had significant impacts on the local population. As shown in Figure 3, the number of people affected by floods has gradually increased over the years, with a noticeable rise in the frequency of these events. The graph provides an insightful analysis of flood-affected individuals in the CMC area, revealing an upward trend both in the number of people affected and in the frequency of flood occurrences. This increase underscores the growing vulnerability of the city to flooding, particularly urban floods, which have become a recurrent issue in the region. The map provides a detailed view of where flood events occur most frequently within the CMC area. It shows that the flood risk is not evenly distributed across the city, and only some parts are in high risk.

The most flood prone areas in Colombo include neighbourhood such as Grandpass South and North, Maradana, Nawagampura, and several others that have been consistently affected by flood events. There areas experienced severe flooding during major events in 1999, 2005, 2010, 2014, and 2022. Key contributing factors include heavy rainfall, inadequate drainage systems, and rapid urbanization. Understanding these patterns is essential for developing effective flood management strategies and enhancing the city's resilience.

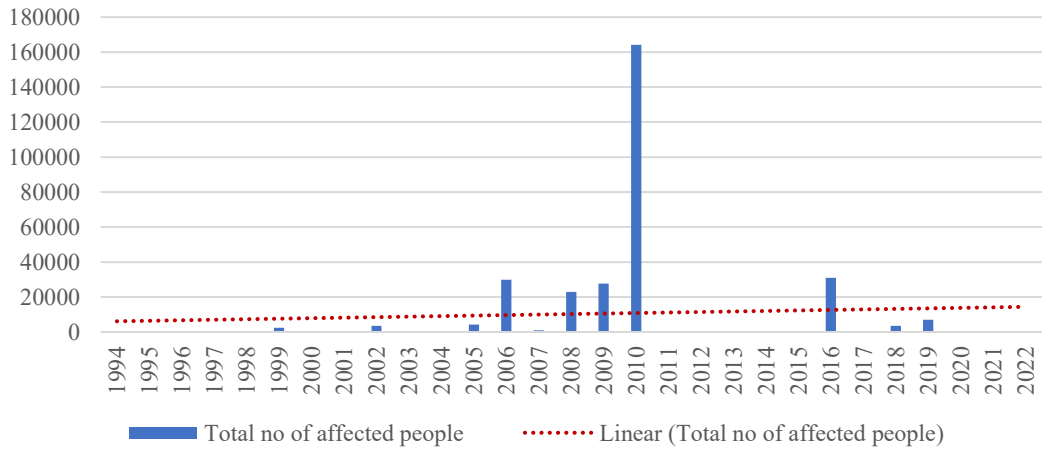


Figure 3: Flood affected people over 1994-2022

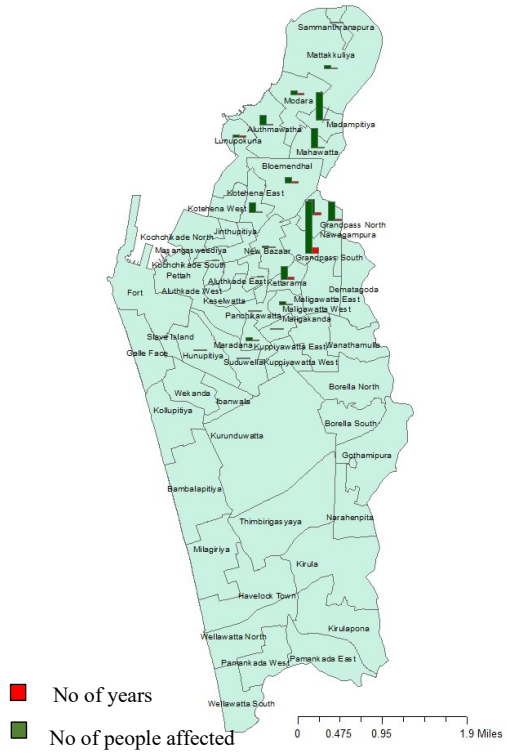


Figure 4:Flood events and severity in different locations

4.2.1 Correlation Analysis of the Land Use Changes and Urban Flood Impact

The correlation of the different land use land cover change and the number of flood affected people was assessed using minitab 20.0 software. The correlation coefficient, R-square, and the *p-value* is presented in the Table 5.

Table 5: Correlation of land use land cover change and the number of flood affected people

Land use type	Correlation coefficient	R-Square (%)	p-value
		No of people affected	
Water bodies	0.522	27.3	0.367
Built-up area	0.063	0.4	0.920
Bare lands	0.505	25.5	0.386
Dense vegetation	-0.142	2.0	0.820
Sparse vegetation	-0.117	1.4	0.851

The correlation coefficient between the extent of water bodies and the no of people affected is moderately positive, r-square is 27.3 % suggest that water bodies have modest predictive influence on the number of people affected and the p value is not statistically significant. The correlation coefficient of the built-up area extent and the number of people affected shows a very weak positive correlation, and the p-value is very high, suggesting that there is no significant relationship. There is a moderately positive relationship between bare lands and the number of flood affected people, and p-value is not statistically significant. The negative correlation suggests that areas with dense

vegetation tend to experience fewer people being affected by flooding, likely because vegetation helps reduce runoff and prevents soil erosion. However, the correlation is weak, indicating that vegetation alone does not have a significant influence on the number of people affected. Dense vegetation explains only 2% of the variation in the number of people affected, confirming that dense vegetation has minimal predictive power in this scenario. The relationship between dense vegetation and the number of people affected is not statistically significant, indicating that vegetation in this case does not have a measurable impact on flood outcomes. Similar to dense vegetation, sparse vegetation shows a very weak negative correlation with the number of people affected. Sparse vegetation accounts for only 1.4% of the variation in the number of people affected, further suggesting that vegetation density (whether dense or sparse) is not a major driver of flood impacts in this case. The p-value is very high, reinforcing the idea that sparse vegetation has no statistically significant impact on the number of people affected by flooding.

4.2.2 Correlation Analysis of the Rainfall Intensity and the Flood Impact

The correlation of the intensity of the rainfall (rainfall within 24 hr) and the number of flood affected people were assessed using minitab 20.2 software. The rainfall data of the selected urban flood events were obtained from the Department of Meteorology. The correlation analysis was conducted for the rainfall intensity and the number of people affected during above mentioned flood events were presented in Table 6.

Table 6: Correlation between the rainfall intensity and the number of people affected

Variable	Correlation coefficient	R-Square (%)	p-value
		No of people affected	
Rainfall intensity	-0.342	32.4	0.317

The correlation coefficient of -0.342 indicates a weak negative relationship between rainfall intensity and the number of people affected. This means that, as rainfall intensity increases, the number of people affected tends to slightly decrease. However, the relationship is weak, and the strength of this correlation is not very strong. The p-value of 0.3174 is greater than 0.05, meaning the correlation is not statistically significant. This suggests that the weak negative correlation observed between rainfall intensity and the number of people affected is likely due to random chance. Therefore, we cannot conclude that rainfall intensity significantly influences the number of people affected.

5. CONCLUSION

This study offers a detailed examination of the LULC changes in Colombo City from 1993 to 2022, using advanced remote sensing techniques and rigorous analytical methods. The research focused on how rapid urbanization, driven by socio-political factors and infrastructure developments, has influenced the frequency and severity of urban floods in the CMC area. The study leveraged high-resolution satellite imagery from Landsat 5-8 to track and classify land use over three decades, providing an in-depth temporal perspective on the transformation of the city's landscape.

The key findings of this research highlight that Colombo has experienced significant land use changes, particularly an expansion of built-up areas and a reduction in green spaces

and natural water retention areas. These changes have directly impacted the city's hydrological dynamics, with the increased urbanization contributing to higher levels of impervious surfaces, which reduce natural water absorption and lead to increased surface runoff. This alteration in land cover has exacerbated the risk of urban floods, as the city's drainage infrastructure, particularly in informal settlements, has struggled to keep up with the rising demand and urban sprawl. Moreover, the loss of wetlands and other natural flood mitigation systems has further compounded the issue.

The accuracy of the LULC maps generated through the maximum likelihood classification technique was assessed through extensive validation processes. The high user accuracy and kappa values (e.g., 0.855 in 2022) confirm the reliability and robustness of the dataset, which serves as a valuable tool for urban planners and policymakers seeking to address the city's growing vulnerability to urban floods.

Additionally, the correlation analysis provided further insights into the complex relationship between land use changes and flood impacts. As stated Sohn et al., (2020), the modification of land cover, particularly the expansion of impervious surfaces such as roads, parking lots, and buildings, directly correlates with increased risk of urban floods in urban areas. This study found that the relationship between the rainfall intensity, and LULC change, and flood impact are more complex, and influenced by multiple factors. Water bodies and barren lands showed moderate positive correlations with the number of flood-affected people, while dense vegetation showed a weak negative correlation, suggesting ta possible mitigating effect. However, these correlations were not statistically significant. The findings suggest that factors like drainage infrastructure and urban planning play a more critical role in flood outcomes than LULC alone. Additionally, the weak negative correlation between rainfall intensity and affected individuals indicates that flood severity depends more on urban response than rainfall volume alone.

Despite efforts to expand drainage systems, problems continue, especially in informal settlements that are highly vulnerable to flooding. While green spaces and water bodies provide some mitigations, they cannot fully counter the risks from unregulated construction and poorly maintained drainage. This highlights the limitations of current flood control efforts. The study emphasizes the need for integrated urban planning that combines flood management with sustainable land use and environmental practices.

This research reinforces the need for continuous monitoring of LULC changes in Colombo and highlights the importance of integrating climate adaptation measures into urban planning processes. Policymakers should prioritize sustainable land management practices, such as preserving natural flood buffers, enhancing green spaces, and improving the capacity of drainage infrastructure. Furthermore, the findings underscore the importance of adopting a holistic approach to urban resilience—one that combines infrastructure improvements with community engagement, disaster preparedness, and climate-conscious governance.

Urban flooding is a significant issue in the CMC area. However, changes in LULC patterns, along with rainfall intensity, are just two factors that exacerbate the impact of these floods. The relationship between urban floods, rainfall intensity, and LULC changes is more complex, with several additional factors that must be taken into account. These include the drainage network of the area, soil water infiltration capacity, and overall hydrological patterns, among others. Study suggest that further research is needed to explore these factors in greater detail.

In conclusion, this study provides valuable insights into the spatial-temporal dynamics of Colombo's urbanization and flood risks and offers important recommendations for building a climate-resilient city. The evidence suggests that while urbanization is inevitable, its negative impacts can be mitigated through informed decision-making, adaptive urban planning, and the integration of nature-based solutions to enhance flood resilience. As Colombo continues to evolve, it is crucial to balance development with sustainable environmental practices to ensure that future generations can live and thrive in a safer, more resilient city.

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EARLY COMMISSIONING OF MEP WORKS FOR BETTER BUILDING PERFORMANCE

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ABSTRACT

Mechanical, Electrical and Plumbing (MEP) systems play a pivotal role in functionality of high-rise building (HRB) projects. Building commissioning helps to ensure that the building systems operate as intended, confirming their compliance with design and owner's requirements. Studies have highlighted the benefits of MEP commissioning from initial stages especially in HRB projects. However, due to a variety of reasons, MEP commissioning is frequently restricted to achieving "practical completion" at the project handover stage, Thus, the maximum benefits of this approach is not experienced due to the absence of commissioning activities in the initial building stages. This study aims to investigate the building commissioning activities for MEP works during the pre-design and design project stages of HRB projects in Sri Lanka. Firstly, the commissioning activities that should be carried out during the stages were identified from the literature. Then, 20 semi-structured interviews were conducted to explore their application in Sri Lankan HRB projects. Findings revealed that most activities were not conducted or conducted in an inadequate manner during the pre-design and design stages. Activities such as appointment of a third-party commissioning authority, establishment of commissioning scope, and preparation of commissioning plan were especially given poor attention. Lack of standards specialised to Sri Lanka, cost and time constraints, and unavailability of technology and experts were found as the major challenges for poor implementation of initial commissioning procedures. The findings provide a useful first step towards enhancing the early implementation of building commissioning procedures for MEP works in the local context.

Keywords: *Building commissioning; High- rise buildings; MEP systems; Sri Lanka.*

1. INTRODUCTION

The Mechanical, Electrical, and Plumbing (MEP) systems function as the lifeblood of the buildings (Khan & Shaari, 2023). These MEP systems consist of plumbing works, Heating, Ventilation, and Air-Conditioning (HVAC), electrical, energy conservation and elevator maintenance and other related installations and comprise complex processes, activities, and resources. Once the operational stage begins, these services are essential for the proper functioning of a building (Han et al., 2022) and for ensuring the expected comfort and safety for occupants. MEP works may constitute up to 40 to 60% of total project costs. Moreover, the rework rate for the MEP installations is also high approaching 20% (Wu et al., 2022). In high rise buildings (HRBs), the percentage of MEP work is around 26% of the total construction work (Riley et al., 2005; Wang & Leite, 2016). Accordingly, Crowe et al. (2020) have highlighted the requirement of a systematic

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approach for involving MEP works in HRBs that consider user requirements and bring more value through business-building alignment.

As described by Crowe et al. (2020), building commissioning is aimed at improving the execution of both new and existing construction endeavours. It attempts to verify the proper installation, testing, and functioning of the building systems according to their intended design (Coyner & Kramer, 2017). In addition, Vejrum (2023) stated that this is a comprehensive approach which centres on confirming and recording that all systems and components authorised are systematically mapped out, conceived, set up, evaluated, and utilized to fulfil the owner's project requirements for a novel structure and substantial refurbishments. Accordingly, commissioning provides remedial actions for minimizing reworks, which has become a significant challenge within the construction industry since they lead to inefficiency and unnecessary resource depletion while impacting both the design and construction stages of projects (Harker, 2018). Thus, commissioning can be identified as a tool that is essential for ensuring project cost, quality, and timeline achievements.

Several studies have highlighted the benefits of MEP commissioning from initial project stages especially in HRB projects. For example, building commissioning during start-up is advantageous for resolving initial issues and ensuring that HRBs operate as intended by bringing systems to full functionality (Caglayan et al., 2022). Furthermore, this proactive approach aims to swiftly address potential design-related issues, minimising the need for later reworks. However, due to time and budget constraints, commissioning is frequently restricted to achieving "practical completion", and the objectives may remain unrealized (Noye et al., 2015). This lack of attention to building commissioning in the early project stages can lead to several drawbacks, such as reworks, incorrect operation, inadequate documentation, missing equipment, and untrained operators, hampering efficiency and long-term functionality (Doloi, 2014). In addition, neglecting commissioning for MEP works from the planning stage can also result in schedule delays, uncontrolled delivery schedules, and increased construction costs, as well as improper fits during installation due to as-built deviations between structures and the MEP layout (Wang et al., 2016). Despite this, still building commissioning is often viewed as an activity or a set of activities to be conducted at project handover. This view is particularly prevalent in the local context as evidenced in the works of authors such as Pilanawithana and Sandanayake (2016) and Samarasinghe et al. (2016). Hence, this study aims to investigate the building commissioning activities for MEP works during the early project stages of HRB projects, which in turn is essential to ensure long-term functionality and efficient building performance. The paper first presents an overview of MEP works in HRBs and the concept of building commissioning. Then, the research methodology is detailed. The findings on the current approach to commissioning in the Sri Lankan context are briefly discussed next. Thereafter, the findings on the application of building commissioning activities during the predesign and design stages and the challenges for implementing the same are discussed. Finally, the conclusions and the implications of the research findings are presented.

2. OVERVIEW OF MEP WORKS IN HIGH-RISE BUILDINGS

MEP systems in HRBs include essential sub-systems such as electrical distribution system, heating, ventilation and air-conditioning (HVAC), potable water supply and distribution, sanitary drainage and sewage systems, fire protection systems and elevators and escalators (Han et al., 2022; Hu et al., 2023). These services are significant for the basic functioning and the quality of life of occupants. For example, MEP services ensure the efficient distribution of power, water, and climate control throughout the building (Jawad et al., 2021). Without the proper functioning of these MEP systems, HRBs would be uninhabitable, impractical, and unsustainable (Monsberger, 2019). Hence, according to Lee and Ahn (2018), MEP systems can be considered as the lifeblood of HRB structures.

3. BUILDING COMMISSIONING

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2019), building commissioning is a "quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria". Thus, commissioning helps to ensure that building systems operate as intended, confirming their compliance with design and owner's requirements, and documenting the process.

According to Doloi (2014), building commissioning should begin during the concept design phase, where project goals and performance criteria was established and ensure that MEP systems are designed to meet specific standards and expectations. Similarly, Monsberger (2019) highlights that to obtain maximum benefits, commissioning must begin in initial stages such as strategic definition, concept design and technical design where the initial MEP designs are outlined in modern construction projects. Thus, several existing literatures (Coyner & Kramer, 2017; Frye et al., 2002; Su & Thomson, 2016) have categorised building commissioning aspects under four main stages, including pre-design, design, construction, and post-construction. These four main stages can be defined using the work stages of the RIBA Plan of Work 2020 as given in Table 1.

Table 1: Categorisation of commissioning stages in existing literature according to the stages of RIBA plan of work 2020

Commissioning stages in existing literature	Relevant stages of RIBA plan of work 2020
Pre-design stage	Strategic Definition stage
	Preparation and Brief stage
Design stage	Concept Design, and
	Spatial Coordination
	Technical Design stage
Construction stage	Manufacturing and Construction stage
Post-construction stage	Hand over
	In-Use stage

Lack of building commissioning for MEP works in the early design stages can lead to several challenges. Eon et al. (2020) identified the drawbacks including discrepancies between the as-designed and as-built energy performance of the building often due to a lack of knowledge and communication between stakeholders. Inadequate consideration of requirements in the early design stages can also result in energy performance gaps in non-domestic buildings, impacting the overall efficiency and sustainability of the HRBs (Thompson et al., 2022). Thus, this paper particularly focuses on the pre-design and design stage commissioning activities for MEP works particularly in the context of Sri Lankan HRBs.

4. RESEARCH METHODOLOGY

This study aimed to investigate the building commissioning activities for MEP works during the early project stages of HRB projects and the challenges associated with the same. Through the literature survey, the commissioning activities that should be conducted in the pre-design and design stages were identified. The study used a qualitative approach as it allowed to gain a deeper understanding about the applicability of these activities in commissioning MEP systems in Sri Lankan HRB projects and challenges in doing the same. Semi-structured interviews were chosen as the data collection method because they offer the flexibility to gather additional pertinent information during data collection without being limited to a structured questionnaire. Interviews were conducted with twenty (20) experts who were passionate, well experienced and have the knowledge regarding the commissioning for MEP systems in the Sri Lankan context as evidenced by their years of experience in the industry and the number of MEP projects involved (refer to Table 2). An interview guideline was prepared based on the literature review findings to guide the interview process. The interviewees were selected using purposive sampling with the aim of covering all perspectives including client, contactor, and consultants. The interviews lasted between 40-55 minutes each and were conducted either in-person or online, based on the availability of the respondents. The number of interviews conducted was limited to 20 due to data saturation. The profile of the selected interviewees is given in Table 2.

Table 2: Profile of interviewees

Respondent	Designation	Experience in MEP context (Years)	No. of MEP projects involved	Current perspective	Specialized systems
E1	Senior consultant	44	100+	Consultant	HVAC systems
E2	Deputy General Manager - Design	30	30+	Contractor	Mechanical, Plumbing system
E3	MEP Manager - Design, Estimation and Quality Assurance	28	25+	Contractor	Overall MEP
E4	Maintenance Engineer	25	10	Client	Overall MEP
E5	Senior MEP Manager, Consultant	20	15	Client	Overall MEP

Respondent	Designation	Experience in MEP context (Years)	No. of MEP projects involved	Current perspective	Specialized systems
E6	MEP Site Manager	19	46	Contractor	Overall MEP
E7	Site Engineer	10	5	Contractor	Electrical System
E8	Maintenance Engineer	10	3	Client	Overall MEP
E9	Engineer - Design & Estimation	8	15	Contractor	Fire, Electrical and LPG
E10	Site Engineer	8	11	Contractor	HVAC, Plumbing System
E11	Assistant MEP Manager	8	10+	Contractor	Fire system
E12	MEP Site Engineer	8	5	Contractor	Overall MEP
E13	Resident Electrical Engineer	8	5	Consultant	Electrical
E14	Lead Engineer	7	6	Consultant	Overall MEP
E15	Electrical Engineer	6	15+	Contractor	Electrical System
E16	Assistance Electrical Engineer	6	20+	Contractor	Electrical systems
E17	Mechanical Engineer	5	3	Consultant	Mechanical, Plumbing Systems
E18	Senior Project Engineer	5	16	Contractor	Plumbing, Fire System
E19	MEP Engineer	4	2	Contractor	Overall MEP
E20	Assistant Quantity Surveyor	2	3	Contractor	Overall MEP

The collected data were analysed using manual content analysis, and the findings are discussed in the following section.

5. FINDINGS AND DISCUSSION

5.1 CURRENT APPROACH TO COMMISSIONING OF MEP WORKS IN SRI LANKA

Interviewees overwhelmingly highlighted how the commissioning process is conducted as an aspect in the handing over stage in the local context. For instance, 06 out of 20 respondents (i.e. E4, E5, E9, E10, E11 and E12) highlighted that even the preparation for the commissioning activities were conducted around 4 months before project completion. According to E13, the method statements and checklists are also prepared at the last moment and submitted to the consultant for approval.

There appears to be a misconception, particularly among the contractors in the local context, regarding commissioning as a final stage activity. For instance, as E4 highlighted, "*contractors think after commissioning everything is over, so they try to finish it as soon as possible".* Similarly, sub-contractors conduct the system start-up checks only after all the installations are completed. Some of the higher-grade contractors have neglected initial commissioning aspects to reduce the overheads required for hiring MEP engineers. It appears that many of the Sri Lankan HRB projects experience delays in completion due to the poor attention given to commissioning activities.

5.2 BUILDING COMMISSIONING ACTIVITIES CONDUCTED IN PRE-DESIGN STAGE

This stage involves the initial planning of MEP systems (Grondzik, 2009). Commissioning works for MEP systems at this stage aim to verify that the design and installation of these systems align with the project requirements and standards (Su & Thomson, 2016). Identifying potential issues or conflicts with other building components is crucial to ensure the overall performance and functionality of the high-rise building (Grondzik, 2009). Accordingly, altogether, 09 commissioning activities that should be conducted in the pre-design stage were identified from the literature. Table 3 provides the interview findings on the application of these commissioning activities during the pre-design stage in Sri Lankan HRB projects.

Table 3: Application of commissioning activities in pre-design stage in Sri Lanka

Activity No.	Commissioning activity	Not conducted	Conducted inadequately	Conducted with deficiencies	Conducted adequately	Conducted appropriately
1	Defining owners' project requirements	0	1	2	17	0
2	Developing the basis of design	1	3	3	13	0
3	Establishing the commissioning scope	10	7	3	0	0
4	Preparation of a preliminary commissioning plan	15	2	3	0	0
5	Appointment of the commissioning authority	18	0	0	2	0
6	Early discussion and collaboration	2	10	8	0	0
7	Integrating commissioning with the project schedule	0	3	7	10	0
8	Budget estimation	0	0	3	17	0
9	Review of certification requirements	2	0	3	15	0

Findings show that most of the commissioning activities in the pre-design stage are not conducted or conducted in an inadequate manner in the Sri Lankan context.

One of the key commissioning aspects that is not conducted in the pre-design stage is activity no 5, the appointment of third-party commissioning authority. According to E2, this was mainly attributed to cost limitations. Findings revealed that in the Sri Lankan

context, many of the commissioning activities were carried out by the project's consultant and contractor rather than a third party. For instance, E12 highlighted that a chartered engineer performs the final approvals of the systems, such as electrical and fire systems. However, 2 respondents identified the use of a commissioning authorities in foreign funded projects. As per E5, *"there is a practice of appointing a third-party authority in foreign funded projects, this should be specified in the tender as well".* Additionally, E3 mentioned that "*the higher-grade contractors have in-house commissioning teams. Actually, this is not a third party".* In addition, 05 out of the 20 interviewees (i.e. E5, E6, E11, E14, E20) also noted that typically clients tend to appoint a third-party for commissioning towards the middle or final stages of a project, if they feel that the process is not properly conducted. However, in such instances, all or most of the installations are completed, and the party has less knowledge regarding the project.

Secondly, the establishment of commissioning scope is another aspect that is not conducted in the Sri Lankan context, according to the respondents. In the pre-design stages mainly, the focus is on the architectural and aesthetic aspects rather than the commissioning aspects. The interviewees also noted that there were difficulties in identifying client requirements, which resulted in difficulties in preparing a proper scope. According to E10, this often leads to contractors providing outcomes that are totally different to what the client asked. Further, it appears that some projects shifted this activity to other stages. For example, E5 stated that this was sometimes considered in the tender stage due to the involved cost. According to him, "*In my point of view because of the less knowledge regarding the scope preparation, this is not conducted in a proper manner. The testing scope is prepared, but we don't prepare a proper commissioning scope in most projects".*

Findings further highlighted the absence of commissioning plans in most of the local HRB projects. Further, it appears that the few projects that do prepare this plan do so in an inadequate manner. As highlighted by E6, due to absence of proper commissioning scope contractors often prepare this according to their own knowledge and submit to consultants. Furthermore, these plans are not implemented in the sites as well. In addition, there are numerous issues and deficiencies in the planning and preparation. According to E16, *"these plans are prepared based on the knowledge of the people involved and not according to the guidelines. There are no guidelines specialised to the Sri Lankan context, even from CIDA. Documents are incomplete and not comprehensive".* 06 out of 20 (i.e. E3, E7, E12, E16, E18 and E19) interviewees stated that this activity is often shifted to the construction stage, while 03 others (i.e. E5, E10, E13) stated that it is sometimes carried out in the handing over stage.

On the other hand, many respondents identified that defining the owners' project requirements is often conducted adequately in this stage. However, poor knowledge that clients have about their project requirements is often an issue. In such scenarios, consultant has the responsibility to clearly determine these requirements. According to E5, "*because of the alterations made by the client time to time and professionals get affected when performing their job."* These aspects act as barriers when implementing commissioning activities properly in this stage.

Allocating a budget for commissioning activities is usually conducted in the pre-design stage. As per E4 and E2, budget allocation depends on the client and E15 and E18 stated that the allocated amount is not sufficient on most occasions. In the local context, a

percentage of the total work done, or a lump sum amount is allocated for these activities based on the experience of professionals without proper identification of the requirements.

Clients who are looking to obtain sustainable certifications and other standard certifications often focus on the certification requirements during this stage. As noted by E1, "*according to the green building requirements there is a must to properly conduct commissioning".* According to E3, "*commissioning clauses must be included in the report. These are considered a prerequisite for the certification. Assurances about the efficiency of the system could be provided through commissioning".* In addition, many of the respondents focused on the COC and other authority certifications such as electricity and fire here as well. As highlighted by E7, *"inspections done by the authorities thoroughly check the commissioning process of electrical and fire systems during the authorisation procedures".*

In the local context, integrating commissioning with the project schedule is mostly conducted in an adequate manner. As highlighted by 04 out of 20 (E1, E5, E6, E110 interviewees, master plans prepared in the pre-design stage include the time allocation for every system that requires commissioning aspects. According to E14, as a thumb rule schedules are included in commissioning. However, the actual application would often differ from these initial schedules. As identified by E5, *"Most of the time, due to project delays, there is no time remaining for commissioning. In these scenarios, the systems are just checked with only start-up checks and determined whether OK."* Accordingly, it was revealed that most of the commissioning activities were actually conducted in different time frames compared to these initial schedules.

As per the above analysis, it was realised that most of the commissioning activities in the pre-design stage were neglected or conducted in an inadequate manner in the local context.

5.3 BUILDING COMMISSIONING ACTIVITIES CONDUCTED IN THE DESIGN STAGE

According to Dehghani-Sanij (2018), this crucial phase focuses on translating the conceptual design into detailed plans and specifications. Further, this phase involves detailed load calculations for equipment selection, meticulous system layouts coordinated with other disciplines, control system design for optimal performance, and comprehensive commissioning plan preparation (ASHRAE., 2019). This diligent work ensures smooth and efficient commissioning, leading to optimal MEP system operation throughout the lifespan of the building (Singh & Anumba, 2023).

Altogether, 13 commissioning activities that should be conducted in the design stage were identified from the literature. Table 4 provides the application of these activities conducted in the design stage of Sri Lankan HRBs.

Table 5: Application of commissioning activities in design stage in Sri Lanka

Activity No.	Commissioning activity	Not conducted	Conducted inadequate	Conducted with deficiencies	Conducted adequately	Conducted appropriately
1	Detailed design review	0	0	1	9	10
2	Construction documents review	0	0	1	4	15
3	Development of commissioning procedures	10	1	4	5	0
4	Basis of design verification	0	3	10	7	0
5	Development of a commissioning plan	10	4	3	0	3
6	Creation of initial checklists and tests	2	0	3	10	5
7	Planning for system manual and training	1	2	4	13	0
8	Development of commissioning specifications	0	6	6	8	0
9	Energy model review	0	2	3	15	0
10	Building performance simulations	12	3	5	0	0
11	Prepare for construction phase commissioning	0	0	5	5	10
12	Regular commissioning meetings	18	0	0	2	0
13	Alignment with the contractor	10	0	3	7	0
14	Preparation of a preliminary commissioning plan	0	0	0	1	0

According to the respondents, there appears to be an improvement of the application of commissioning activities in the design stage compared to the pre-design stage. As given in Table 4, activities such as detailed design review, construction document review, and preparing for construction phase commissioning are usually practised in an appropriate manner in the local context. However, activities such as development of commissioning procedures, development of a commissioning plan and building performance simulations are highlighted as absent in the design stage. On the other hand, the activities such basis for design verification, planning for system manual and training are conducted in an adequate manner. However, the interviewees noted that even these activities *needed further improvement.* In addition to the activities, identified from literature, 'preparation of a preliminary commissioning plan' was identified by E11 as a commissioning activity that should be conducted in this stage.

Findings revealed a lack of collaboration among professionals regarding commissioning activities. It was found that there were no arrangements for the regular commissioning meetings in the projects. As per 04 out of the 20 respondents (E2, E4, E5 and E10), regular progress meetings are utilised to discuss any requirements of commissioning. This drawback could impact the overall efficiency and coordination of commissioning in the projects.

When considering the building performance simulation activities, 12 respondents identified that this activity is not conducted in the local context. As highlighted by E8, typically AutoCAD or project management tools such as Microsoft Project or Primavera

were used for managing the commissioning requirements rather than any software specialised for commissioning. E13 also stated that in the local context commissioning often relied upon manual calculations and rules of thumb.

The development of commissioning procedures and a commissioning plan was another activity that was neglected in the local context. Findings highlighted that this activity was often delayed to the handover stage.

Involving the contractor for commissioning activities in this design stage was only carried out in the design and build type projects. In the traditional procurement method, involvement of the contractor happens after the design aspects. E7 quoted that, *"as I experienced, in the traditional construction projects, there is no involvement of contractor during design stage"*.

On the other hand, most of the experts illustrate the adequate procedures of planning for system manual and training within the context. Most of the owners stated the training requirements in the tender documents themselves. E10 stated that the planning activities in this stage were performed as a norm in the industry, and E4 highlighted the standardisation of training procedures in this stage. In the design and build projects, contractors ask the employers to appoint operational staff to these procedures even though some clients delay these appointments. In addition, several respondents stated that the planning activities for system manuals are conducted adequately in this stage. According to E18, *"we usually plan to obtain system manuals of each and every system by the manufactures and three copies of the same files are submitted with system manuals in the handing over stage".*

Creation of initial checklists and tests are also usually carried out in an adequate manner in this stage. Some organisations prepare these checklists according to the international standards. However, 04 out of the 20 respondents (i.e. E5, E13, E16, and E17) also noted that these checklists are prepared in the construction stage. E16 also highlighted that, *"checklists are created and submitted later for approvals 3 or 4 months before the commissioning activities in the construction stage".*

Activities such as detailed design review and construction documents review appear to be conducted in an appropriate manner. Specifications should be thoroughly evaluated for commissioning aspects at this stage. In the local context, British standards are followed when reviewing these aspects. E17 highlighted that design parameters such as decibel levels, flow rates, lux levels and pressure rates are considered when reviewing designs. E3 stated that, "*in here the drawings and method statements should be double checked and confirmed. The type of material installation thickness and manufacture characteristics are considered".* As per E1, all the construction drawings should be reviewed with the aim of confirming all the components and arrangements that need to be in commission are included in the designs. Ultimately, these two aspects assist maintain the ability of commissioning throughout the projects.

5.4 CHALLENGES TO IMPLEMENT COMMISSIONING IN THE PRE-DESIGN AND DESIGN STAGES IN SRI LANKAN HRB PROJECTS

Several challenges could be identified as root causes for the absence of initial commissioning activities in the HRB projects. Table 5 provides findings from interviews with regard to the challenges of initial implementation of commissioning aspects.

Table 5: Challenges for implementing commissioning in the pre-design & design stages in the Sri Lankan context

No	Challenge	No of respondents
C1	Complexity of systems	8
C2	Issues in stakeholder coordination	8
C3	Cost and time constraints	20
C4	Limited design information	6
C5	Requirement changes during construction	10
C6	Unavailability of expertise and skills	16
C7	Lack of technology and tools	17
C8	Regulatory and compliance issues	6
C9	Issues in documentation	9
C10	Lack of awareness of the benefits	18
C11	Effect of owner/ client's expectations	3
C12	Unavailability of the specialized standard	10
C13	Lack of third-party commissioning experts	13
C14	Payment issues for the consultants	1

Most of the experts highlighted that the cost and time constraints in the projects as the major challenge affecting the initial implementation of commissioning activities. E5 noted insufficient bidding amounts allocated for commissioning activities, and as per E4, *"Due to the financial constraints, owners do not thoroughly go through the commissioning process"*. Lack of awareness of clients regarding the importance of proper commissioning practices is another common challenge. According to E4, "*professionals often fail to showcase the benefits of commissioning to their clients"*.

According to E3, E4, and E8, the economic crisis has led many experts to migrate, resulting in difficulties in appointing qualified professionals. Further, E4 noted that there is a lack of training and poor uptake of technology with regard to commissioning aspects. In addition, respondents also highlighted the lack of a third-party commissioning authority and the unavailability of commissioning standards specialised to Sri Lanka as challenges for proper commissioning in the local context. According to E11, the industry utilises British standards or standards from a developed country. There is a mix of standards, and sometimes these do not fit with the Sri Lankan project environments.

Overall, the findings revealed a widespread misconception of commissioning as a final step in the construction process rather than an ongoing process. Further, it appears that many of the activities that need to be performed in the early stages are carried out at later stages. According to Crowe et al. (2020), incorporating commissioning in the initial stage of a HRB construction project facilitate to ensure that all MEP systems are designed and built to perform optimally and efficiently. Furthermore, Felter and Gelfo (2022) stated that it promotes better communication and coordination among the project team and helps identify and address potential performance issues early in the project life cycle.

Lack of standards specialised to Sri Lanka, cost and time constraints and unavailability of technology and experts are found as the major challenges for the lack of initial

commissioning of MEP works. As noted by Lohne et al. (2015), limited time and budget often restrict the commissioning process to achieving basic functionality rather than optimising performance. Similarly, Caglayan et al. (2022) has also highlighted the difficulty in finding qualified personnel/service providers as a main challenge associated with commissioning.

6. CONCLUSIONS

The aim of this study was to investigate the building commissioning activities for MEP works during the early project stages of HRB projects and the challenges associated with the same. The study was limited to the pre-design and design stages of the building process. Proper commissioning of MEP works from the initial project stages is essential for ensuring that HRBs operate as intended by bringing systems to full functionality. Such a proactive approach can swiftly address any design-related issues, minimising the need for later reworks. However, this study found that there is a widespread misconception in the local context that commissioning is a sole step conducted in the final stages of a project (often before handing over). Key aspects such as preparation of commission plans, commissioning scopes are not conducted in a proper manner the local context. Lack of standards specialised to Sri Lanka, cost and time constraints and unavailability of technology and experts were found as the major challenges for poor implementation of initial commissioning procedures. The findings shed light on the current deficiencies of building commissioning of MEP works in HRBs. This lays the foundation for developing targeted strategies to improve proper application of commissioning activities from initial project stages, thereby leading to improved building performance. As such, it provides a useful first step towards enhancing the early implementation of building commissioning procedures for MEP works in the local context.

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EMBODIED CARBON VARIABILITY IN INDIAN HIGH-RISE RESIDENTIAL BUILDINGS: A CASE-BASED ASSESSMENT

K.G. Akshatha[1], Sivakumar Palaniappan[2] and M.K. Pradeep Kumar Rao[3]

ABSTRACT

The results of studies on embodied carbon in high-rise residential buildings are frequently given as a single-point estimate without considering the variability in results due to input parameter variability. This study examines the variability in embodied carbon of a 30-storey high-rise residential shear wall building with four datasets of embodied carbon factors that help to set up a baseline. The building embodied carbon was found to range from 373 $kgCO_2eq/m^2$ (IFC Indian database) to 530 $kgCO_2eq/m^2$ (EPiC database), with a mean of 454 $kgCO_2eq/m^2$ and a standard deviation of 65.3 $kgCO_2/m^2$. Concrete and reinforcement steel are major influencers that contribute 80% of the embodied carbon of the high-rise residential building. The minimum and the maximum embodied carbon of concrete are 157 $kgCO_2eq/m^2$ and 247 $kgCO_2eq/m^2$, respectively. The embodied carbon of reinforcement steel varies from 141 $kgCO_2eq/m^2$ to 207 $kgCO_2eq/m^2$. The analysis highlights the importance of understanding the variability in embodied carbon for establishing a reliable baseline, primarily for high-consumption materials.

Keywords: *Embodied Carbon Assessment; High-rise Residential Building; Sensitivity Analysis.*

1. INTRODUCTION

The building sector accounts for around 37% of the global greenhouse gas (GHG) emissions and more than 35% of global energy consumption, making it one of the most significant contributors to environmental impacts (United Nations Environment Programme [UNEP], 2023). In 2023, the worldwide greenhouse gas emissions touched a record 57.1 $GtCO_2eq$, representing a 1.3% increase from 2022. India's total greenhouse gas emissions in 2023 were 4140 $MtCO_2eq$, accounting for 8% of global emissions, a 6% rise over 2022. With per capita GHG emissions of 2.9 tCO_2eq, India stays below the world average, but has substantial problems regulating growing emissions (UNEP, 2024). In India, compared to 2011, 0.6 billion people, or 40% of the population, will be living in metropolitan areas by 2036 (Kouamé, 2024), fostering a massive demand for residential housing, particularly high-rise residential buildings in urban cities like Delhi, Mumbai,

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Chennai, and Bengaluru. High-rise buildings have significant material intensity, which makes addressing the embodied carbon a critical priority in the built environment.

The entire life cycle of a building includes four phases: production, construction, operation, and demolition. The total life cycle carbon of a building consists of embodied carbon and operational carbon (Royal Institution of Chartered Surveyors [RICS], 2023). The building embodied carbon refers to the emissions from the mining of raw materials (A1), transport of raw material to the factory (A2), manufacturing of building material (A3), transport of material to the project location (A4), and onsite construction works (A5). Adding to this are the emissions from energy used for maintenance, repair, and renovation at regular intervals during the building's service life (B2, B3, B4, and B5). The operational carbon is from the energy consumed for lighting, heating, cooling, ventilation, appliances, and equipment. According to Ramesh et al. (2010), buildings typically account for 80–90% of their total energy consumption through operational energy and 10–20% through embodied energy. However, embodied carbon alone makes up 27–58% of the building's total lifecycle carbon emissions, depending on the future energy mix (Robati et al., 2021).

Whole-life embodied carbon (WLCA) yields a benchmark of 1,300kgCO_2eq/m² for A-C stages, aligning with data from RIBA, GLA, and LETI (World Green Building Council [WGBC], 2022), making it a helpful baseline for future comparisons. In a high-rise residential building, 85% of the carbon emissions are related to the production phase (A1-A3) (Zhang et al., 2023). The embodied carbon intensity for the production phase varies from 210.4 kgCO_2eq/m^2 to 769.4 kgCO_2eq/m^2; mean and median values are 379 kgCO_2eq/m^2 and 370.8 kgCO_2eq/m_2, respectively. The embodied carbon intensities attributed to the material production and transportation phases are evaluated as 379 kgCO_2eq/m^2 (89.9%) and transportation to the location, 45.1 kgCO_2eq/m^2 (10.1%) on average, respectively. The variations in the embodied carbon are higher due to the uncertainty in the data quality of the emission factors, due to the use of material energy, manufacturing process, and lifespan of products, primary energy sources, chemical processes, transport fuel type, and the extent of waste or recycling (Ibn-Mohammed et al., 2013), additional variations also from inaccurate quantity measurements and the methodologies adopted for calculations.

This paper presents a case study to demonstrate the variability in embodied carbon of high-rise residential buildings using four different datasets, focusing on the contributions of material-specific embodied carbon to the overall building emissions. The scope of the study is limited to the production phase (A1-A3), and the materials commonly used in high-rise residential buildings, such as civil and finishing. The embodied carbon factors are considered for virgin materials without any replacement or waste material content included. The goal is to establish a more reliable baseline for future embodied carbon calculations.

2. METHODOLOGY

Figure 1 shows the method for assessing the embodied carbon emission with the different data sources and the sensitivity analysis at the building level. The input parameters for the embodied carbon calculation are the quantity of materials and the embodied carbon factors. The scope of the study is limited to the product stage. The data related to the embodied carbon factors are taken from peer-reviewed literature and technical reports.

The material quantities are taken from the bill of quantities (BOQ) and the related building drawings. The life cycle inventory data for the material are taken from the technical reports of ICE UK BATH, EPiC of Australia, IFC Indian data set, and the In-house tool. These datasets have been selected because they are publicly available and account for global geographical conditions to understand the variability.

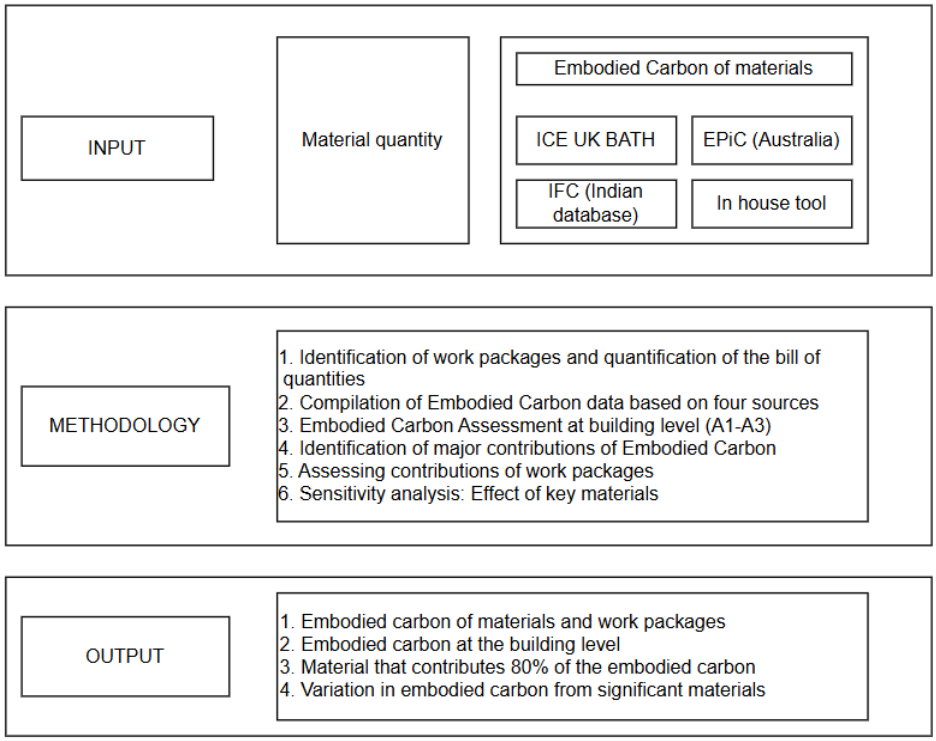


Figure 1: Methodology considered for the embodied carbon assessment

3. CASE STUDY

A high-rise residential building project is considered for the embodied carbon assessment and to understand the variations in the embodied carbon factor's effect on the building-level carbon emission. The project details are mentioned in Table 1. The work packages and the bill of quantities considered for the embodied carbon assessment are shown in Figure 2 and Table 2.

Table 1: Description of the building

Specification	Building
Number of floors	2B+G+30 floor
Number of dwellings	420
Floor height	3m
Total building height	92.625m
External wall	Concrete shear wall 160mm
Total area of the project	4.1 Acres
Super built-up area	6,98,321 sqft
Total built-up area	8,97,710 sqft
Type of dwellings	4BHK, 3BHK, 2BHK and 1BHK

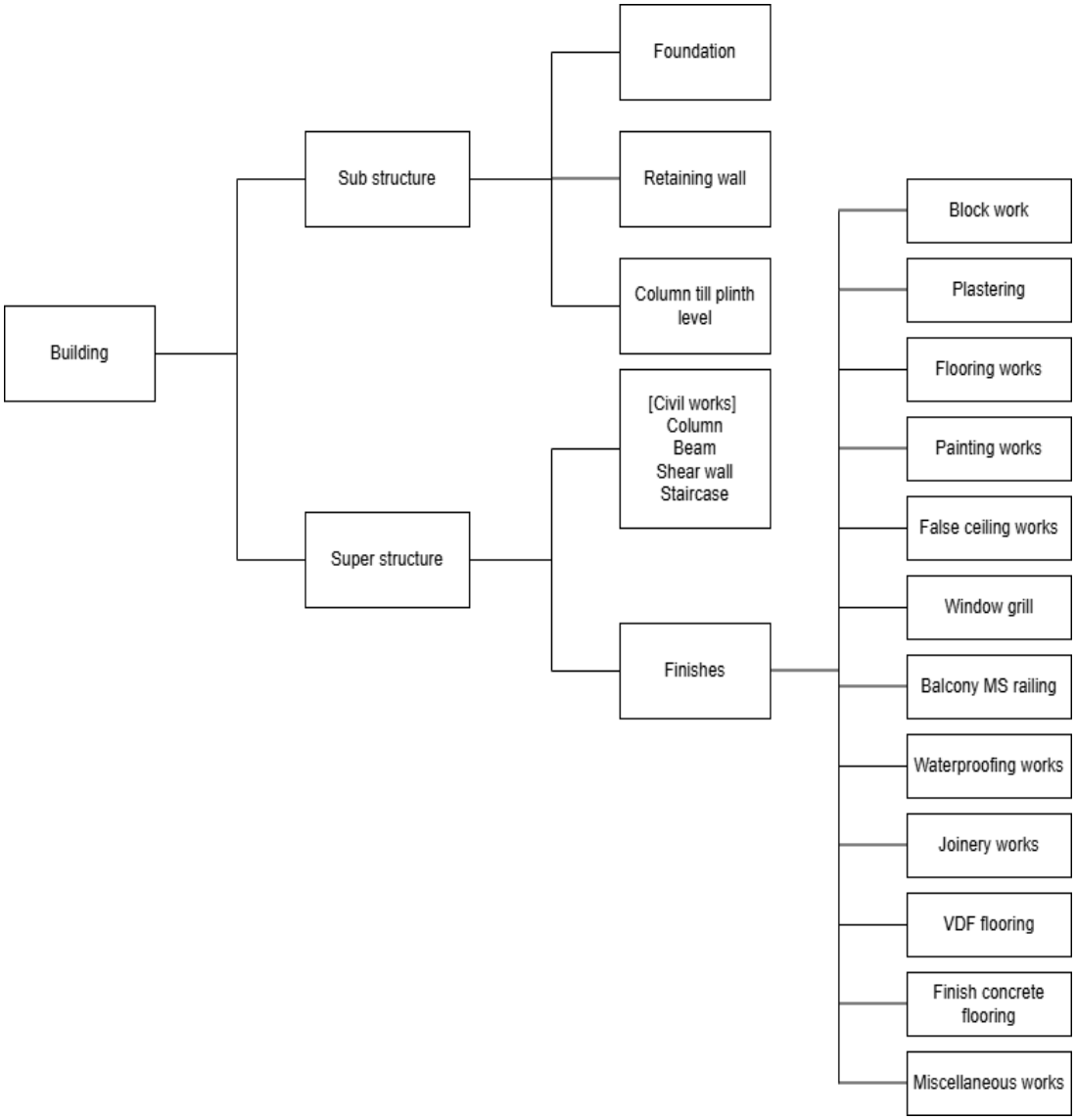


Figure 2: Work breakdown structure

4. EMBODIED CARBON ASSESSMENT

Life cycle assessment is a process that quantifies and evaluates the material and energy flows of a system to understand its environmental impact. The embodied carbon of the material from cradle to factory is considered for the assessment because the impact is highest in the construction phase (Zhang et al., 2024). The material quantities were converted to the required unit, and the embodied carbon factor was multiplied to get the embodied carbon contribution under each material. Consistent material quantities were considered to manage variability across the database, while only the emission factors varied. The effect of variability in the embodied carbon coefficients of construction materials on the embodied carbon of the residential building is evaluated. The embodied carbon factor variation for each material for four different databases is presented in Figures 3 and 4. Calculation is done for all four cases. The embodied carbon calculated at the material level is represented in $kgCO_2eq$, and at the building level in $kgCO_2eq/m^2$.

Table 2: Bill of quantities

Building components	Building materials	Quantity	UoM
Foundation	PCC	1459	m^3
	Concrete	10817	m^3
	Reinforcement	1350	MT
Column, beam, and shear wall	Concrete	16550	m^3
	Reinforcement	3150	MT
Block work	Solid blocks	5265	m^2
Plastering	Cement	270300	kgs
	M sand	1126.62	m^3
Flooring	Vitrified tile	76750	m^3
	Cement tile	3432	m^2
	Granite	2295.3	m^2
	Cement	1398911	kgs
	M sand	5701.24	m^3
Painting	Gypsum plaster	8000	m^2
	Texture	56149	m^2
	Putty	409048	m^2
	Primer	262536	m^2
	Paint	153568	m^2
	Enamel painting	11416	m^2
Doors	Wooden frame	2712	No’s
	Wooden shutters	2712	No’s
	Fire-rated GI door	1254	m^2
Window	UPVC	445.71	m^2
	Glass	9164.29	m^2
Waterproofing	HDPE membrane	12605	m^2
	Polymer cementitious	29887	m^2
	Cement	104672	kgs
	Sand	291	m^3
False ceiling	Gypsum boards	9221.15	m^2
	Calcium silicate boards	4365	m^2
Railing, Window grills	MS	141.4	MT
Miscellaneous works	RCC precast slab	40	m^2
	Aggregate	60	m^2
	Concrete	5003.37	m^3
	Steel	100	kgs

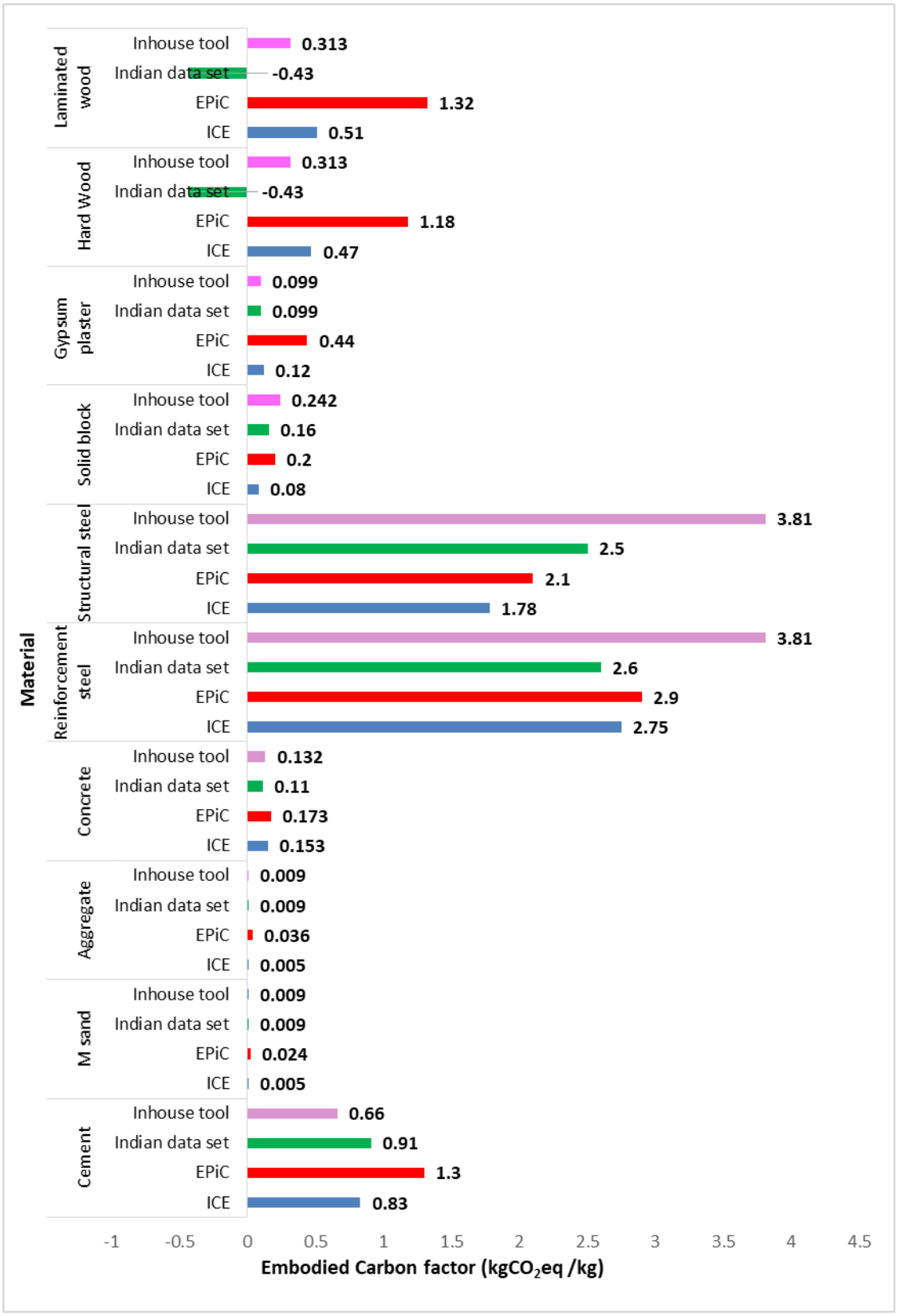


Figure 3: Material embodied carbon factors for the four databases

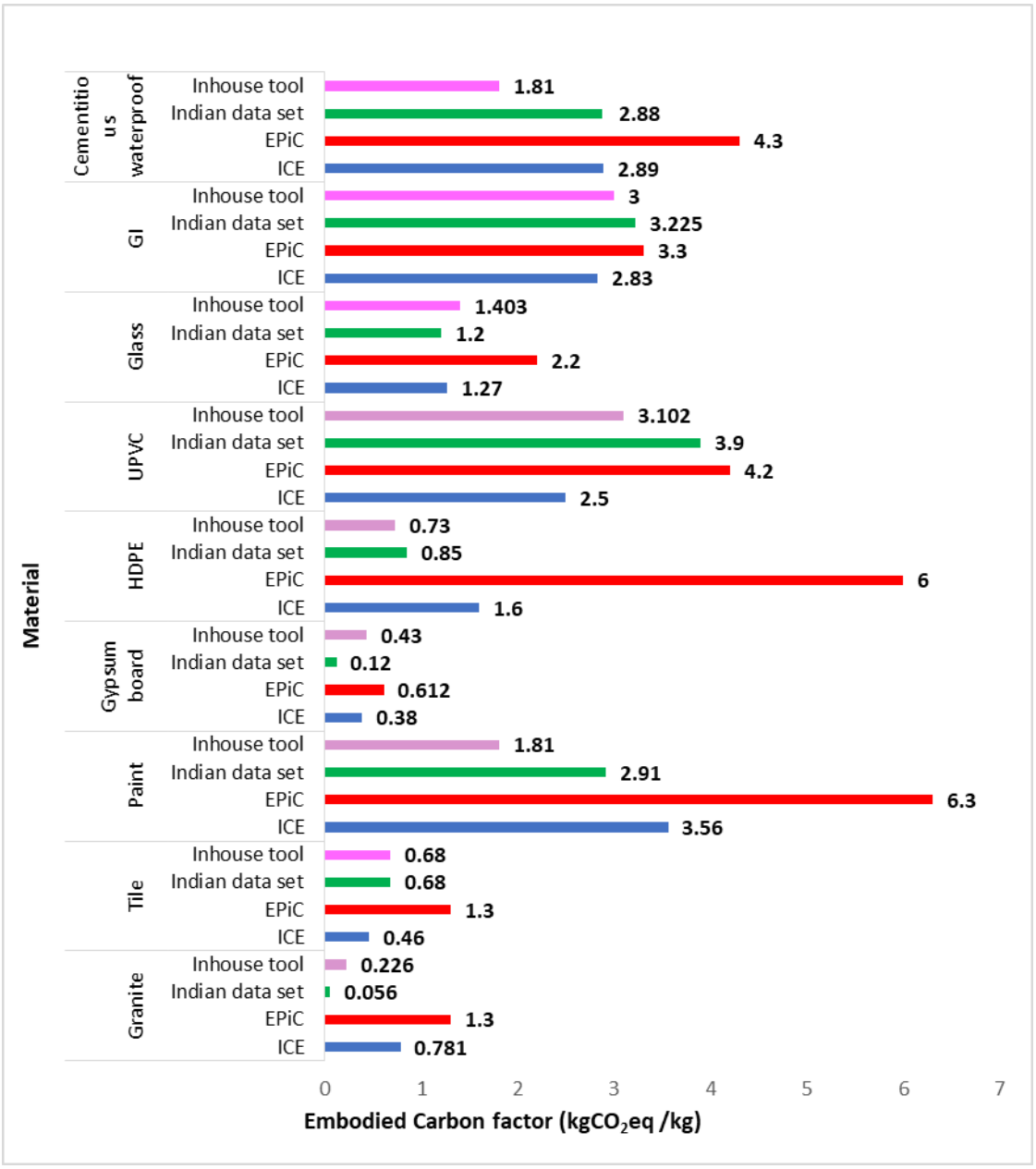


Figure 4: Material embodied carbon factors for the four databases

5. RESULTS AND DISCUSSION

The embodied carbon of the building, from the sources considered, has the lowest value of 373 $kgCO_2eq/m2$ (IFC) and the highest of 530 $kgCO_2eq/m2$ (EPiC). This is due to the variation of embodied carbon factors. The average value is 454 $kgCO_2eq/m^2$, the standard deviation is 65.3 $kgCO_2eq/m^2$, and the Coefficient of variation (CV) is 14.40%. The embodied carbon emission from the material for all the cases at the building level is represented in Figures 5 and 6.

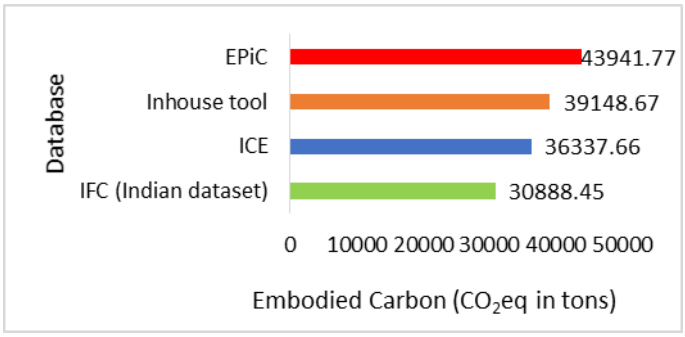


Figure 5: Embodied carbon emission (TonsCO_2eq)

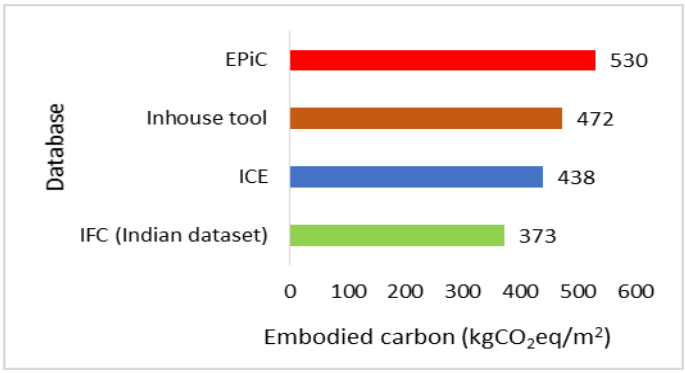


Figure 6: Embodied carbon emission (kgCO_2eq/m^2)

The concrete works and reinforcement steel contribute 80% of the embodied carbon for the overall embodied carbon emission, as shown in the Pareto chart in Figure 7. This is due to the shear wall construction and more RCC quantity. The variations in the embodied carbon of high-rise residential buildings are due to the variability in the embodied carbon factors of materials. The variability is mainly due to inaccurate and insufficient information for the quantification, diverse methodologies for assessing, improperly defined system boundaries, data quality, and a lack of data on all the construction material processes (RICS, 2023). The system boundaries set for the LCA also play a significant role in embodied carbon emissions at the building level.

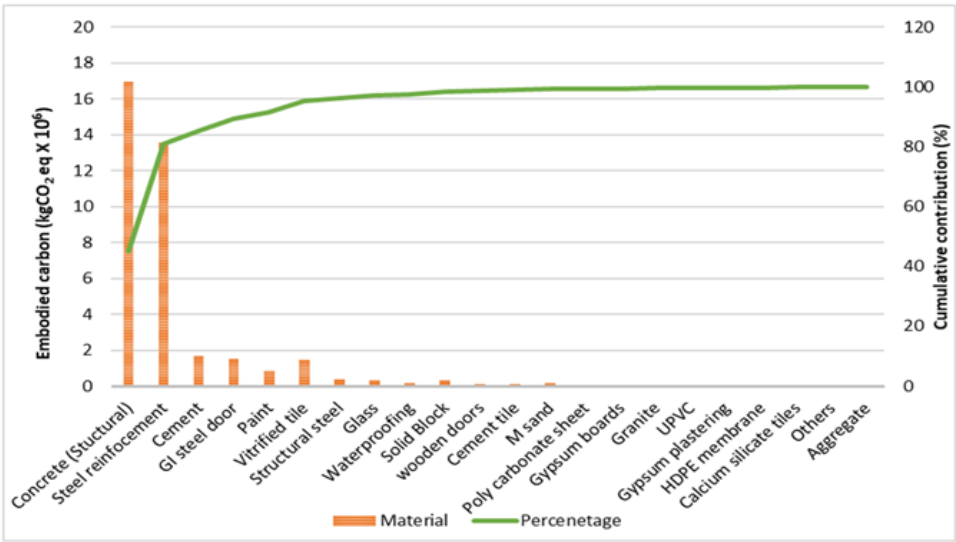


Figure 7: Pareto chart on material embodied carbon contribution

Considering the work package level, substructure and superstructure contribute the most, followed by finishing, joineries, and site work, as shown in Figure 8. Even though the embodied carbon value of the finishing materials is higher in most cases, due to the quantity of usage being less than that of RCC, the overall contribution is significantly less. So, optimization in the quantity of materials used in the structural part helps significantly reduce the carbon emissions at the building level.

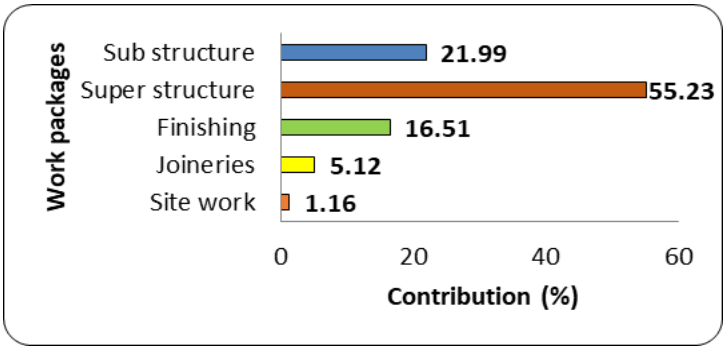


Figure 8: Work packages contributions to the overall carbon emissions (Mean value)

The top materials contributing 95% of the embodied carbon are concrete, reinforcement steel, cement, GI door, Tile, and paint. The quantity of materials and the embodied carbon values also play an important role. Even though the concrete embodied carbon value is less than the reinforcement steel's, 50% of the embodied carbon emission comes from concrete due to the large quantities. Figure 9 shows that the embodied carbon of concrete varies from 156.85 $kgCO_2eq/m^2$ to 246.68 $kgCO_2eq/m^2$ at the building level. The embodied carbon of reinforcement steel varies from 141.3 $kgCO_2eq/m^2$ to 206.81 $kgCO_2eq/m^2$ in the overall building. When the quantity is higher, variability plays a crucial role in the LCA calculation of the embodied carbon. Setting up a baseline for embodied carbon calculation is very important. The highest and lowest values are 89.63 $kgCO_2eq/m^2$ for concrete and 65.51 $kgCO_2eq/m^2$ for reinforcement steel. So, the variation in the dataset needs to be addressed by collecting more samples from the manufacturers in Indian conditions and setting a baseline for the embodied carbon factors, especially cement and steel, where the consumption is highest for the construction works in India. Since concrete and steel are the highest contributors of shear wall-based high-rise residential buildings, wastes like GGBS and fly ash can be used partially instead of cement, which has the highest embodied carbon in the concrete component. For the same grade of concrete, 42% of embodied carbon emission can be reduced using geopolymer concrete (Kiruthika et al., 2024), where the main components are GGBS and Fly ash. For the reinforcement, we can use the recycled steel, where embodied carbon is 0.42 $kgCO_2eq/kg$ (ICE data), compared to 2.68 $kgCO_2eq/kg$, resulting in up to 80% carbon reduction.

Table 3 shows a comparative analysis of embodied carbon values across the global case studies. This reveals the significant regional variation based on construction practices, building typologies, and life cycle scope definitions. The embodied carbon of the high-rise residential building assessed in this study ranged from 373 to 530 $kgCO_2eq/m^2$ (A1–A3), depending on the emission factor dataset. This variation aligns well with the international benchmarks reported for similar building types. For instance, embodied carbon values for high-rise buildings in Chicago (338.22 $kgCO_2eq/m^2$, A1–A3) and Hong Kong (465 $kgCO_2eq/m^2$, A1–A3) fall within or near this range (Ma et al., 2024; Zhang et

al., 2024). The lower bound of the present study is also close to the German DGNB benchmark (365 $kgCO_2eq/m^2$, A1–A3), whereas the upper bound slightly exceeds it. In contrast, the IGBC Net Zero Carbon rating suggests a much higher indicative value of 700 $kgCO_2eq/m^2$ (A1–A4) for Indian contexts.

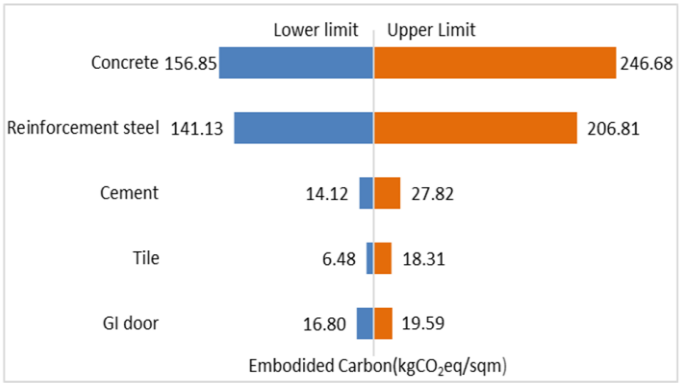


Figure 9: Variation in embodied carbon ($kgCO_2eq/m^2$)

Table 3: Comparison of embodied carbon

Country	Building type	Life-cycle stages	Embodied carbon ($kgCO_2eq/m^2$)	Reference
China	Residential	A1-A3	210.4–769.4	Zhang et al., 2023
Chicago	High-rise Office & Retail	A1-A3	338.22	Ma et al., 2024
Hong Kong	High rise Office & Retail	A1-A5	524.63	Yan et al., 2010
UK	2-storey residential	A1-A5	521.78	Keyhani et al., 2024
Hong Kong	High-rise Residential	A1-A3	465	Zhang et al., 2024
India	-	A1-A4	700	IGBC Net Zero carbon rating
Germany	-	A1-A3	365	DGNB
Denmark	More than 1000 m^2 building	A1-A3,B4,B6,C3-C4	600	Denmark county policy, WGBC, 2022

6. CONCLUSION AND FUTURE SCOPE

The variability in the embodied carbon of materials across different databases may be attributed to differences in the mining methods, quality of raw materials, materials processing, production technology, transport methods, electricity mix, packaging, and supply chain processes. Understanding the variability in embodied carbon of building materials from different sources plays a vital role in assessing the embodied carbon of high-rise residential buildings. This paper presents a case study on variation in embodied carbon of high-rise residential buildings in India. The high-rise residential building is based on RC monolithic concrete construction. The significant findings are listed below:

- The total embodied carbon (A1-A3) of the building (Built up area: 82,902 m2) varies from 373 $kgCO_2eq/m^2$ (IFC Indian dataset) to 530 $kgCO_2eq/m^2$ (EPiC) based on four embodied carbon datasets. The mean value of embodied carbon of the high-rise residential building is 454 $kgCO_2eq/m^2$. The standard deviation associated with the building embodied carbon is 65.3 $kgCO_2eq/m^2$. Considering India's urban development and high-rise residential building construction, the variability would be significant at the aggregate level.
- Concrete and steel emerge as the most significant contributors to embodied carbon, accounting for approximately 80% of total embodied carbon. Specifically, concrete contributes to about 45%, while reinforcement steel accounts for 36%. The total embodied carbon of concrete ranges from 157 $kgCO_2eq/m^2$ (based on the Indian dataset) to a maximum of 247 $kgCO_2eq/m^2$ (as per the EPiC dataset), with a mean value of 277$kgCO_2eq/m^2$. For reinforcement steel alone, the embodied carbon varies from 141 $kgCO_2eq/m^2$ (Indian dataset), 207 $kgCO_2eq/m^2$ (In-house tool), with a mean of 164$kgCO_2eq/m^2$.
- Even though the embodied carbon intensity of finishing materials is higher, their contribution is not prominent due to the lower usage in the building. We can observe that the substructure and superstructure represent 80% of the total embodied carbon. In particular, replacing cement with waste fine materials with the lowest embodied carbon is much appreciated in reducing carbon emissions.
- The variability in embodied carbon has critical implications for designers and builders, directly affecting material selection, design optimization, and compliance with carbon benchmarks. This study helps to set a benchmark for carbon emissions in the Indian context and the importance of having a standard dataset.

Suggestions for future research work are:

- Multiple case studies of high-rise residential buildings are needed to validate the findings that help set benchmarks in India.
- The scope can be extended to on-site construction (A4-A5) and the recurring embodied carbon due to periodical maintenance and repair work.
- Data collection to determine the embodied carbon of MEP components.

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ENHANCING LABOUR PRODUCTIVITY IN THE SRI LANKAN CONSTRUCTION INDUSTRY THROUGH COMPUTER VISION

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ABSTRACT

Labour productivity is a crucial factor in the success of construction projects. However, Sri Lankan construction industry has been struggling to enhance labour productivity due to inadequate labour management, poor monitoring systems and safety-related problems. These various challenges have led to problems such as project delays and cost overruns, and poor site performance. Computer vision (CV) has been found to overcome these issues and enhance labour management in the construction industry. Additionally, CV can monitor the activities of labours, track activities, control behaviour, detect the location and identify objects continuously, which ultimately enhances the labour productivity. By automating data collection through cameras and AI models, site managers gain accurate insights into performance without disrupting workflows. It ensures transparency, accountability, and quick response to inefficiencies. This research study focuses on deploying CV to improve labour productivity in the Sri Lankan construction industry. This study was based on information gathered from 16 expert interviews involving construction professionals and IT specialists. The findings highlight CV applications in labour management and further present substantial possibilities to transform the construction industry through CV. Moreover, the study highlights real-time monitoring together with task optimization, safety improvement and workforce efficiency enhancement. Finally, this research provides CV applications and key stages as follows with a view to indicating appropriate decisions to make. Application of CV can assist in avoiding problems and identifying the best practices in the application of CV technologies in the Sri Lankan construction industry.

Keywords: *Computer Vision (CV); Labour Productivity; Smart Construction; Sri Lanka, Sustainability.*

1. INTRODUCTION

Construction industry is one of the largest industries which deals with gross domestic product (GDP) in both developing and developed countries (Yu et al., 2022). It plays a critical role in the economic landscape of nations, serving as a key driver of growth and development (Norouzi et al., 2021). According to Lawal and Rafsanjani (2021), the construction sector consists of residential buildings along with commercial structures and infrastructure projects including roads, bridges, and airports. Zhang et al. (2021) added that the construction industry is a highly labour-intensive sector with numerous

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construction activities. Despite its crucial role, the construction industry faces persistent challenges in terms of labour productivity, which hinder its efficiency and growth (Abdel-Hamid & Abdelhalim, 2020).

Labour productivity plays a critical role in ensuring the timely and cost-effective completion of construction projects (Gondia et al., 2019). However, traditional labour management practices such as manual monitoring and paper-based reporting have proven to be insufficient. Because these methods fail to provide the real-time performance data needed for effective decision-making (Abdelalim & Said, 2021). This has contributed to recurring project delays, cost overruns, and inefficient resource allocation within the sector (Almamlook et al., 2020; Tokarsky et al., 2020). In the Sri Lankan construction industry, ineffective monitoring and lack of real-time tracking systems have been identified as significant barriers to improving productivity (Manoharan et al., 2023a). In addition, the lack of automated safety monitoring systems further exacerbates operational inefficiencies and increases the risk of on-site accidents (Manoharan et al., 2023b).

In order to address these challenges, the modern construction industry applies automated data collection (ADC) techniques that enhance the real-time measurement of labour productivity (Fang et al., 2020). Presently, several intelligent technologies are being applied such as building information modelling (BIM) (Olugboyega et al., 2021), sensor technologies (Rao et al., 2022), CV (Ekanayake et al., 2021), and data analytics tools for construction labour productivity monitoring. Among these technologies, CV is considered the most applicable in the construction industry (Li et al., 2024). Evidently, Rao et al. (2022) stated that CV allows machines to interpret visual data, so that serves as an effective method for real-time monitoring and labour tracking and safety management on construction sites. Moreover, Fang et al. (2020) highlighted that CV systems have revolutionized construction labour management systems by enabling tasks including motion tracking, behaviour analysis, location estimation and object recognition. According to Lim et al. (2022), the integration of sensors and cameras with CV systems has enabled enhanced site monitoring which ensures operational labour optimization and safe compliance standards.

CV has benefited many countries to continuously monitor workforce activities, helping track movement to boost productivity, control behaviour, and recognize objects (Fang et al., 2020). Lim et al. (2022) stated that in South Korea, CV systems have been used to promote construction automation to speed up processes, increase productivity, and reduce safety risks by monitoring personal protective equipment, labour productivity and safety on construction projects. In China CV has assisted in ensuring safety regulations compliance by monitoring the behaviour and site conditions of the workers (Fang et al., 2020). Even though studies have shown its advantages in different global contexts for enhancing construction efficiency and safety (Fang et al., 2020), there has been limited research on the feasibility of applying CV in the Sri Lankan context (Dilaksha et al., 2024; Liyanage et al., 2023; Herath et al., 2022).

Therefore, this research aims to bridge the existing gap by exploring the potential of CV to enhance labour productivity in Sri Lanka's construction industry. It focuses on improving labour supervision, real-time performance tracking, and enforcing safety measures on construction sites. By examining how CV technologies have been used globally, CV can be adapted to the local context. The study seeks to provide valuable

insights into integrating CV for more efficient and safer construction practices in Sri Lanka.

2. LITERATURE REVIEW

2.1 LABOUR PRODUCTIVITY IN CONSTRUCTION INDUSTRY

Labour productivity stands as a critical performance factor for construction projects to reach their successful completion (Kim et al., 2019). However, the construction industry face persistent inefficiencies due to delays, cost overruns, and poor resource management (Mahamid, 2018; Abdel-Hamid & Abdelhalim, 2020). These challenges arise from a heavy reliance on manual labour, limited automation, and insufficient real-time monitoring, as described by Naoum (2016). Moreover, Perera et al. (2023) stated that traditional labour management methods such as manual reporting and human observation fail to deliver precise evaluations of labour performance and site conditions which results in coordination issues and productivity losses. Additionally, inefficient labour management systems further contribute to operational delays, inefficient task distribution, and deviations from project schedules and budgets (Erdogan et al., 2019; Zhang et al., 2021). The current approaches to labour management systems do not solve problems regarding unproductive works, inefficient task distribution and insufficient labour performance feedback (Dev & Mishra, 2020; Guo et al., 2017). Therefore, growing complexity of projects is creating the need for improved labour monitoring solutions, as current methods are becoming less effective (Rao et al., 2022).

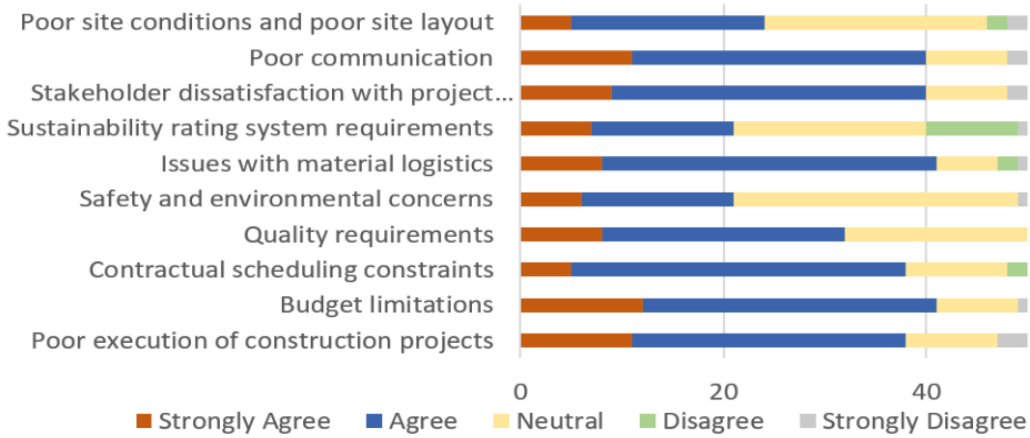


Figure 1: Issues in the current construction industry (Source: Developed by authors)

Figure 1 presents the most critical issues influencing labour productivity in the construction projects. According to figure 1, the scale includes project execution challenges starting from budget restrictions progressing to safety risks with participants mostly disagreeing about proficient management.

2.2 TECHNOLOGICAL INNOVATIONS TO ADDRESS LABOUR PRODUCTIVITY ISSUES IN CONSTRUCTION

The construction industry needs modern technological solutions to resolve its existing productivity problems (Abdelalim & Said, 2021). Several organizations place digital technologies and artificial intelligence (AI) among key elements capable of transforming labour productivity (Gondia et al., 2019). In recent years, there has been a growing

emphasis on adopting technologies such as BIM, use of drones, internet of things (IoT), and robotic systems to streamline construction processes and enhance efficiency (Rao et al., 2022). Furthermore, Heidari et al. (2023) mentioned that several intelligent technologies such as BIM (Olugboyega et al., 2021), AI, sensors (Rao et al., 2022), CV (Ekanayake et al., 2021) and data analytics tools have been applied for construction labour productivity monitoring (Elghaish et al., 2020). These technologies automate manual execution of tasks to create improved resource utilization and better project oversight which results in safer workplace conditions (Rao et al., 2022). This shift has brought the industry toward automated approaches which leads to improved project control and management (Wang et al., 2020). Through automating processes and improving resource utilization, these technologies have the potential to significantly enhance labour productivity, project management, and overall efficiency (Rao et al., 2022; Chen et al., 2022), subsequently, transforming the construction sector into a more streamlined and safer industry.

2.3 COMPUTER VISION EVOLUTION AND BENEFITS IN CONSTRUCTION

CV stands out as one of the most effective tools among various technological solutions to address labour productivity challenges in the construction sector (Li et al., 2024). According to Liu et al. (2021), CV helps machines interpret visual elements and perform processing operations that perform better than other technologies. Although BIM and IoT are mainly focused on the maintenance of structural elements and resource management systems, CV provides dynamic, real-time, on-site monitoring of employee performance and behaviour (Li et al., 2024). The combination of cameras, sensors, and image processing algorithms enables CV to monitor labour activities and performance with safe compliance without constant human supervision (Paneru & Jeelani, 2021). Key applications of CV include tracking worker activities, verifying compliance with safety protocols such as the use of personal protective equipment (PPE), and detecting unsafe or non-standard practices (Fang et al., 2020; Li et al., 2024). Furthermore, CV facilitates location tracking to enhance safety in hazardous areas and optimize the distribution of labour across the site (Son et al., 2019). As a result, these functionalities contribute to improved safety, reduced human error, and more efficient site monitoring, thereby enhancing overall labour productivity in construction environments (Fang et al., 2020; Li et al., 2024).

Table 1 presents the widely used applications of CV in labour management within the construction industry, many of which are currently being implemented in various countries around the world.

Table 1: Main applications of CV in labour management

Application	Description	References
Safety Assurance	Automatic detection of PPE compliance and safety hazard areas	Fang et al. (2020); Lim et al. (2022)
Labour Behaviour Recognition	Identify and monitor labour activities.	Li et al. (2024); Paneru & Jeelani (2021)
Location and Tracking	Labour location tracking in real-time in the site, where proactive safety measures and efficient site navigation can be done.	Fang et al. (2020); Li et al. (2024)

Application	Description	References
Labour Activity Recognition	Tracks specific labour activities for safety and operational standards.	Fang et al. (2020); Liu et al. (2021)
Blindspot Monitoring	Monitor and determine the dynamic range of equipment blind spots to prevent accidents caused by limited visibility.	Guo et al. (2017); Akinsemoyin et al. (2023)

CV delivers substantial promise for improving labour productivity levels throughout Sri Lanka. CV implementation at Sri Lankan construction sites will lead to improved tracking of real-time labour activities and enhanced performance analytics (Dilaksha et al., 2024; Liyanage et al., 2023). Moreover, Madugu (2023) stated that project managers can detect underperforming team members and inefficient processes using this system thus enabling them to take prompt corrective actions which stop project delays and prolongation costs. Implementation of CV systems enables both safety standard compliance tracking and lower work-related accident rates which lead to increased employee satisfaction (Ji et al., 2023; Liu et al., 2021). The construction industry of Sri Lanka benefits from CV as it represents a cost-effective approach to increase productivity while protecting workers from harm and optimizing project delivery.

3. METHODOLOGY

The study adhered a qualitative research approach. It is a process that focuses on interpreting the deeper meanings of textual data collected from interviews, focus groups, and open-ended surveys (Rampin & Rampin, 2021). Researchers use this method to investigate experiences as well as behaviours and social processes (Bingham, 2023). A purposive expert sampling method was used to select participants with both construction and IT expertise to ensure the relevance and depth of data. Semi-structured interviews served as the data collection method to allow open discussions while ensuring participant consistency. For analysis, content analysis was conducted using NVivo 12 software, allowing to identify key themes and insights that aligned with the objectives of the study. Interview transcripts were systematically coded and grouped into relevant categories, allowing for the recognition of expert opinions and practical considerations related to the integration of computer vision in construction practices.

Research data was obtained from in-depth interviews with industry professionals who held positions as project managers, and quantity surveyors, as well as IT specialists with expertise in CV. The research design included semi-structured interviews that provided both in-depth conversational opportunities as well as standardized interview protocols. Through this methodology, the research gathered extensive insights in a standardized format. Interview sessions lasting 30 to 45 minutes were conducted physical meetings and online meetings via Zoom and Microsoft Teams, depending on the availability of participants. Sixteen interviews were conducted, leading to data saturation was achieved at 13 interviews and it confirmed from 3 more interviews. The data collected was categorized into specific sections to represent all aspects of CV integration in the practices of the construction sector in Sri Lanka.

Although the selected respondents did not have direct experience in applying CV in construction projects. But they have significant knowledge of both the construction industry and related CV applications. Their insights were considered valuable due to their expertise, as they were able to provide informed perspectives on the potential CV

applications for labour productivity. Accordingly, their contributions were used to explore the practical implications, feasibility and future integration of CV in the Sri Lankan construction context. Table 2 presents the summary of each expert with relevant experience in the construction industry and IT field.

Table 2: Profile of the experts

Respondent	Discipline	Designation	Experience (in Years)
R1	Civil Engineer	Project Manager	31
R2	Quantity Surveyor	Academic cum Quantity Surveyor	14
R3	Quantity Surveyor	Chartered Quantity Surveyor	09
R4	Quantity Surveyor	Academic cum Quantity Surveyor	10
R5	Quantity Surveyor	Academic cum Quantity Surveyor	08
R6	Quantity Surveyor	Academic cum Quantity Surveyor	12
R7	Quantity Surveyor	Quantity Surveyor	09
R8	Quantity Surveyor	Chartered Quantity Surveyor	28
R9	Quantity Surveyor	5D BIM Quantity Surveyor	08
R10	Quantity Surveyor	Senior Quantity Surveyor	15
R11	Quantity Surveyor	Chartered Quantity Surveyor	28
R12	Quantity Surveyor	Academic cum Quantity Surveyor	08
R13	Quantity Surveyor	Senior Quantity Surveyor	10
R14	Software Engineer	Senior Software Engineer	12
R15	Software Engineer	Senior Software Engineer	09
R16	Software Engineer	Senior Software Engineer	08

4. FINDINGS AND ANALYSIS

4.1 THE ROLE AND IMPACT OF COMPUTER VISION IN LABOUR MANAGEMENT

The practical application of CV in Sri Lanka's construction industry remains limited, but experts are highly optimistic about its potential to improve labour productivity and safety. R4 emphasized that "*CV has enormous potential, especially in areas such as safety, quality control and labour management*," while R6 noted that it improves efficiency and reduces accidents. Respondents highlighted CV's capabilities in real-time labour monitoring, PPE compliance, and hazard detection near heavy machinery. R14 added that CV can automate workforce tracking and reduce manual errors, while R15 emphasized its role in real-time project analysis for improved productivity. Despite these benefits, R4, R9, and R12 observed that the industry still depends heavily on manual processes due to slow technology adoption and low awareness. As R13 concluded, CV presents a powerful opportunity for real-time workforce monitoring, with the potential to transform labour management practices across the Sri Lankan construction sector.

4.2 APPLICATIONS OF COMPUTER VISION IN CONSTRUCTION

The wide range of possible applications of CV on Sri Lankan construction sites offers both enhanced safety performance and higher productivity levels. Most respondents highlighted that few applications such as real-time monitoring, automated attendance tracking, safety compliance monitoring, work progress tracking, strategic workforce planning and resource optimization. Moreover, they stated that real-time worker identification through this technology removes the need for manual attendance sheets while simultaneously decreasing time fraud incidents on the site.

Figure 2 illustrates the various benefits and applications of CV in the construction industry, highlighting its role in improving labour productivity.

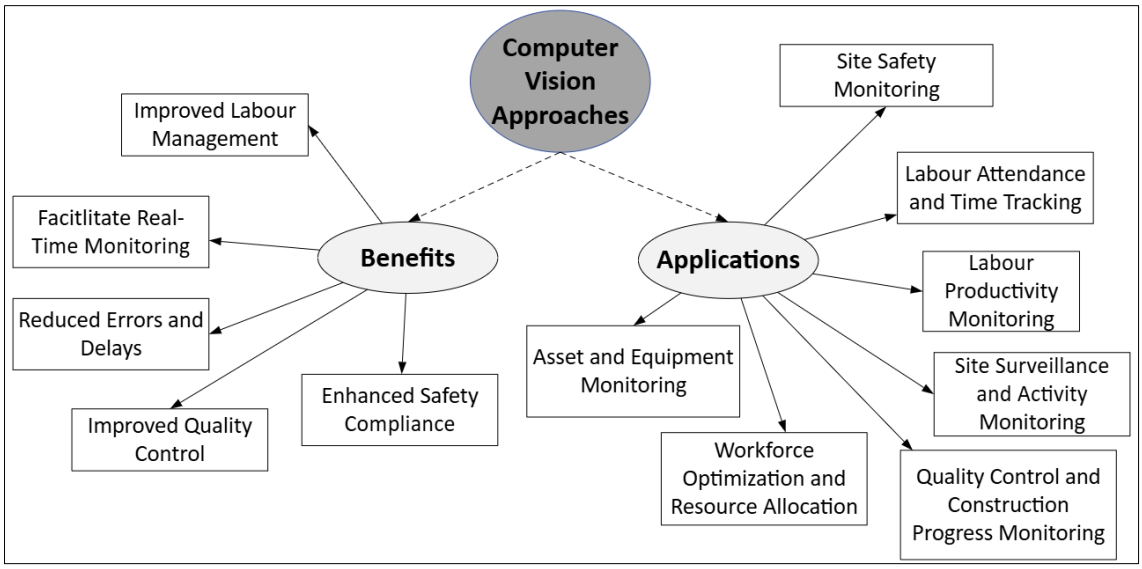


Figure 2: CV benefits and applications (Source: Developed by authors)

4.2.1 Automated Attendance Tracking

R1 along with other experts suggested that automated attendance tracking systems using facial recognition can simplify employee check-in procedures by eliminating human errors from manual attendance systems. This system would reduce tracking time and enhance staff recording precision in a field where errors frequently occur. Similarly, R12 and R15 explained that automated attendance tracking through facial recognition technology speeds up attendance procedures with more accuracy. Moreover, R3 explained that facial recognition systems used for employee attendance tracking provide detailed attendance documentation that minimizes both false reports and unauthorized personnel.

4.2.2 Real-Time Activity Monitoring & Productivity Tracking

Beyond attendance tracking, real-time monitoring of labour activities is another crucial application. According to R6 "real-time employee location tracking allows better workforce management through the identification of unnecessary site movements to prevent downtime occurrences". R2 and R10 stated that this monitoring system provides immediate productivity benefits to managers because they can swiftly detect operational inefficiencies and resolve them. Moreover, AI systems enable the distribution of tasks into smaller divisions according to employee daily work activities according to R5.

Supervisors gain enhanced performance metric tracking abilities through this approach to optimize resource distribution.

4.2.3 Safety Compliance and Hazard Detection

Most respondents highlighted that CV assists with safety monitoring tasks by detecting unsafe worker behaviours and hazardous materials and improper equipment handling to minimize accidents. Moreover, R3 and R12 explained that CV serves as a monitoring system to check if workers wear appropriate PPE because it helps maintain safety standards and protect workers from site accidents. Similarly, R4 pointed out "*CV can monitor worker safety by detecting whether they are wearing the proper PPE and alerting supervisors to any non-compliance*". Additionally, the various capabilities of CV position it as an excellent option for both safety improvement on construction sites and worker adherence to essential safety requirements.

4.2.4 Work Progress Analysis and Task Completion Tracking

CV functions as a tool to track work progress as well as to analyse task completion. R1, R5, R11 and R12 respondents explained how AI systems use project timelines to analyse site images for work progress evaluation. Furthermore, these respondents noted that this information gained enables accurate reporting and prevents delays because it detects slow progress at an early stage. R6 indicated "*automated workflow optimization through AI-based systems delivers predictive information to optimize staffing assignments and reduce operations expenses*". As mentioned by R14, verification of project progress is effectively emerging through time-lapse imagery combined with object recognition and BIM model integration.

4.2.5 Strategic Workforce Planning and Resource Optimization

The respondents R2 and R13 explained that CV helps organizations with strategic workforce planning as well as resource optimization. Similarly, R8 stated that the analysis of worker movement patterns through CV systems produces predictive information which helps organizations properly distribute their workforce into low-productivity areas that risk delays. Moreover, R8 highlighted that this form of data-driven decision-making supports better scheduling, reduces downtime, and enhances overall operational efficiency.

Table 3 summarizes the basic applications of CV in construction labour management. It outlines the primary functionality of each application and explains how it is implemented using CV on construction sites.

Table 3: Functional applications and execution of CV on construction sites

Application	Functionality	CV-based Implementation Approach
Automated Attendance Tracking	Records worker attendance accurately and prevents time fraud	Facial recognition systems at entry points automatically identify and log workers in real time
Real-Time Activity Monitoring	Tracks worker movements, identifies idle time, and classifies daily tasks	AI analyses CCTV/video feeds to detect and categorize worker actions across the site

Application	Functionality	CV-based Implementation Approach
Safety Compliance Monitoring	Ensures workers wear PPE and follow safety guidelines	Object detection identifies missing helmets or vests, behaviour recognition flags unsafe practices
Work Progress and Task Completion Tracking	Monitors task progress and verify if scheduled work is completed	Time-lapse videos and object recognition compare actual site visuals with planned models or drawings
Workforce Optimization and Planning	Enhances labour allocation and reduces inefficiencies	AI-based movement analysis highlights resource gaps; predictive models suggest adjustments

4.3 KEY STAGES IN IMPLEMENTING A COMPUTER VISION SYSTEM FOR LABOUR MANAGEMENT

All respondents highlighted that the implementation of a CV system comprises several critical stages designed to improve labour productivity. As suggested by many experts, the first phase is data collection, where tools such as CCTV cameras, drones, and IoT sensors capture images or videos of workers and on-site activities. After data is collected, it goes through pre-processing, where irrelevant information such as blurry images is removed and quality is improved for better accuracy. R4, R7, and R11 described this as "data pre-processing," which ensures that the data is ready for analysis. After pre-processing, the system enters the model training phase, where it learns to recognize patterns such as PPE compliance and inactive workers, as noted by R5.

Once trained, the system is optimized to operate effectively in real time, and R7 emphasizes that this includes system adjustments and the use of high-performance hardware to "optimize performance". R12 further added that "real-time alerts and reports" support rapid management responses. The final stage is deployment, which involves integrating the CV system into daily operations for continuous monitoring and updates. As R4 explained, this includes tracking task progress and PPE compliance, and R16 noted that it is essential to link CV outputs with existing project management tools to make informed decisions.

Figure 3 illustrates the workflow of applying CV for labour productivity analysis in construction industry. It begins with data preparation, where raw images and videos are cleaned, labelled, and normalized. The processed data is then used in the training phase, where learning algorithms such as machine learning, deep learning, and image processing are applied and optimized. Finally, in the inference stage, the trained model is deployed to analyse new images and draw meaningful insights related to site activities and labour productivity.

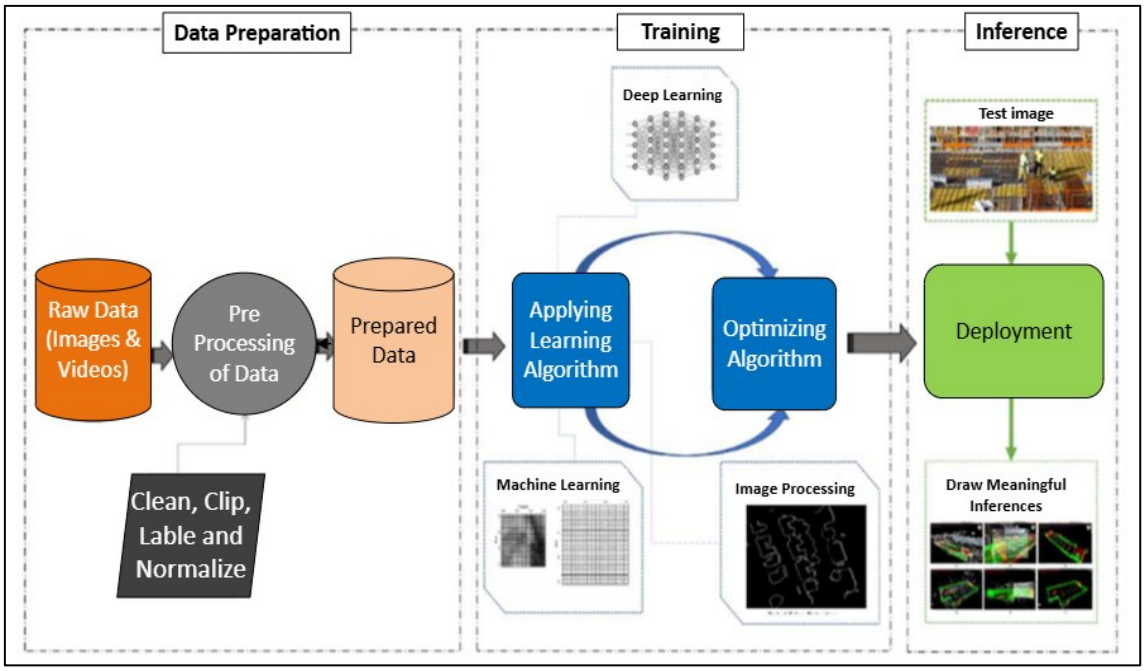


Figure 3: CV process (Source: Developed by authors)

4.4 INTEGRATION OF CV-BASED LABOUR MONITORING SYSTEMS INTO CONSTRUCTION OPERATIONS

The integration of CV into real-time labour monitoring systems presents a significant advancement in construction workforce management. As highlighted by R1, "*CV-based real-time tracking systems serve to both verify compliance with safety requirements and work completion progress*," thereby enabling remote supervision and reducing the reliance on constant physical oversight. R5 further noted that CV can identify idle workers, detect inefficiencies, and provide feedback for process optimization, contributing to enhanced productivity and more efficient use of labour resources. In terms of safety, R7 stated "*CV systems can detect workers without PPE and instantly alert site supervisors for corrective actions, ensuring immediate compliance with safety standards*". Similarly, R13 emphasized that "*CV-based systems notify managers of inefficiencies or safety risks in real time, helping prevent accidents before they occur*". Moreover, CV technologies offer predictive capabilities through real-time dashboards that monitor labour productivity and attendance. R9 stated that integration with enterprise resource planning (ERP) systems allows for optimized workforce scheduling and resource allocation. Additionally, R5 and R15 noted that such integration enables managers to anticipate workforce limitations and make timely adjustments, ultimately improving project efficiency and delivery outcomes.

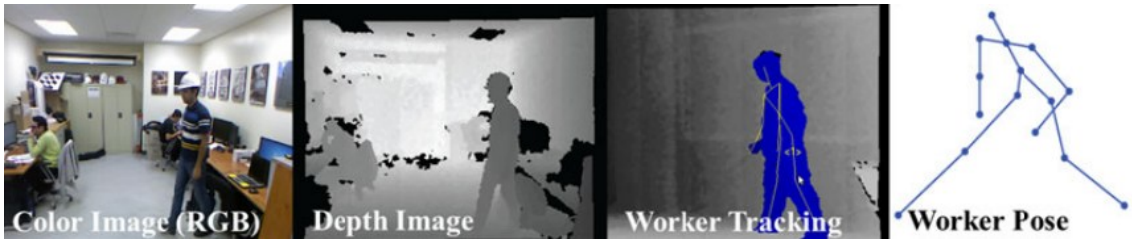


Figure 4: Recognize the worker pose
Source: Developed by authors

Figure 4 illustrates the process of tracking workers using CV on construction sites. The system starts with an RGB image before applying depth data to determine worker positioning. Next, the software tracks the highlighted worker through its monitoring system. The system generates an outline of the worker's movements to evaluate their physical location for both safety and productivity assessment. This data is analysed to assess whether workers are actively engaged in tasks or idle. By identifying inactive periods or inefficiencies, the system provides valuable insights that can be used to enhance labour allocation, reduce idle time, and ultimately improve overall productivity on construction sites.

5. CONCLUSION

The research examined the role of CV in improving construction labour productivity across Sri Lanka by addressing workforce management issues. Sri Lankan construction sites rely heavily on supervisors for labour management, but this system creates multiple inefficiencies and tracking errors in workforce monitoring. Furthermore, Existing systems lack real-time data with detailed insights that hinder timely decision-making processes, leading to project delays or increased costs. Therefore, some companies implement the modern technologies to address labour productivity issues. Among these technologies, CV is the most suitable technology.

CV provides an innovation through automated labour monitoring technology that improves real-time productivity tracking and safety compliance systems. Implementing key systems that identify and track labour activities, track attendance, monitor progress, and identify risks delivers significant operational benefits and increased site accountability. Furthermore, this technology generates useful data that enables better workforce performance evaluation and improved workforce management programs. In this context, the successful implementation of CV requires close collaboration between technology providers and construction companies and employees to achieve smooth integration and maximize its potential.

Finally, this study confirms that integrating CV can significantly improve labour productivity by reducing downtime, optimizing task allocation, and minimizing human errors in reporting. In addition, it improves safety by identifying unsafe practices in real-time, thereby preventing potential accidents and ensuring compliance with safety regulations. Future development efforts in this area should be continued, and these technologies should be refined for widespread construction use, making them accessible, affordable, and scalable to the Sri Lankan construction industry. Furthermore, it is recommended that future research continues to examine the limitations to CV adoption in Sri Lankan construction industry, explore practical strategies for CV implementation and develop customized CV technologies tailored to the specific needs of small and medium-sized contractors.

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ENHANCING SUSTAINABILITY IN RENOVATION PROJECTS: THE ROLES OF THE CONTRACTOR AND CONSULTANT

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ABSTRACT

The construction industry significantly impacts the global economy, with renovation projects offering key opportunities for sustainable practices due to their flexibility and resource efficiency. However, in Sri Lanka, stakeholder collaboration particularly between contractors and consultants remains weak, hindering effective sustainability integration. This study investigates how contractors and consultants contribute to adopting sustainable practices in renovation projects. A qualitative research approach was adopted, combining a comprehensive literature review and semi-structured interviews with twelve construction industry professionals. The interview responses were analysed using manual content analysis methods to identify the roles of contractor and consultant, challenges, and to develop suitable recommendations for improving the integration of sustainable practices in renovation projects. The research findings revealed that consultants primarily contribute to sustainability assessments, material selection, and client advising, while contractors focus on implementing sustainable practices on-site, such as waste minimisation and efficient resource management. Although, the findings identified the key challenges including lack of understanding among clients, high initial costs, and limited availability of resources, which significantly affect the practical integration of sustainability in Sri Lankan renovation projects. The study contributes to the integration of sustainable renovation by providing recommendations including improved stakeholder communication, the adoption of sustainable materials, design Integration and climate adaptation. Moreover, it mainly highlights the importance of government support, policy changes and proper training to improve the sustainable integration. These findings provide a strong foundation for improving policy frameworks and professional practices in renovation projects across Sri Lanka.

Keywords: *Buildings; Consultant; Contractor; Renovation Projects; Sustainability.*

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1. INTRODUCTION

Sustainable development is an approach that meets current needs without compromising the ability of future generations to meet their own needs (Purvis et al., 2019). The goal of sustainable development is to establish a balance between social, economic, and environmental sustainability (Mensah, 2019). The demand for renovation projects is growing as buildings in many developed nations age and people pay increasing attention to sustainability (Vilches et al., 2017). The term "sustainable renovation" defines a comprehensive approach for improving existing structures that minimises energy and resource consumption, improves safety and resilience against natural disasters, and reduces environmental impacts throughout every stage of the building's life cycle (Passoni et al., 2024). Sustainable building renovation has gained increasing importance in recent years due to excessive energy consumption in existing buildings (Jowkar et al., 2022). According to Jafari and Valentin (2017), sustainable renovations provide significant long-term cost benefits by reducing operating expenses and increasing property values, although they need higher initial costs. On the social level, improved indoor air quality enhances health, comfort, and productivity (Wei et al., 2015).

Developing guidelines for sustainable renovation projects will be critical to addressing the environmental challenges facing the built environment while meeting the increasing need for higher building performance and occupant satisfaction (Nielsen et al., 2016). In addition, sustainable renovations improve resource efficiency and contribute to the development of a circular economy in the construction sector (Sáez-de-Guinoa et al., 2022). The construction industry plays a key role in achieving sustainability objectives by integrating sustainable concepts into renovation methods, thereby increasing the durability, efficiency, and safety of built environments (Sev, 2009). Stakeholder engagement is essential for renovation project success, as it aligns project goals with stakeholder demands, promotes innovative approaches, and minimizes disputes (Aapaoja et al., 2013).

In Sri Lanka, there is a noticeable lack of developed guidelines or policies for sustainable renovation practices, and poor involvement of stakeholders has a negative impact on adoption and implementation. A comprehensive, stakeholder-inclusive guideline is essential for reducing pollution, increasing efficient resource use, and achieving global sustainability objectives, which requires a more stakeholder-focused approach. Therefore, this research aims at investigating how contractors and consultants contribute to adopting sustainable practices in renovation projects. The research explores three main dimensions of sustainability: environmental, economic, and social. These dimensions are examined through practices such as increasing energy efficiency and minimising construction waste, improving cost-effectiveness and assessing lifecycle performance, and enhancing occupant well-being through effective stakeholder collaboration.

This paper begins with an introduction to the topic and provides a comprehensive literature review on stakeholder engagement and challenges in renovation projects. Subsequently, the research methodology, comprising data collection and data analysis, is elaborated. The conclusion summarizes the study and presents recommendations.

2. LITERATURE REVIEW

2.1 SUSTAINABILITY CONCEPT

Sustainability is designed to achieve an equilibrium of both the global environment and human civilisation (Yang & Zeng, 2020). Moreover, the sustainability concept is currently extended to include wider social and economic aspects, highlighting the need to balance resource utilisation with economic growth and social equality (Purvis et al., 2019). Sustainability practices in different industry sectors are evolving and needing a common concept for achieving sustainable development across all sectors (John & Narayanamurthy, 2015). The need for sustainability is an essential aspect of the construction industry, which is one of the primary consumers of natural resources and a major contributor to environmental degradation (Akhanova et al., 2019).

2.2 SUSTAINABILITY PRACTICES IN RENOVATION PROJECTS

Sustainable practices for renovation projects are becoming more essential while considering that buildings contribute a significant portion of Global Greenhouse Gas (GHG) emissions (Sabet & Easterbrook, 2016). Renovating existing structures, instead of deciding on demolition and new construction, is an effective way to reduce carbon emissions (Zimmermann et al., 2023). Sustainability is essential in renovation projects as it involves an integrated strategy that examines economic, social, and environmental aspects (Simpson & Owen, 2020). Sustainable renovations can considerably reduce operational costs and increase property values (Hardie et al., 2011). Moreover, the adoption of green technology and materials can improve the marketability of properties, consequently determining higher rental and sales prices (Liao et al., 2023). Social sustainability in renovation projects prioritises community engagement and occupant participation, ensuring effective stakeholder awareness for successful renovation outcomes (Simpson & Owen, 2020). Renovating existing structures for environmental sustainability can be more sustainable than new construction, related to the embodied energy utilised in the original materials (Psilovikos, 2023).

Researchers identified numerous sustainable practices in renovation projects, including sustainable material utilisation, waste management, biophilic design, value management, and Building Information Modelling (BIM). Sustainable material utilisation considers the building's overall lifetime impacts, while waste management reduces environmental impact (Liu, Bengtsson, et al., 2020). Biophilic design focuses on natural elements, while value management improves resource efficiency and cost-effectiveness (Ekanayake et al., 2018; Sharifi & Sabernejad, 2016). A BIM system is important for stakeholders to integrate sustainable design principles using the detailed simulations of the project (Lu et al., 2017).

In Sri Lanka, previous research has mainly focused on the sustainable practices for new construction projects and a few for renovation projects (Ekanayake et al., 2018). However, a limited number of researchers have focused on the roles of consultants and contractors in sustainable renovation projects. It shows a clear gap in understanding of how stakeholders support sustainability when working within the technological, legal, and physical limitations of existing buildings.

2.3 CHALLENGES IN RENOVATION PROJECTS

Renovation projects possess environmental, economic, technical, and social challenges, with constructing and demolition waste causing a massive load on the environment, with 60-85% ending up in landfills (Al-Raqeb et al., 2023). Urban degradation due to pollution, loss of biodiversity, and reduction of green spaces are also major challenges in urban renovation initiatives (Shahraki, 2022).

Challenges in the renovation projects can be divided into four main categories: economic, environmental, technical, and social challenges (Al-Raqeb et al., 2023). Economic challenges include high initial investments (Haase et al., 2020; Liao et al., 2023), cost overruns (D'Oca et al., 2018; Liao et al., 2023), low awareness of energy efficiency benefits, and lack of integrated solutions for energy saving (Haase et al., 2020). Environmental challenges involve high greenhouse gas emissions (Ntouros et al., 2022), demolished waste issues (Al-Raqeb et al., 2023), and poor thermal performance (Yang et al., 2021). Although, technical challenges include lack of standardisation process (Ntouros et al., 2022; Pikas et al., 2021), insufficient data (Konstantinou et al., 2021; Prieto et al., 2024)and limited space around buildings (Pikas et al., 2021). Moreover, social challenges consist of regulatory challenges (Ntouros et al., 2022; Prieto et al., 2024), safety risks (Haase et al., 2020), and occupant disruption (D'Oca et al., 2018; Liao et al., 2023)

2.4 ROLES OF KEY STAKEHOLDERS IN IMPLEMENTATION OF SUSTAINABLE PRACTICES

Stakeholders in renovation projects include owners, contractors, consultants, and governmental and non-governmental organisations, requiring careful consideration of various views and interests (Liao et al., 2023). Each of the parties performs a unique function in establishing the renovation process, making decisions, and verifying that sustainability goals are achieved (Ilkhanizadeh, 2021). Sustainable renovation projects engage stakeholders who ensure effective implementation of sustainable practices, ensuring environmental, economic, and social goals are satisfied throughout the project lifetime, from initial planning to post-completion evaluation (Prieto et al., 2024).

Table 1 illustrates stakeholder engagement over five phases of a renovation project. The phases are Phase 1 (Pre-project)- focusing on initial feasibility and planning; Phase 2 (Concept design)- developing preliminary designs; Phase 3 (Final design)- preparing detailed technical plans; Phase 4 (Execution and handover)- involving construction and delivery; and Phase 5 (Post-construction)- focusing on maintenance and operations. The colour intensity illustrates the various levels of participation of stakeholders in each phase. Where darker colours indicate stronger involvement, and lighter colours represent lower involvement. The following subsections discuss the key stakeholders: consultants and contractors' involvement in renovation projects.

2.4.1 Contractors

Contractors play a major role in the process of renovation, executing projects with an understanding of sustainable construction methods and materials to ensure energy-efficient solutions (Hofmann et al., 2014). However, various smaller contractors can lack the expertise and tools needed to implement sustainable practices effectively (Jung et al., 2014). Therefore, training and developing capacity operations are essential to provide small companies with the skills required for sustainable renovation (Zagonari, 2024).

Moreover, contractors' engagement in sustainable renovation is usually focused on the construction phase, allowing for a small percentage of the entire project's sustainability implementation, although their significant contributions into design and planning (Holloway & Parrish, 2015). Effective project management is essential for contractors as it ensures well-coordinated phases, sustainable practices, and effective resource management (Yoon & Yu, 2019). Moreover, the considerable waste produced by renovation activities, highlighting the importance of sustainable approaches develop and execute by the contractors such as deconstruction and material reuse, which reduce landfill contributions and promote a circular economy (Lynch, 2022). The following Table 1 presents the different levels of key-stakeholder involvement in renovation projects.

Table 1: Key stakeholders' involvement in renovation projects
Source: (Prieto et al., 2024)

Stakeholder	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Architects					
Engineering Consultants					
Contractors					
System Suppliers					
Energy Solution Providers					
Building Users and Managers					
Building Owners					
Developers / Investors					
Government Bodies					

2.4.2 Consultants

Consultants assist clients in selecting sustainable materials, and advising clients of long-term benefits, including reduced energy consumption, which involves the total energy utilised during the product's entire lifespan (Hu, 2021). Consultants are responsible for examining contractors' work, monitoring the implementation of sustainability standards, and confirming that contractors utilise specified sustainable practices on-site (Ghuzdewan et al., 2023). Moreover, Simpson and Owen (2020) stated that consultants collaborate with local stakeholders, including community members, local governments, and industry professionals, to encourage sustainable renovation by obtaining different perspectives that guide the renovation process. Consultants conduct sustainability assessments during renovations, evaluate energy performance, identify improvement opportunities, and analyse environmental impacts (Hu, 2021).

The stakeholder involvement in the renovation projects are usually varies from traditional new construction projects as contractors in renovation projects are responsible for managing selective demolition, reusing materials, and implementing sustainable practices within site restrictions, while consultants need to evaluate existing conditions, advise on sustainable materials, and coordinate with various stakeholders to ensure legal

compliance. These roles are determined by the limits and challenges of working within existing structures, which makes renovation a unique environment for collaboration among stakeholders (Kaewunruen et al., 2024).

3. METHODOLOGY

The comprehensive literature review was focused on existing sustainable practices in building renovation projects. A qualitative approach was applied to accomplish the study goals effectively. Further, all objectives required in-depth investigation of experts to get broad knowledge. Semi-structured interviews were conducted to gain information from professionals who are actively involved in renovation projects. The interview guideline was structured into two main sections, including the general information of the interviewee, and then it defines sustainability in renovation projects, analysing contractor and consultant roles, identifying common challenges, and proposing suitable recommendations for improvement of the integration of sustainable practices. The interview participants included 12 professionals including quantity surveyors, engineers, architects and project managers in both the consultant and contractor firms selected through purposive sampling and snowball sampling methods with broad experience in renovation projects and sustainability practices. The qualitative data have been analysed using manual content analysis. The profile of experts is presented in below Table 2.

Table 2: Profile of the respondents

Expert Code	Type of the Organization	Profession	Industry Experience	Work Experience in Renovation Projects	
				No. of Projects	Type of Projects
R1	Contractor	Quantity Surveyor	10 Years	2	Hotels, Commercial
R2	Consultant	Quantity Surveyor	27 Years	5	Commercial
R3	Contractor	Civil Engineer	8 Years	4	Residential
R4	Consultant	Charted Architect	24 Years	22	Apartment, Commercial, Institutional, Banks, Military
R5	Contractor	Quantity Surveyor	5 Years	4	Hotel, commercial
R6	Contractor	Quantity Surveyor	5 Years	13	MEP Projects
R7	Contractor	Civil Engineer	13 Years	11	Infrastructure, Resort
R8	Contractor	Civil Engineer	9 Years	4	Mall, Road
R9	Contractor	Civil Engineer	8 Years	4	Warehouses, Utility Spaces
R10	Consultant	Chartered CE	13 Years	5	Historical, Clinics
R11	Consultant	Chartered Architect	7 Years	12	Residential, Cafes, Clinics, Hotels
R12	Consultant	Chartered Architect	29 Years	52	Apartments, Banks, Factories, Showrooms, Hotels, Temples

4. RESEARCH FINDINGS

4.1 ROLES OF CONSULTANTS AND CONTRACTORS IN RENOVATION PROJECTS

The following subsections present the involvement of consultants and contractors in renovation projects across the main five phases: planning & research, design & concept development, demolition, execution & handover, and post construction.

4.1.1 Phase 1 - Planning and Research

According to the respondent's answers, during the planning and research phase, contractor engineers are assigned to the projects for the purpose of conduct site assessments for resource efficiency and identify reusing opportunities, and **R3** highlighted "*Ensuring stakeholders understand the environmental, financial, and social benefits of adopting sustainable practices is essential in the early stages of the project*." Additionally, material selection is one of the important responsibilities in this stage for maintaining the durability and recyclability of materials for both parties, and R8 emphasised material selection, including locally available and long-term usage options, passive lighting implementation, and water efficiency. Respondents mentioned that the consultant quantity surveyors are mainly responsible to do the site inspections, feasibility studies, and cost analysis works to verify that the sustainable features are always aligned with budgets during this stage. Considering contractor project managers, as expressed by R7 and R9, they must carry feasibility studies and examine the possibilities of sustainable solutions to check that sustainability is integrated from the project's inception stage, and **R7** expressed that "*I make sure that sustainability elements are incorporated from the design phase to minimises future inefficiencies*." R10 expressed the consultant engineers largely contribute to sustainable integration by influencing the project's design and execution strategies by focusing on resource planning, historical data analysis, and operational scheduling throughout the planning stage and **R10** highlighted "*Gathering available data, operation planning, and resource planning are the primary responsibilities*."

4.1.2 Phase 2 - Design and Concept Development

In the design and concept development stage in renovation project, contractor engineers are needs to improve the sustainable material selection process and integrate passive design techniques, as **R8** recognised "*It must improve material choices, integrate passive ventilation strategies, and make sure design efficiency in every aspect*." Consultant architects, as **R12** said, "*Understanding client needs and educating them on sustainable options are essential, where they implement cost-effective sustainable materials and finishes and check that energy-efficient techniques are established*."

4.1.3 Phase 3 - Demolition

During the demolition stage, contractor engineers are focused on minimising pollution and salvaging reusable materials, as stated by R3, the importance of reducing waste and make sure the materials are salvaged for reuse or recycling, while **R10** added that "*Operation planning, logistics, and safety arrangements are essential components of a structured demolition process*." Consultant quantity surveyors, as underlined by **R2**, "*I require planning selective demolition to maximise salvageable materials and overseeing on-site segregation of waste materials for reuse or recycling*." Contractor project

managers, according to R7, focus on considering waste management strategies, such as reusing demolition waste for backfilling. Consultant engineers verify that the safety precautions and suitable procedures are followed, and R10 highlighted operation planning, logistic planning, and safety arrangement planning. Consultant architects focus on minimising waste and salvaging useful materials, as R11 pointed out minimising waste generation by careful deconstruction while R12 highlighted salvaging reusable materials like bricks and timber.

4.1.4 Phase 4 - Execution and Handover

In the execution and handover phase, contractor engineers are responsible for supervising the implementation of sustainable practices for the effective application, and **R3** suggested that "*Ensuring sustainable practices are consistently implemented during construction is essential for creating long-term project sustainability*." Additionally, engineers supervise inspections, resource allocation, and the acquisition of sustainable materials. Contractor quantity surveyors, as mentioned by **R1**, "*I am responsible for supervising labour and subcontractors, monitoring quality, reducing pollutants, ensuring health and safety, and managing the budget*." Contractor project managers are requiring verifying accordance with specifications, including sustainable aspects such as solar panels, and R9 advised that collaboration between consultant, contractor, and client is necessary to facilitate the process. Consultant engineers, as **R10** said "*I perform responsibilities such as obtaining necessary approvals, overseeing handing over document preparation, and final inspections, and carry out progress monitoring, quality control, and inspections*."

4.1.5 Phase 5 - Post-Construction

During the post-construction stage, contractor engineers must analyse the functioning of implemented sustainable features, where R8 focused on long-term maintenance planning, make sure optimal performance, and minimising renovation costs, while **R3** emphasised "*Conducting follow-up evaluations to make sure energy systems and other features are performing as expected is essential*." Contractor quantity surveyors, as commented by **R5**, "*I check sustainability performance, update certifications, and check that everything follows cost-efficient sustainability measures*." Contractor project managers, according to R7, are responsible for analysing final connections of sustainable systems, such as linking solar panels to the power grid, to guarantee long-term operating efficiency. Consultant engineers work on getting completion certifications and retention management, and **R10** stated, "*Attending to defects and ensuring the long-term performance of sustainable features is part of our responsibilities*."

Table 3 highlights the major roles of contractors and consultants in integrating sustainability practices through each phase of renovation projects. The key terms were identified and highlighted separately to clearly present their contributions at each stage of renovation projects.

Table 3: Key roles of consultants and contractors at each phase of renovation projects

Phase	Consultant	Contractor
1	Conduct site inspections, Perform feasibility studies, Cost analysis, Resource planning	Conduct site assessments, Review material options, Evaluate sustainability alternatives
2	Understand client requirements, Educate clients on sustainability, Assess energy efficient techniques, Recommend cost effective solutions	Improve material choices, Implement passive design strategies and design efficiency
3	Plan selective demolition, Ensure safety precautions are in place, Evaluate opportunities for reuse or recycling	Minimize pollution & environmental impact, Salvage reusable materials, Arrange site safety measures, Waste management, Plan site logistics
4	Obtain necessary approvals, Inspection, Quality control, Progress monitoring	Supervise construction activities, Resource allocation, Procure sustainable materials, Monitor quality, Ensure safety compliance and manage budget effectively
5	Conduct Post-occupancy evaluations, Establish long-term maintenance strategies, Maintain sustainability documentation	Develop maintenance plans, Conduct follow-up evaluations

4.2 CHALLENGES IN INTEGRATING SUSTAINABILITY PRACTICES IN RENOVATION PROJECTS

According to the respondents, the cost for implementation of sustainable practices is considered as one of the primary challenges to renovation projects. Nine out of twelve professionals mentioned the high initial cost of sustainable materials as a challenge, with R1 highlighting that the "High cost of sustainable materials can become more challenging for contractors to justify the application of sustainable alternatives over traditional materials." Additionally, **R1** said that "*Time delays caused by using sustainable materials also increase project expenses, which leads to preventing stakeholders from investing in sustainability."* R4, R5, R6, R7, and R8 also expressed similar concerns throughout the cost impact related to sustainable construction materials. R9 and R10 recognised the unwillingness of clients to adopt sustainability due to cost concerns. **R9** stated that "*Client's unwillingness due to cost concerns usually restricts the adoption of sustainable options*."

Another major challenge mentioned by five professionals is the difficulties in obtaining sustainable materials. **R1** clearly emphasised "D*ifficulty in finding sustainable materials, which leads to project delays and extra costs*." R5 and R6 identified similar difficulties, with **R5** stating that "*Difficulty in sourcing renewable and recycled materials frequently makes contractors decide for conventional options*." Furthermore, quality concerns contribute to this difficulty, as **R10** pointed out that "*Lack of methods to verify the quality of recycled materials leads to unwillingness among engineers and employers when considering sustainable options*." Proper disposal and recycling of construction waste become essential challenges in sustainable renovation, as emphasised by the respondents R1, R4, R5, R8, R10 and R12. R4 and R5 examined the practical challenges involved,

with **R4** pointing out that "*Removing debris and finding places to dump is an important difficulty in renovation projects*." Similarly, **R12** emphasised its challenge to waste separation and reuse, stating that "*Contractors prefer quick disposal over reuse, which opposes the principles of sustainability*." The lack of skilled laborers with expertise in sustainable construction is identified as a common challenge in renovation projects by R1, R2, R3, R4, R5, R8, R9 and R11. **R10** further focused on it, mentioning that "*Lack of trained professionals limits the use of digital tools like BIM in renovation projects*". R3 and R5 also observed that BIM is not widely used in Sri Lanka due to the lack of past building drawings and the high initial cost of software and training. Regulatory challenges were another common challenge identified by the three professionals through the interviews. **R2** highlighted that "*Regulatory challenges and lack of standardisation processes lead to difficulty in integrating sustainability effectively in renovation projects*." Moreover, R10 stated that these challenges, including the difficulty in getting approval from local authorities, is a significant challenge created more complexity to sustainable renovation, since regulatory delays generally discourage contractors from adopting sustainable renovations.

Another major challenge mentioned in the interviews by seven out of twelve professionals included the resistance from the stakeholders, such as clients and contractors. **R3** noted that "*Resistance from contractors due to perceived additional effort commonly restrict the integration of sustainability*." R5 and R7 highlighted client dissatisfaction, with **R5** indicating that "*Clients may reject reused materials due to appearance concerns*". Similarly, **R12** said that "*Clients assume low-cost finishes look cheap*", clarifies about the preference for conventional materials over choosing the sustainable materials. **R10** further highlighted that "*The attitude of engineers and employers regarding the reuse and recycling of materials is often unfavourable, making it difficult to encourage sustainable methods*." R11 also observed that sustainability is not always integrated into renovation projects, indicating a common lack of adoption among industry professionals.

4.3 RECOMMENDATIONS FOR IMPROVING THE INTEGRATION OF SUSTAINABLE PRACTICES IN RENOVATION PROJECTS IN SRI LANKA

Respondents highlighted the need for training, government support, improved design approaches, sustainable materials, and engagement of stakeholders through interviews. **R1** stated that "*Providing proper knowledge and training is essential*," while **R2** discussed that "*Conducting workshops and training sessions for clients, contractors, and professionals can improve awareness of sustainability benefits, such as cost savings and environmental impact reduction*." Similarly, **R4** suggested, "*Arranging specialized training is needed for workers through workshops to provide proper idea about the sustainable design*," while R6, R9, and R1 pointed out the significance of education and awareness campaigns to improve the integration of sustainability in the construction industry. Government support is also another significant aspect in supporting sustainable renovation. **R1** proposed that "*Tax reductions should be provided for sustainable practices*", while R2 emphasised the necessity for financial incentives such as tax breaks and subsidies, along with stronger sustainability regulations. R3, R6, and R7 highlighted strengthening policies to promote renewable energy adoption and recycling initiatives. According to the respondents, sustainability should be focused on from the design process itself. **R1** said that "*Energy efficiency should be considered early in the process*," while

R3 emphasised the need for integrating biophilic design and adapting designs to Sri Lanka's tropical climate."

R5 emphasised the need to improve regulations related to waste management and drainage systems, especially for hotel renovations. **R7** mentioned "*Promoting the recycling of demolition waste through proper processing facilities*", while **R12** suggested "*Implementing policies that incentivise sustainable waste disposal and encouraging clients to prioritise sustainability over aesthetics*." R6, R9, and R11 pointed out the significance of arranging awareness campaigns and training programmes to provide clear ideas for professionals and the public on sustainable practices. **R8** expressed "*Increasing awareness about lifecycle cost benefits to encourage clients to invest in sustainable solutions*." Overall, the responses from the professionals show that improving sustainability in renovation projects needs an integrated strategy, including training programmes, government incentives, sustainable design integration, eco-friendly materials, stakeholder collaboration and waste management improvements.

5. DISCUSSION

The findings of the study provide more helpful information related to the contributions of contractors and consultants to adopting sustainable practices in renovation projects. The study mainly indicates that while awareness of sustainability is increasing, its actual implementation in the industry remains limited due to various challenges. Through the literature review, various sustainable practices were recognised to be essential in renovation projects. While considering the roles of contractor and consultant, the interview findings confirmed that they are important to sustainable integration, which relates to previous studies. Consultants were described as key advisors for clients in material selection and design solutions. However, many respondents indicated that their influence is often behind client interests and project cost constraints, which limits the scope of sustainable choices (Ghuzdewan et al., 2023; Hu, 2021). Contractors, on the other hand, were found to be mainly involved during the construction stage but rarely engaged in early decision-making phases. This is opposed to the literature review that advocates early-stage collaboration as important to achieving sustainability goals (Holloway & Parrish, 2015; Liu, Pauli, et al., 2020). Moreover, the findings revealed that many small and medium-sized contractors lack the technical training required to implement sustainable techniques effectively, reflecting concerns raised in earlier research (Jung et al., 2014; Mensah et al., 2022).

The study also highlighted several challenges that are similar to the literature review. High initial investment, absence of clear policy, limited incentives, and low client awareness were commonly identified challenges by professionals during interviews. These challenges relate to the literature review regarding cost-related challenges and institutional gaps that limit sustainability adoption in construction (D'Oca et al., 2018). Moreover, interviews emphasised the need for governmental support, awareness campaigns, and supportive regulations to improve sustainable practices in the construction industry. The literature review provides a comprehensive overview of the contributions of contractors and consultants in renovation projects. Although the research findings verify the importance of the identified sustainable practices, they expose major gaps in stakeholder engagement and policy support. Best practices, including educating the clients, integrating sustainability in contracts, conducting training, and better

communication required to bridge this gap among all stakeholders to align the Sri Lankan renovation projects with global sustainability objectives.

6. CONCLUSIONS

This section presents the conclusions drawn from the research conducted to investigate how contractors and consultants contribute to the adoption of sustainable practices in building renovation projects in Sri Lanka. The findings indicate that although many sustainable practices are conceptually recognised in Sri Lanka, their practical implementation remains limited and unbalanced. Consultants were identified as key contributors by advising clients, selecting appropriate sustainable materials, and addressing environmental considerations. On the other hand, contractors are mainly responsible for on-site works such as waste minimisation and efficient resource management. However, contractors and consultants mainly face numerous challenges related to lack of awareness, higher initial costs and lack of incentives from government in implementing the sustainable practices. To address these issues, several recommendations have been provided to enhance effective communication and facilitate the integration of sustainability into renovation projects. These recommendations focus on supporting a more coordinated and informed approach to sustainability, encouraging the adoption of locally available materials, the application of climate-responsive design strategies, and the implementation of policies. Overcoming the identified challenges requires an integrated and multi-stakeholder strategy incorporating expertise, supporting governmental frameworks, and enhanced client engagement to improve sustainable renovation methods in Sri Lanka. This study provides a comprehensive understanding of the practical roles of consultants and contractors throughout the phases of the renovation projects. Additionally, this research study provides specific industry-related recommendations that support practical implementation, policy improvements, and workshops for stakeholders on how to effectively integrate sustainable practices in renovation projects. Given that the scope of the study was limited to building renovation projects within the Sri Lankan context from the perspectives of contractors and consultants, future research could explore the role of client engagement in improving sustainable renovations and their decision-making. Additionally, investigating the impact of advanced technologies, financial incentives, and educational involvement could offer further insight into overcoming current limitations in renovation practices.

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ESTABLISHING SCHEDULE QUALITY PARAMETERS FOR EFFECTIVE DELAY ANALYSIS IN CONSTRUCTION PROJECTS

Sneha Baskar[1], Murali Jagannathan[2], Dheeraj K Ubhayakar[3] and K. Hariharan[4]

ABSTRACT

The construction industry is vital to national development, yet it often faces inefficiencies due to time and cost overruns, largely stemming from a variety of factors. These delays lead to project disruptions, disputes, and claims. Various delay analysis methods—categorized as prospective and retrospective—are employed to manage and mitigate such delays. However, the success of these methods highly relies on the quality of the project schedule. While general schedule quality parameters exist, there has been limited focus on parameters specific to delay analysis. This study investigates preferred delay analysis approaches and identifies challenges in their application. A survey and focus group study involving real-time projects established key schedule quality parameters for delay analysis. These include: Sequencing of Activities, Inclusion of All Activities, Use of Lags, Use of Non-Finish-to-Start Relationships, Date Constraints, and Float Colour Coding. Among these, "Inclusion of All Activities" emerged as the most critical, while the "Use of Lags" was found to be the least sensitive parameter. By highlighting these parameters, the study provides valuable insights for practitioners to enhance schedule robustness. A well-structured schedule allows for accurate prospective delay analysis, helping mitigate potential time as well as cost overruns and improving overall project performance.

Keywords: *Delay Analysis; Prospective Delay Analysis; Schedule Quality Parameters; Sensitivity Analysis.*

1. INTRODUCTION

Frequent delays and cost overruns are prevalent challenges in the construction industry, often stemming from various factors that, if unaddressed, can escalate into significant project setbacks (Al-Momani, 2000). For instance, consider delays linked to alterations in design drawings during the construction phase (Bajjou & Chafi, 2020). There are two types of delay analysis: Retrospective and prospective (Bubshait & Cunningham, 1998). Retrospective delay analyses the root cause and ownership of delay at the end of the project completion (Doloi et al., 2012). Prospective delay analysis is performing delay analysis contemporaneously or predicting the delay before and mitigating it (Hossen et

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al., 2015). Irrespective of the approach (prospective or retrospective), a construction programme/schedule is a core requirement for delay analysis. Inadequate or inaccurate schedules impede the precise assessment of delays, underscoring the necessity for well-defined schedule quality parameters tailored to delay analysis. Yet, adherence to all these parameters can be challenging in practice. Effectively, this study addresses the research question: What are the schedule quality parameters to implement the industry preferred delay analysis, and how can they be prioritised?

2. LITERATURE REVIEW

2.1 SCHEDULE QUALITY AND DELAY ANALYSIS

A high-quality construction schedule is a crucial tool for effective delay analysis, providing a structured framework for tracking project progress and identifying deviations from the planned timeline (Hendradewa, 2019). It enables accurate delay assessments, ensuring that project managers can precisely pinpoint the causes and consequences of delays.

2.2 PARAMETERS TO DETERMINE THE SCHEDULE QUALITY

One of the fundamental schedule quality parameters is ensuring that all activities are captured in the schedule, providing a comprehensive breakdown of work packages, activity descriptions, and dependencies. Proper sequencing of activities and including the use of lags, leads, and logical constraints only in unavoidable circumstances ensures that the schedule reflects realistic project timelines (Marcinkowski & Krawczynska-Piechna, 2019). A well-structured schedule must also incorporate risk assessment measures, ensuring that potential disruptions are accounted for and mitigated effectively (Siddika & Lu, 2023). Real-time updates and periodic schedule reviews help maintain accuracy and adaptability in dynamic project environments. By defining and analyzing these key schedule quality parameters, construction projects can improve delay analysis, enhance project control, and support proactive risk management strategies. Establishing robust schedule quality parameters is critical to achieving efficient project execution and minimizing scheduling-related risk timelines (Marcinkowski & Krawczynska-Piechna, 2019). While there are many schedule quality guides available, like the Earned Value Management System (EVMS), Program Analysis Pamphlet (PAP) (Winter, 2009) and Planning and Scheduling Excellence Guide (Kavad et al., 2019), the parameters as per the (U.S. Government Accountability Office, 2015) were selected considering their agreement with standards like the Defence Contract Management Agency (DCMA) guidelines and their suitability for the assessment of construction project schedules (Srinath & Varghese, 2023). The differences between the retrospective and prospective delay analysis techniques are reviewed next.

3. RESEARCH GAP AND OBJECTIVES

Despite extensive research on delay analysis methodologies, a critical gap remains in the literature regarding the role of schedule quality in conducting reliable delay analysis. While the requirements for delay analysis may vary depending on the method chosen, the focus in this study is specifically on the most preferred delay analysis technique. Nevertheless, while numerous studies have examined both retrospective and prospective techniques (El-Sayegh, 2008), no research has specifically defined the schedule quality

parameters necessary for conducting effective prospective delay analysis (Ajayi & Chinda, 2022) or retrospective delay analysis. Accordingly, the study's first objective is to determine which delay analysis industry professionals prefer (prospective or retrospective). The second objective is to arrive at schedule quality parameters for the most preferred delay analysis technique and conduct a sensitivity analysis to understand the most influential schedule quality parameters.

4. METHODOLOGY

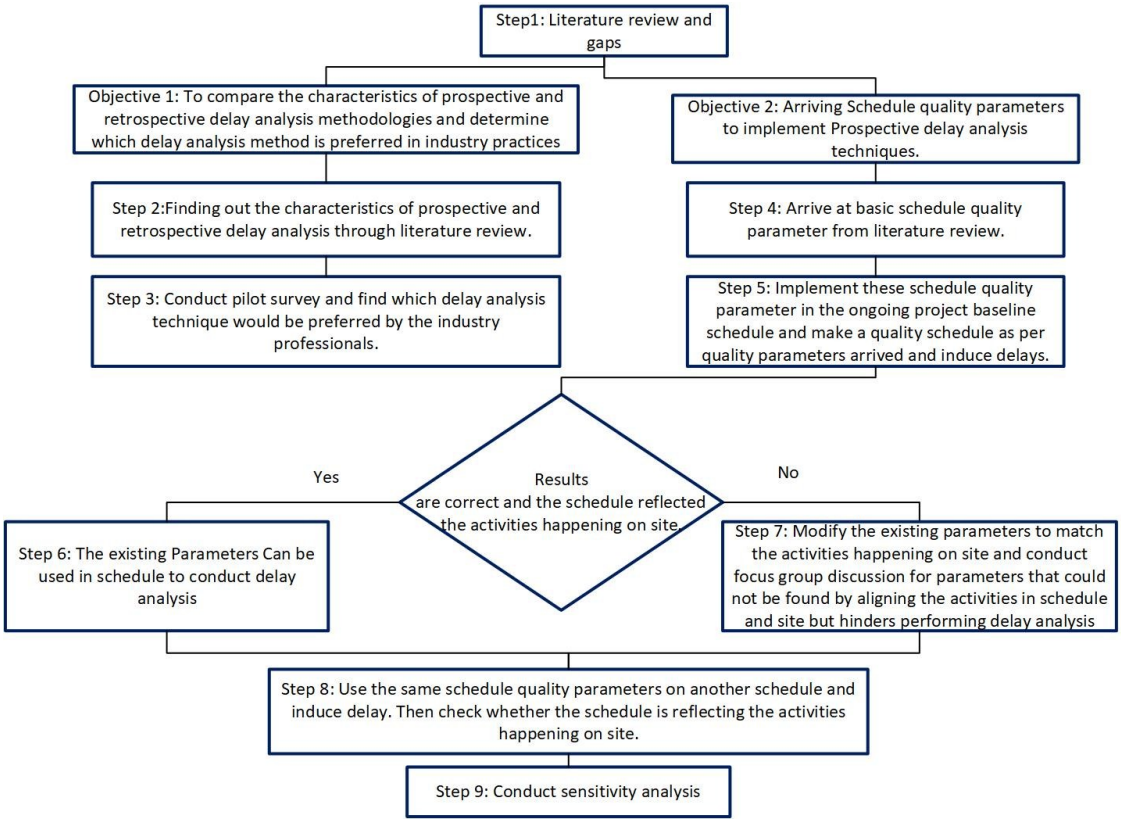


Figure 1: Methodology

As outlined in the methodology (Figure 1), a literature review (discussed earlier) was first conducted to identify the research gaps and assess the advantages and disadvantages of prospective and retrospective delay analysis techniques. However, the industry choice was not clear. Moreover, the link between a "quality" schedule and delay analysis had to be empirically established. Specifically, the absence of a "quality" schedule for successful delay analysis had to be verified through practitioners, especially the contractors who are often involved in the task of detailed schedule preparation. Therefore, a questionnaire survey form was developed. The survey form was used to collect primary data like working experience of the respondents, preferred delay analysis method, and reasons for delay analysis being a challenging task from industry professionals, including project managers, planners, and delay analysis experts, ensuring practical relevance. This primary data helps us understand which delay analysis is mostly preferred and why. And once the challenges while conducting delay analysis are known, it helps in the study to reduce those challenges. Of the 93 questionnaires distributed, 75 responses were received,

yielding an 80% response rate. Respondents' experience levels were grouped in five-year intervals to study their influence on delay analysis practices. A Likert scale assessed the adoption of structured delay analysis methods, while a multiple-selection question identified reasons limiting the use of structured delay analysis techniques. The Likert scale responses were used to conduct a T-test to determine whether the mean significantly differs from the neutral value. In parallel, a project schedule was developed using Microsoft Project with established schedule quality parameters, and actual delays were introduced to evaluate their impact. Then the schedule with delay was compared with the actual site progress. However, the initial schedule failed to accurately mirror site progress, indicating gaps in existing parameters. To improve alignment, additional parameters were proposed and tested. A focus group comprising three professionals, each with over 15 years of experience in planning and contracts, evaluated the considered qualitative parameters. A revised schedule incorporating the modified parameters was tested on a different project. Iterative refinements were made until the schedule closely aligned with actual site progress, confirming the updated parameters' robustness. Sensitivity analysis was then used to assess each parameter's influence by intentionally degrading schedule quality and observing the resulting time shifts. More sensitive parameters led to larger deviations, highlighting their critical role. Subsequently, the schedule was improved in stages, beginning with the most sensitive parameters, to measure enhancement in accuracy. This structured approach provided insight into each parameter's contribution to reliable delay analysis and effective project control.

5. RESULTS

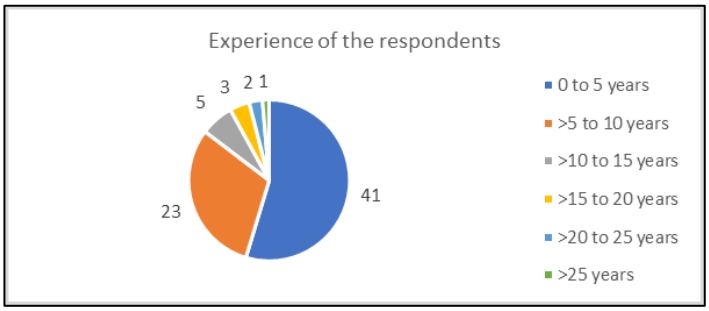


Figure 2: Experience of the respondents

It is evident from Figure 2 that most of the respondents have experience of 0 to 5 years, as the freshers are typically involved in initial planning. The next highest respondents, with 5 to 10 years of experience, were involved in delay analysis. The other questions asked to understand the delay analysis process among the industry professionals are tabulated in Table 1, with questions and the results of the T-test.

Table 1: T-test results

Statements	Null Hypothesis	Alternate Hypothesis	Mean Response	Is the p-value significant?	Result
Tools like Microsoft Project or Primavera are used for planning	The mean responses to Q1 are not significantly different from	Very frequently, MSP and Primavera are used for	2.533	Yes	Reject the null hypothesis and retain the

Statements	Null Hypothesis	Alternate Hypothesis	Mean Response	Is the p-value significant?	Result
project progress (Q1)	the neutral value	Project progress			alternative hypothesis
Schedules are used for monitoring and control (Q2).	The mean responses to Q2 are not significantly different from the neutral value	Very frequently, schedules are used to monitor and control	1.76	Yes	Same as above
Structured delay analysis technique is used to identify the impact of delays on the project completion (Q3)	The mean responses to Q3 are not significantly different from the neutral value	Very frequently, a structured delay analysis technique is used to identify the impact of the project	2.555	Yes	Same as above
Structured delay analysis technique (example: as-planned vs. as-built, time-slice analysis, etc.) helps to improve chances of success in delay-linked claims (like acceleration claims, disruption claims, etc) (Q4)	The mean responses to Q4 are not significantly different from the neutral value	It is fully agreed that structured delay analysis increases the success in delay-linked claims	1.453	Yes	Same as above
Structured Delay Analysis is a challenging task (Q5)	The mean responses to Q5 are not significantly different from the neutral value	It is fully agreed that delay analysis is a challenging task	1.653	Yes	Same as above
Mostly delay analysis method is prescribed in a contract document (Q6)	The mean responses to Q6 are not significantly different from the neutral value	Very frequently method of delay analysis is prescribed in the contract	2.708	No	Retain the null hypothesis

It is evident from Table 1 that the null hypothesis for most of the questions is retained, implying that structured analysis is important in effective claims management. However, structured delay analysis is a challenging task (Q5). The preference approach for the delay analysis (prospective) and the reasons why structured delay analysis is challenging are shown in Figures 3 and 4. The top reason for not adopting the structured delay analysis is "project schedules are not up to the mark", which points to the schedule quality, establishing the relevance of the study and also justifying the need for the survey questionnaire and the subsequent analyses. More details are presented in the "Discussion" section.

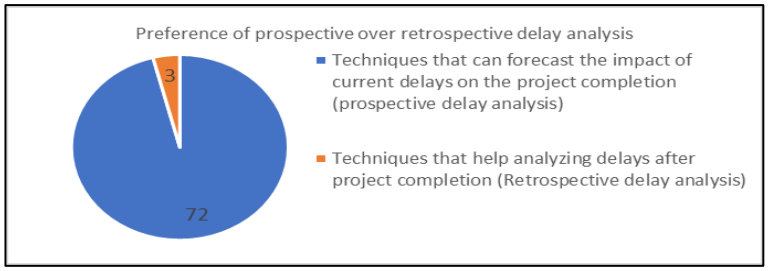


Figure 3: Graph showing preferences between prospective and retrospective delay analysis

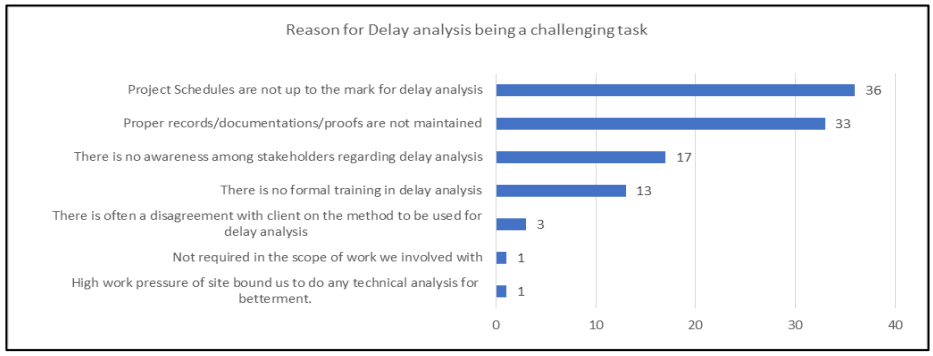


Figure 4: The reason for delay analysis being challenging

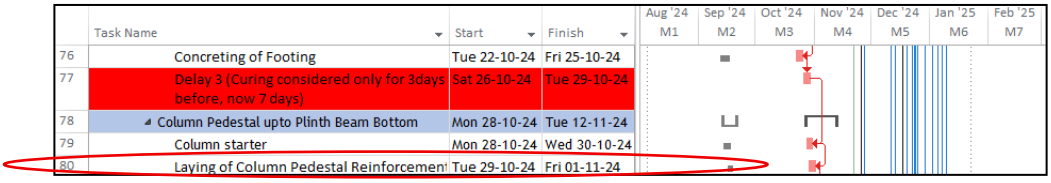


Figure 5: Schedule aligned with existing schedule quality parameters and induced delay events

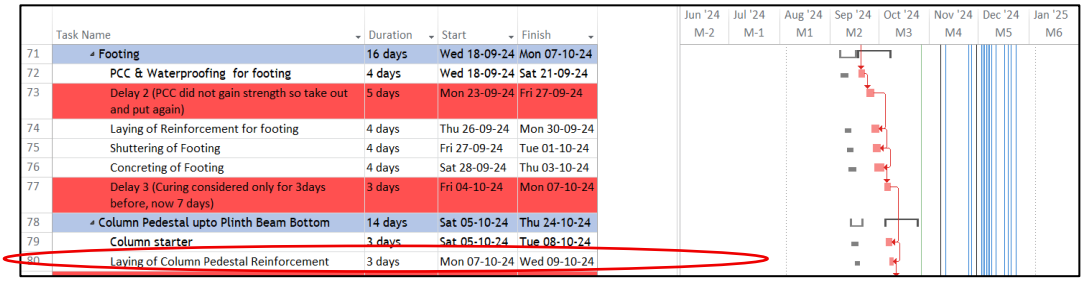


Figure 6: After inducing the delay events in the quality schedule, activity 80: Laying of column pedestal reinforcement starts on 07-10-24 and completes on 09-10-24

The schedule, refined following the existing schedule quality parameters, was updated to incorporate the identified delays. Delayed activities were visually distinguished in red, allowing for clear identification within the project timeline. Three distinct delay events

were recorded and integrated into the schedule for further analysis. The scheduled start and completion dates for laying column pedestal reinforcement (Activity ID 80) were October 7, 2024, and October 9, 2024, respectively. However, based on actual site conditions, the activity commenced significantly later, on October 25, 2024. This discrepancy highlights a misalignment between the planned and actual project timelines, emphasizing the need for modified schedule quality parameters to ensure better synchronization between the schedule and on-site progress. When site activities are not carried out as per the schedule, a misalignment occurs between the planned schedule and actual site execution. This misalignment introduces an additional parameter: sequencing of activities. For instance, if the laying of plain cement concrete (PCC) had to be redone due to inadequate strength on the specified date, the procurement of materials had to be repeated. However, the successor activity for "Laying of PCC" was "Laying of reinforcement for footing," with no direct link to procurement. The absence of a field to track redoing as a delay resulted in inefficiencies. If an activity, "Testing of PCC," had been included and linked to "Procurement of Material," project tracking could have been more effective. This highlights the need for the parameter "Inclusion of all activities." The literature suggests that lags should be used only in unavoidable situations. However, in the Site 1 schedule, non-finish-start relationships were applied to activities such as column reinforcement, shuttering, and concreting. Since not all columns require full reinforcement before shuttering begins, a finish-to-finish relationship was used. During focus group discussions, industry professionals found non-finish-start relationships challenging to interpret. The site could be divided into sectors to address this, with activities named accordingly, such as "Sector 1 Column Concreting." This led to modifying the parameter to "Use of non-finish-start relationships. “The use of non-finish-start relationships inherently includes lags. To eliminate this dependency, the parameter "Use of lags" was modified from "Usage during unavoidable situations" to "No usage" for delay analysis. Similarly, the parameter "Date constraints" did not allow for a natural schedule flow. When delays were introduced, activities did not shift accordingly. Therefore, this parameter was also modified from "Usage during unavoidable situations" to "No usage. “Additionally, focus group discussions emphasized the importance of visualizing float ownership within the schedule. To enhance this, colour coding was introduced. As a result, the parameters "Sequencing of activities," "Inclusion of all activities," and "Float colour coding" were added, while "Use of lags," "Use of non-finish-start relationships," and "Date constraints" were modified.

Table 2: Identified schedule quality parameters

Parameter	Refinement for Improved Delay Analysis
Sequencing of Activities	All activities must have proper sequencing with clearly defined predecessors and successors, ensuring alignment with actual site progress.
Inclusion of All Activities	Every activity, including minor tasks like curing, must be included to represent the construction process comprehensively.
Use of Lags	Lags should be avoided; a dedicated activity name and duration should be assigned to maintain clarity in delay analysis.
Use of Non-Finish-Start Relationships	This relationship should not be avoided, as it complicates progress monitoring and delay tracking.

Parameter	Refinement for Improved Delay Analysis
Date Constraints	It should be completely removed to maintain transparency and ensure accurate representation of project delays.
Float Colour Coding	Float ownership should be clearly defined using distinct representations, such as colour coding, to improve accountability and tracking of delays.

To check the robustness of the arrived parameters, the modified schedule quality parameters were applied to a different project site, resulting in a schedule that accurately reflected the on-site activities. Once the as-planned schedule, following all the schedule quality parameters with delay induced, reflected the site progress for other projects as well, the arrived parameters were concluded to be a robust list of parameters. As there were many parameters, a sensitivity analysis was conducted. Plots were generated by plotting the number of days of variance on one axis against the percentage increase in non-compliance on the other, providing a visual representation of the relationship between schedule deviations and adherence to quality parameters. The initial 0.11% arrived when non-adherence was applied to one activity.

Table 3: Sensitivity analysis

Description (Independent Variable)	Count of activities in the schedule with description parameters	Total activities in the schedule	[(Count of activities in the schedule with description parameters/ Total activities in the schedule) x 100] = A	Difference between delay-induced and impact	[(Difference between delay induced and impact / Duration of project in days) x 100] = B	B/A	Ranking on the basis of B/A value
When "no lags" was not followed	1	914	0.11%	5	1.82%	16.68	1
When "no leads" was not followed	1	914	0.11%	5	1.82%	16.68	1
When "no dangling activity" was not followed	1	914	0.11%	13	4.74%	43.36	3
When "no linking to summary activity" was not followed	1	914	0.11%	9	3.28%	30.02	2

Description (Independent Variable)	Count of activities in the schedule with description parameters	Total activities in the schedule	[(Count of activities in the schedule with description parameters/ Total activities in the schedule) x 100] = A	Difference between delay-induced and impact	[(Difference between delay induced and impact / Duration of project in days) x 100] = B	B/A	Ranking on the basis of B/A value
When "no date constraints" was not followed	1	914	0.11%	15	5.47%	50.04	4
When "well sequencing of activities " was not followed	1	914	0.11%	18	6.57%	60.04	5
When "inclusion of all basic activities" was not followed	1	914	0.11%	25	9.12%	83.39	6

The analysis revealed the sensitivity of schedule quality parameters in ascending order, from least to most sensitive, as follows: Use of lags and Use of leads, Summary activities, Dangling activities, Proper sequencing of activities, Use of date constraints, and Inclusion of all basic activities. This same sensitivity analysis (considering the schedule parameters as independent variables and the delay impact as the dependent variable) was performed for seven projects with the same characteristics, revealing the same trend in the sensitivity of the parameters. To further validate these findings, a poorly structured schedule was selected and systematically refined, starting with the most sensitive parameter and progressing toward the least sensitive, ensuring a structured approach to improving schedule accuracy and alignment with on-site activities.

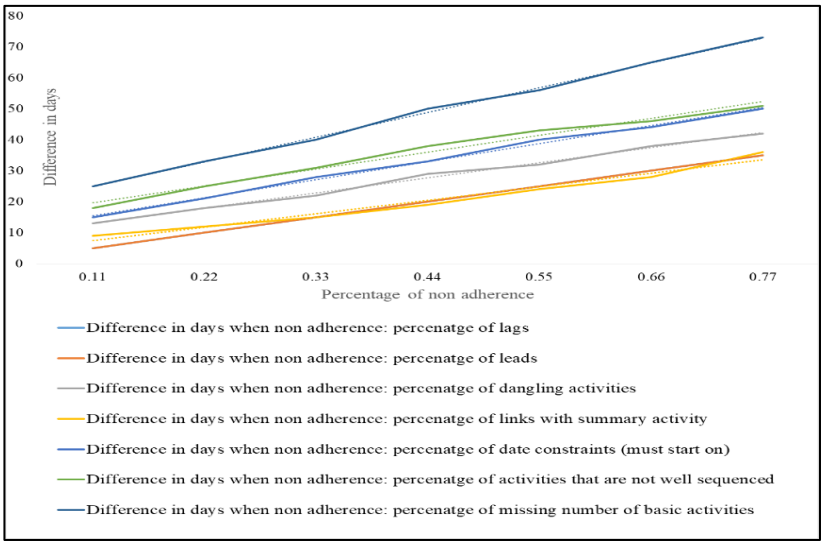


Figure 7: Plots showing sensitivity and linearity trend

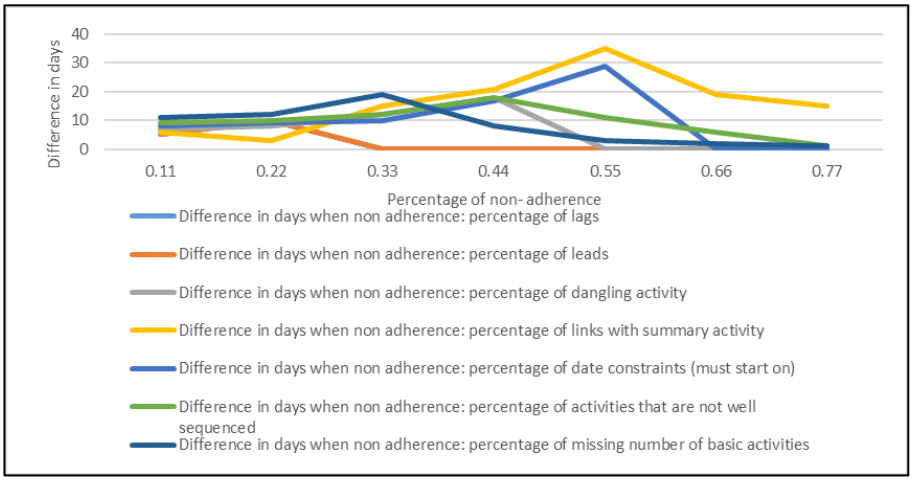


Figure 8: Plots showing a non-linear trend

6. DISCUSSION

As presented in Table 1, Microsoft Project and Primavera are among the most frequently used tools for tracking project progress. The data from Table 1 further reveals a consensus that delay analysis significantly improves the success rate of delay-related claims. However, practitioners also recognize that delay analysis remains a complex and challenging task. Notably, the specific delay analysis method is rarely stipulated in contractual documents. Although scheduling tools are widely adopted, effective delay analysis often proves difficult due to discrepancies between baseline schedules and actual site progress. Both prospective and retrospective delay analysis methods are available; however, survey results (Figure 3) indicate a preference for prospective techniques. These methods offer the advantage of forecasting delays, thereby facilitating the timely implementation of corrective measures. As illustrated in Figure 4, major delay analysis challenges include the substandard schedule quality and inadequate record-keeping, documentation, and proof. Addressing the issue of poor documentation, prospective delay analysis emerges as a viable solution, as it is performed contemporaneously and relies less on historical data. Nevertheless, enhancing the accuracy of schedules remains essential, particularly for effective delay analysis. While Table 1 outlines fundamental

schedule quality parameters, initial attempts to align schedules with actual site progress using these parameters proved insufficient, as reflected in Figures 5 and 6. According to the literature, there were 23 schedule quality parameters, and through this study, specifically focusing on the quality parameters for delay analysis, three were revised and three were added, thereby developing schedule quality parameters for reliable prospective delay analysis. However, due to the extensive nature of these parameters and their potential to reduce scheduling flexibility, it may not be feasible for planning professionals to implement all of them in practice. Therefore, a sensitivity analysis was conducted (Table 3) to identify the most critical parameters, allowing planners to focus on those with the greatest influence on schedule reliability when full compliance is not feasible. The sensitivity analysis results (Figure 7) revealed a possible linear relationship between non-compliance with schedule quality parameters and the discrepancy (in days) between delay duration and actual delay impact. However, this linearity cannot be generalised as it is observed under certain specific conditions owing to the scheduling logic and treatment of delays. For example, an increase in the percentage of lags and leads showed a linear effect due to the uniform float consumption across an increasing number of activities, which may not always be the case. Further, focus group discussions highlighted that using lags and leads introduced errors. Leads, in particular, were found to be confusing, especially in finish-start relationships, because they could result in the premature start of successor activities before the completion of their predecessors. When delays occurred, these premature starts distorted the actual project timeline. The presence of lags, leads, dangling activities, and date constraints contributed to a linear impact pattern because the activity configurations ensured that impacting activities (on the non-critical path with uniform float) preceded impacted activities (on the critical path). Similarly, linking summary activities added complexity by introducing alternate paths, thereby influencing the impact of delay. Poor sequencing and improper inclusion of activities also exhibited linear behaviour due to consistent activity configurations across schedules, which may not always be the case. In summary, the linearity was caused by a) the presence of uniform float in similar activity, b) impacting and impacted activities are present in the same path, c) same date constraint (as soon as possible) in all activities and d) the same relationship (finish-start) in all activities e) the same duration of delay impacted and f) the induced delays not exceeding the float available in the non-critical activity. Therefore, the linearity cannot be generalised and is limited to a specific case. When the above conditions leading to linearity were not followed, the trend moves towards non-linearity as shown in Figure 8. The variation in delay impact associated with date constraints and dangling activities stemmed from the creation of additional dependency paths. These findings collectively underscore that each increment in schedule non-compliance proportionally degrades schedule reliability, reaffirming the importance of adhering to established schedule quality parameters. When poorly structured schedules were systematically corrected, the resulting improvement in schedule accuracy was observed. The rate of improvement varied across parameters, indicating that some factors had a greater effect on enhancing schedule quality than others. The difference between delay duration and delay impact, measured in days, effectively indicates each parameter's sensitivity. Among the parameters analyzed in the schedules considered in the study, "Inclusion of all activities" was found to be the most sensitive, while "Percentage of lags" was the least sensitive. This trend was consistently observed across all seven case studies, suggesting that the results are reasonably generalizable. However, it is crucial to note that the excluded activities in each case were uniformly assigned a duration of 15 days;

different durations might alter the sensitivity ranking. Additionally, the "must start on" constraint used in the analysis is hard, which magnified its adverse impact. A different type of constraint could yield different sensitivity outcomes. The linearity observed was also a product of how activities were selected and hence cannot be generalised; alternative configurations could result in non-linear relationships. By focusing on the most influential parameters, planners can enhance schedule accuracy and ensure that project timelines reflect actual construction progress more closely.

7. CONCLUSION

This study highlights critical schedule quality parameters for accurate prospective delay analysis and evaluates their sensitivity. Prioritizing sensitive parameters enhances schedule reliability, enabling timely mitigation. Despite challenges in full compliance, standardizing scheduling improves project control, reduces disputes and overruns, and supports effective delay analysis in construction project management.

8. LIMITATIONS AND FUTURE SCOPE

This research focused on a water supply and a hostel construction project, limiting its generalizability. Future studies should incorporate these project types to validate and refine schedule quality parameters for wider delay analysis relevance.

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EVALUATING THE EFFECTIVENESS OF APPROVED DOCUMENT O IN MITIGATING OVERHEATING IN BUILDINGS: A FOCUS ON MODERN METHODS OF CONSTRUCTION

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ABSTRACT

In recent years, the adoption of modern methods of construction (MMC) to help achieve net-zero goals and enhance construction efficiency has risen. However, concerns have emerged regarding its thermal performance and effect on occupant comfort, particularly in an era where building overheating has become an increasing risk. This challenge has drawn stakeholders' attention, including the UK government which has published a regulatory framework to mitigate the adverse effects of building overheating. This study seeks to evaluate the effectiveness of Approved Document O in mitigating overheating in modern buildings. The study employed multiple method qualitative research, including a comprehensive literature review, a desk study of existing regulatory framework and semi-structured interviews among 6 participants to assess the overheating risk in modern buildings and the effectiveness of regulatory frameworks. Findings from the literature review identified key factors contributing to overheating, such as high ambient temperature, solar radiation, design and construction practices, and occupancy behaviours. Thematic analysis of interview data highlighted inappropriate ventilation as the primary cause of overheating, regardless of the construction method, with lightweight materials and energy-efficient building posing additional challenges. The interviewees emphasized the necessity for consistent regulatory frameworks across all construction methods and the importance of passive design strategies. The study contributes to the understanding of regulatory effectiveness of Approved Document O and offers recommendations for improving overheating mitigation in MMC buildings.

Keywords: *Modern Method of Construction; Overheating; Approved Document O; Ventilation Strategies.*

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1. INTRODUCTION

As we stand at the intersection of climate crisis and construction innovation, there is a growing recognition that the way we build, and the materials we use, hold the key to both mitigating the adverse effects of climate change and adapting to its inevitable impacts (Keeffe & McHugh, 2014). These escalating impacts of climate change, such as high temperature, rise in sea level and extreme weather events pose unprecedented challenges to global sustainability and human health (Balogun, et al., 2020; Intergovernmental Panel on Climate Change, 2023). This has necessitated the need for innovative and integrated approaches that will enhance climate change adaptation and mitigation strategies for built environment.

The built environment contributes to environmental degradation and global warming due to high energy consumption and carbon emissions (Sudhakaran et al., 2020; Röck et al., 2020). Adopting sustainable construction methods, such as Modern Methods of Construction (MMC), can mitigate the effects of environmental degradation and global warming by minimizing pollution, reducing energy consumption, and maximizing resource use (Nazir et al., 2020). MMC, which includes prefabrication and modular construction, often enhances construction efficiency and environmental performance (Kaushal et al., 2022). The implementation of MMC has experienced a surge globally, including in the United Kingdom (UK), who aim to deliver high-quality buildings with reduced cost and environmental footprints as outlined in the UK's 2025 construction strategy (Bertram et al., 2019; Buckley et al., 2020; Maqbool et al., 2023a).

While MMC known for lightweight construction have become integral to addressing climate-related issues, which are in alignment with the 'Construction 2025: Strategy', a joint strategy from the UK government and industry for the future of the UK construction industry (Maqbool et al., 2023; Wuni & Shen, 2020), it however, presents the challenge of overheating (Ozarisoy, 2022; Chartered Institution of Building Services Engineers (CIBSE) 2024). The Chartered Institution of Building Services Engineers (CIBSE) offers guidance on managing overheating as outlined in Technical Memorandum 59 (TM59), which should be considered in building development, but factors such as airtightness, high insulation, limited natural ventilation, and lightweight limits the ability for MMC structures to adhere completely to this guidance, and contributing to overheating (Ozarisoy,2022; Gupta & Gregg,2020; Fifield et al., 2018). These unintended impacts necessitate the enactment of a regulatory framework to ensure building standards are compatible with all seasons (Fifield et al., 2018).

Furthermore, different countries have adopted various strategies to address the challenges of environmental degradation and global warming (Howarth et al., 2018; Intergovernmental Panel on Climate Change Technical Support Unit Working Group, 2018). In particular, the UK government inaugurated a committee in 2012 to prepare climate change risk assessment (CCRA) report with a review period of five years. The latest report was published in January 2022, which highlights eight priority risk areas for the government, out of the most significant risk applicable for this research is Priority Risk No. 7, "Risks to human health, wellbeing and productivity from increased exposure to heat in homes and other buildings".

Priority risk -No. 7 of the CCRA report underscores the escalating risks of overheating in buildings, suggesting that policies aimed at achieving Net Zero emissions may inadvertently exacerbate overheating risks. Likewise, Salimi and Al-Ghamdi (2020)

proposed that the built environment requires research which should focus on enhancing building codes to address challenges posed by extreme heat waves and power outages. Additionally, Drury and Lomas (2020) as well as Hamdy et al. (2017) delineated various issues relating to building overheating, which include impaired sleep quality, reduced productivity, and health risks. These issues are expected to worsen with the increase in global warming (IPCC, 2018).

Acknowledging the pressing need to combat climate change within the realm of construction, the UK government has implemented a range of policies and regulations with the aim of enhancing thermal comfort and energy efficiency (Howarth et al., 2018). Notable initiatives include the Building Regulations for overheating, detailed in "Approved Document O," alongside the Future Homes Standard and the Clean Growth Strategy, which set forth mandates and objectives for reducing energy consumption and carbon emissions within the built environment. However, an analysis of "Approved Document O" highlights the need for additional clarification, particularly concerning acoustic limits, assessment methodologies for glazing areas, allowances for mechanical cooling, and guidance on selecting suitable sample units (Diamond, 2022). These concerns have identified a notable gap in regulatory guidance for addressing overheating in modern buildings (Jariwala & Taki, 2023).

Given the anticipated rise in both the intensity and frequency of heatwaves in the UK, along with forecasts suggesting a 5.4°C increase in summer temperatures by 2080 (MetOffice, 2018), immediate measures are imperative to prepare ourselves for the present and future alterations in weather conditions. This challenge necessitates effective regulations to address environmental sustainability concerns (Brimicombe et al., 2021; Jariwala & Taki, 2023). While the UK government has enacted policies aimed at facilitating sustainable development, there is a pressing need to assess the effectiveness of the existing regulations in addressing overheating risks in sustainable buildings.

Therefore, this study seeks to evaluate the effectiveness of Approved Document O in regulating overheating in modern buildings. Using the key research question “How effective is Approved Document O in addressing overheating in modern method of construction”, the following research objectives: (1) exploring the problem of overheating in buildings, (2) investigate how various MMC techniques susceptible to overheating (3) examining the effectiveness of Approved Document O for mitigating overheating in buildings in England and (4) developing actionable recommendations for policy enhancements for mitigating overheating in modern buildings were explored.

2. LITERATURE REVIEW

2.1 OVERVIEW OF MMC

There has not been a universally accepted definition for Modern Methods of Construction (MMC), as various authors have described the term based on their individual perspectives. According to Nazir et al. (2020), MMC encompasses innovative approaches and procedures that diverge from conventional on-site building practices. Maqbool et al. (2023b) and Saad et al. (2023) broaden this definition to include “panelised frames, volumetric systems, hybrid systems, and modular systems”. These methods offer alternatives to the traditional approaches and hold the promise for significantly enhancing productivity, efficiency, and quality in the construction industry and the public sector. Additionally, Maqbool et al. (2023a) highlight the substantial benefits associated with

MMC techniques, emphasizing their pivotal role in achieving the objectives outlined in the 'Construction 2025: Strategy'. Furthermore, Sánchez-Garrido et al. (2022) emphasize the potential MMCs in minimising life cycle impacts by optimising material usage. Taken together, MMC can be described as an innovative technique, which diverges from traditional on-site building methods and creates emphasis on efficiency, sustainability, and precision. Therefore, Table 1 is used to highlight some advantages and disadvantages of MMC as described by various authors.

Table 1: Advantages and disadvantages of MMC with emphasis on overheating
Sources: (Gupta & Gregg, 2020; Davenport & Partington, 2021; Ozarisoy, 2022; Maqbool et al., 2023; Jariwala & Taki, 2023)

Advantages	Disadvantages
High thermal insulation properties of MMC systems enhance indoor thermal comfort and energy efficiency.	Low thermal mass in lightweight MMC systems (e.g., steel or timber) can increase the risk of overheating, especially in
Reduced thermal bridging due to precise factory fabrication improves building envelope performance.	High levels of insulation and airtightness can lead to overheating if not paired with adequate ventilation strategies.
Reduction in completion timeframe and environmental impact from construction activities.	Slower establishment of standardised designs, quality assessment systems, and accreditations
Reduced construction waste and environmental impact through off-site manufacturing.	Pre-completed designs limit flexibility, making it harder to adapt thermal strategies
Panelized wood structure provides advantages such as reduced weight, potentially resulting in decreased requirements for foundation design.	Thermal comfort challenges arise from low thermal mass and airtightness, requiring careful passive design integration.

2.2 OVERHEATING RISK

The implementation of MMC known for lightweight construction, has been accompanied by a growing concern over high temperatures in buildings that have adopted MMC techniques (Ozarisoy, 2022; Jariwala, & Taki, 2023; CIBSE 2024). Additionally, CIBSE has described overheating as *"conditions where the indoor temperature surpasses 28°C for more than 1% of the annual occupied hours in the living areas of dwellings without mechanical cooling systems, or when the bedroom temperature exceeds 26°C for more than 1% of the annual occupied hours, unless ceiling fans are present".* This description along with other criterions formed the basis for which Fifield et al., (2018) identified Bradford Royal Infirmary UK, as being at risk of overheating. Their study highlighted overheating complaints from residents, resulting in discomfort during the summer period. Additionally, the study identified the use of penalized wall as a major contributor to high indoor temperatures in this building.

However, other articles have identified and described various factors contributing to overheating in buildings. The authors have categorized these factors into three categories, as shown in Table 2.

Table 2: Causes of building overheating

Category	Sub-category	Description	Sources
Environmental Drivers	High outdoor temperature Solar radiation Urban heat island Greenhouse gas	Environmental drivers which can include climate related factors, such as high weather temperature, humidity, and wind pattern, affect indoor thermal dynamics. With hot and humid climates, comes the stress of high ambient temperatures and low air movement which hinders natural ventilation and exacerbates heat. Similarly, Urban heat islands, marked by heightened temperatures in densely populated regions, can exacerbate overheating. While MMC offers efficiency and sustainability, its airtight and highly insulated designs can restrict natural ventilation and thermal mass, potentially worsening overheating if not adapted to local climate conditions.	(Hamdy et al., 2017), (Lomas and Porritt, 2017), (Diamond et al., 2019), (Rahif et al.,2022), (Bo et al.,2022), (Chen, 2019), (Alrasheed and Mourshed, 2023), (Jariwala, & Taki, 2023).
Design and Construction	Lack of double-glazed windows High level of insulation Inappropriate ventilation Underperforming insulation Building orientation Reduction in green spaces Increase level of airtightness Lack of external shading	Many newly built energy-efficient homes are designed without fully accounting for future climate warming. Design factors such as orientation, glazing, and insulation, directly affect solar gains, ventilation, and thermal comfort MMC systems, particularly light steel panelised methods, often feature extensive glazing for facades and windows), which, without adequate shading, can lead to excessive solar heat gain. High insulation levels and thermal bridging may further impair heat regulation Additionally, MMC's reliance on lightweight, low-mass materials reduces thermal buffering capacity, increasing overheating risk during high solar exposure	(Fifield et al 2018), (Morgan et al., 2017), (Lomas and Porritt, 2017), (Diamond et al., 2019), (Bo et al.,2022), (Alrasheed and Mourshed, 2023), (Drury et al.,2021) (Mitchell & Natarajan, 2019), (Davenport & Partington, 2021 (Habitzreuter et al, 2020), (Ozarisoy, 2022). (Milovanović et al., 2022). (Rakotonjanahary et al., 2020)
Operational factors	Activities of occupant Level of occupancy Heat gain from boilers Equipment usage	Building operational factors including occupancy patterns and activities, appliance usage, and ventilation practices of the occupants contribute to internal heat gains, this can elevate indoor temperatures, particularly in poorly ventilated spaces with airtight envelopes or limited access to outdoor air.	(Fifield et al.,2018), (Lomas and Porritt ,2017), (Rahif et al.,2022), (Drury and Lomas, 2020), (Chen, 2019), (Habitzreuter et al, 2020), (Mitchell & Natarajan, 2019)

2.3 OVERHEATING MITIGATION STRATEGIES

Mitigating overheating in contemporary construction necessitates a strategic implementation of passive design techniques, greenery strategy, and innovative technologies. Alrasheed and Mourshed (2023) proposed a classification of passive cooling techniques into three categories: "solar and heat protection, heat modulation, and heat dissipation," providing a systematic approach to alleviate overheating risks in residential structures. Similarly, Gamero-Salinas (2021) underscored the significance of passive cooling design strategies in mitigating overheating in tropical climates like Tegucigalpa (TGU) and San Pedro Sula (SPS). Furthermore, greenery solution such as green roofs emerges as highly effective for cooling and energy savings, particularly in Mediterranean regions, potentially reducing the reliance on cooling systems (Zinzi & Agnoli, 2012). While innovative technologies like mechanical ventilation with heat recovery (MVHR) also play a crucial role by extracting warm and humid air from spaces such as bathrooms and kitchens, recovering waste heat through a heat exchanger, and reintroducing tempered fresh air into living areas, thereby diminishing the need for heating and subsequent energy consumption. However, meticulous planning during the design and construction phases is imperative (Karampour & Burgess, 2022). Implementing these strategies can effectively regulate indoor temperatures and enhance thermal comfort. However, consideration needs to be made on adherence to government regulation like Approved Document O that provides guidelines for assessing overheating in building, when deciding on a mitigation strategy. Figure 1 provides an indicative summary of overheating mitigation strategies.

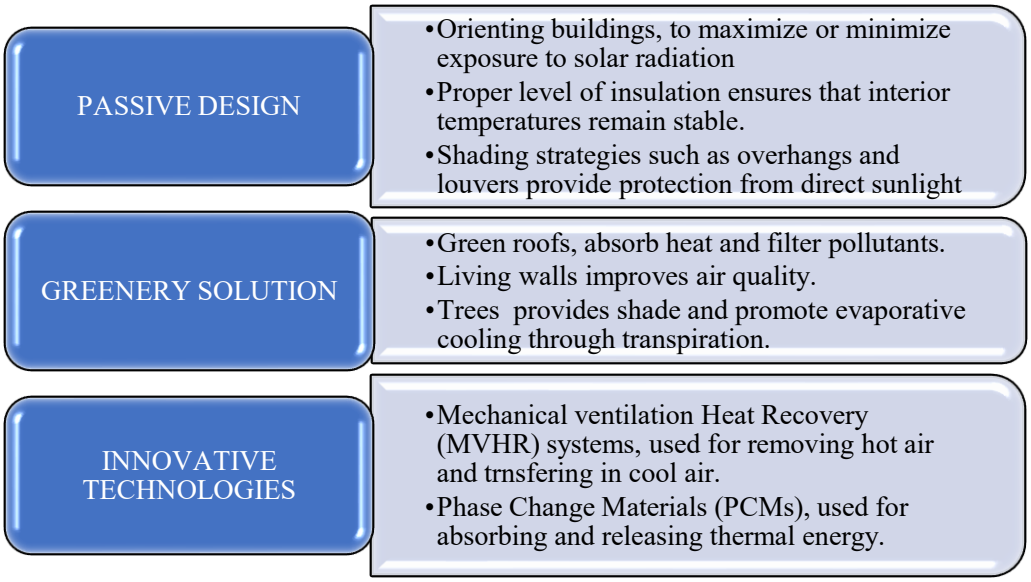


Figure 1: Overheating mitigation strategies
Sources: (Zinzi & Agnoli, 2012; Auzeby, 2017; Hamdy et al., 2017; Diamond et al., 2019; Elaouzy, & Fadar, 2022; Karampour & Burgess, 2022; Alrasheed & Mourshed, 2023)

3. RESEARCH METHODS

The research, which centres on investigating the effectiveness of existing UK government policies on MMC in mitigating overheating risks in buildings and achieving net-zero, adopted an interpretivism approach for its research philosophy. Multiple qualitative research methods were employed. These include secondary data collection from

databases such as ScienceDirect, SpringerLink, and the UK Government website, with selection criteria including articles published within the last ten years and a focus on keywords related to MMC buildings in the UK. Additionally, the authors reviewed regulatory publications from the UK government to identify suitable manuscripts for this study, presenting a descriptive desktop study of Approved Document O.

The primary data collection involved semi-structured interviews with six participants who were selected through purposive sampling based on their experience with MMC and overheating regulatory compliance. Open-ended questions which include seeking interviews opinions on the main strengths and weaknesses of the Approved Document O**,** were utilized to assess experts' views on the effectiveness of regulatory policy. Thereafter, thematic analysis, was used to analyse qualitative data and identify key themes. These themes are presented in subsequent sections.

4. DESKTOP STUDY OF THE APPROVED DOCUMENT O

The desktop study examines the Approved Document O, which is a part of the Building Regulations in the UK. It is designed specifically to address overheating concerns in residential buildings. This document was introduced in 2021 and came into effect on 15th June 2022. Previous building regulations L and F were used for regulating heat loss in winter. However, with the rising temperatures due to global warming, overheating in urban areas is becoming a bigger problem. Approved Document O now tackles the need to mitigate excessive heat in buildings, to keep buildings from overheating during the warmer months with specific focus on new buildings.

Approved Document O stipulates two core performance objectives:

- Measures should be taken to limit excessive solar heat gain during summer
- Ensure adequate methods to remove heat from indoor spaces with a preference for passive cooling strategies over mechanical cooling systems.

Therefore, Section 3 of the Approved Document O provides passive mitigation strategies that are deemed acceptable for occupant comfort, such as:

- Eliminates noise levels during sleeping hours,
- Minimizes intake of external pollutants,
- Ensures security of ventilation openings,
- Reduces the risk of falls from height,
- Prevents entrapment hazards.

These are not standalone mitigation strategies. However, they provide enabling conditions that support safe and effective implementation of passive ventilation strategies and compliance with the regulatory requirements.

Individuals can demonstrate compliance with Approved Document O using two specific strategies. A simplified method, which uses fixed parameters such as glazing ratios, openable window areas, cross-ventilation, and regional climate zones, offering ease but limited flexibility to accommodate innovative or non-standard construction typologies; and dynamic thermal modelling, which uses CIBSE TM59-based simulations with strict input constraints, allowing greater design adaptability but posing challenges for buildings using mechanical ventilation systems like MVHR. Although MMC is not explicitly referenced, its typical features—lightweight construction, low thermal mass, and airtight

envelopes—heighten overheating risks and may conflict with passive cooling assumptions.

4.1 CHALLENGES FOR MMC IN ADHERING TO APPROVED DOCUMENT O

The authors while undertaking this desktop study, have also reviewed various sources of information available on Approved Document O such as (CIBSE 2021: Diamond, 2022). This review has enabled them to identify factors in approved Document O, which may impose a challenge for buildings constructed using MMC techniques. These Factors are described below.

Integration of Mechanical Systems: MMC buildings often incorporate integrated mechanical systems for ventilation and heating. However, the existing standards outlined in Approved Document O do not explicitly specify conditions under which mechanical ventilation is permissible within a building.

Design Impact on Glazing: Approved Document O mandates higher guarding heights and maximum reach for window handles, impacting glazing design in buildings. This could necessitate raised sill heights and limit the width of opening panes, posing design challenges for MMC projects.

Integration of Noise Mitigation Measures: Implementing noise mitigation measures within MMC components can present a complex challenge for professionals.

Limited Flexibility during Construction: MMC processes typically follow standardized manufacturing techniques, leaving limited room for on-site adjustments or modifications to address noise-related issues as they arise. This lack of flexibility can hinder the ability to tailor noise control measures to specific site conditions, potentially affecting compliance with Approved Document O.

5. DATA ANALYSIS AND DISCUSSION

The authors have used Figure 2 to provide an overview of participants' profiles and their knowledge levels in two domains MMC and ADO. Participants' profiles column details

PARTICIPANT ID	PARTICIPANT PROFILE	KNOWLEDGE AREA	
		MMC	APPROVED DOCUMENT O
P1	MSC, Director, 30 Years		
P2	MSC, Sen. Director, 17Years		
P3	MSC, Ass.Director, 25Years		
P4	PHD, Sen. Lecturer, 20 Years		
P5	BSC, Partner, 20 Years		
P6	PHD, Lecturer, 20 Years		

KEYS
HIGH LEVEL KNOWLEDGE
MODERATE LEVEL KNOWLEDGE
LOW LEVEL KNOWLEDGE

Figure 2: Overview of participants information and knowledge

their academic qualifications, job roles, and years of experience. Knowledge levels are color-coded: green for high (≥7 years), yellow for moderate (4–6 years), and red for low (1–3 years). All participants show high knowledge in MMC, whereas only half show high knowledge in Approved Document O. The table offers a clear visual summary of participant expertise and familiarity with key subject areas.

From Figure 2, it is visible that all participants have a significant level of knowledge of the subject area to enable them to make effective contribution to the existing body of knowledge.

5.1 PRIMARY FACTORS ENHANCING BUILDING OVERHEATING

The participants highlighted several factors contributing to overheating, such as inadequate ventilation, large glazing area solar heat gains, limited green spaces, and occupant density. From the interviews conducted, ventilation emerged as a major concern for all participants with P1 further emphasizing that flats are at a higher risk of overheating: "*Yes, there were many examples of people at that time living in flats where the internal environment just became untenable from a living perspective".* -P1. Therefore, there is a need for flats to be designed with the right ventilation strategy. Additionally, the participants debated on how design and construction materials contributed to building overheating, P2 stated that building materials with low U-values trap heat and lack the ability to disseminate the heat once absorbed. However, P1 and P6 argued that lightweight materials do not significantly impact overheating. With P6 further describes the challenge of building overheating as design related, stating that the increased reliance on floor to ceiling glass ratio has impacted the level of heat gains into the building. These findings are consistent with those reported by researchers (Alrasheed & Mourshed, 2023; Drury et al.,2021; Habitzreuter et al, 2020; Mitchell & Natarajan, 2019; Diamond et al., 2019).

5.2 MMC TECHNIQUES SUSCEPTIBLE TO OVERHEATING RISK

The participants were asked which MMC techniques are more likely to bring about high temperatures in buildings. This aims to gather insights from individuals on their experience with techniques they have adopted to help mitigate building overheating, specifically in response to rising temperatures caused by climate change. It is important to know which MMC techniques are more likely to be susceptible to overheating. The interviewees expressed diverse opinions on the susceptibility of techniques to overheating, where three participants, namely P1, P2 and P5, did not agree that any single technique significantly increases a building's likelihood of overheating when compared to other techniques. Moreover, P5 was very assertive that neither the thermal mass nor the energy efficiency of the building or its component can make it susceptible to overheating. Two key themes namely energy efficient buildings and Lightweight materials were derived from participants' response. Moreover, the discourse surrounding the correlation between a building's energy efficiency and its susceptibility to overheating has garnered varied perspectives. While certain researchers, such as Bo et al. (2022) and Fifield et al. (2018), have suggested that highly energy-efficient buildings are prone to overheating, contrasting viewpoints have been presented by scholars like Lomas et al. (2024), who argues that because a building is energy efficient, does not necessarily make the building vulnerable to overheating.

Furthermore, two participants P2 and P6 associated susceptibility to lightweight construction material. P2 pointed out that lightweight construction techniques, such as light steel gauge construction, are particularly vulnerable to overheating due to their inherent characteristics. P6 further pointed out that, unlike heavier materials with greater thermal mass, which can absorb and store heat during the day and release it slowly at night, lightweight materials lack this capacity.

The assertions that lightweight buildings are susceptible to overheat, are corroborated by existing literature, where researchers such as Mavrogianni (CIBSE, 2024) and Milovanović et al. (2022) stated that lightweight buildings are more likely to overheat compared to their heavier counterparts. This susceptibility is attributed to factors such as thermal bridging, which presents challenges in achieving a stable and comfortable indoor environment, necessitating increased energy consumption by heating and cooling systems to effectively regulate temperatures.

5.3 STRENGTHS AND CHALLENGES OF APPROVED DOCUMENT O FOR BUILDING OVERHEATING

To assess the third and fourth objectives of the research, participants were asked about their perceptions on the influence of Document O on design and construction stage of a project. Four participants stated that Document O would have some level of influence on these stages. However, one participant described that the level of influence depends on project location. Finally, the last participant expressed a differing view but provided statements indicating that the design stages are indeed influenced by Document O. Consequently, it can be inferred that the document does impact the design stage.

Three key themes, which include awareness of regulatory requirements, positive health and safety impact, and climate variability, are used to highlight the strength of Approved Document O on building overheating, and the challenges associated with the same.

Regulatory Requirement awareness: The transition of Approved Document O from a mere appendix to a mandatory regulation underscores the government's pivotal role in addressing overheating concerns within the construction industry. This statement was further highlighted by the interviewees who noted that this has compelled stakeholders to consider overheating mitigation strategies at project design stage.

Positive Health and Safety Impact: The interviewees highlighted that raising awareness of overheating among all stakeholders early in a project’s life cycle would reduce the risk to occupants. This factor was highlighted in the CCRA 2022 Report, where it noted that public awareness regarding protective measures during heatwaves is crucial. Therefore, through the adoption of suitable design strategies outlined in the Approved Document O, this risk can be further mitigated.

Regional and Climate Variability: Section 1.1 of the Approved Document O acknowledges regional variability by emphasizing the importance of considering local climatic conditions when assessing overheating risks in buildings. While the influence of regional climate conditions on overheating risks and the efficacy of regulatory frameworks was recognised by P3 and P5, P3 emphasized the importance of continuous refinement and updates to accommodate regional variability and evolving construction techniques. Similarly, P5 highlighted concerns about the document's applicability in low-risk regions and suggested the need for a simpler compliance method tailored to regional climate conditions.

With respect to the challenges of Approved Document O, two themes were determined. Which includes compliance challenges and MMC specific considerations.

Compliance Challenge: Some interviewees expressed concerns about the complexity and stringency of compliance methods outlined in Approved Document O. P4 commended the document's two-tiered approach, which offers simplified compliance checks for

straightforward buildings and dynamic thermal simulation for complex structures. However, the interviewee also noted the challenges associated with dynamic simulation, such as the need for extensive input assumptions, stating, "*if you use dynamic thermal modelling, you have to have an assumption for all these things, because it is a required input into the model*." These observations underscore the need for a balanced approach to compliance that accounts for building complexity while ensuring feasibility and cost-effectiveness.

MMC Specific Considerations: The interviewees had varying opinions on this, with P5 stated that it would not be necessary for Approved Document O to differentiate between traditional and MMC buildings. However, all participants recognized the unique challenges associated with MMC construction. P2 noted that MMC buildings, with their superior airtightness and insulation, may be more prone to overheating due to limited natural ventilation opportunities. P3 echoed these concerns, emphasizing the need for tailored guidelines to address MMC-specific challenges, such as lightweight construction materials and sealed building envelopes.

5.4 RECOMMENDATIONS FOR ENHANCING OVERHEATING MITIGATION STRATEGY IN APPROVED DOCUMENT O

The interviewees were asked to provide recommendations they believed could enhance the effectiveness of Approved Document O in mitigating overheating in modern buildings. From their responses, four key themes were identified, as illustrated in Figure 3 and discussed below.

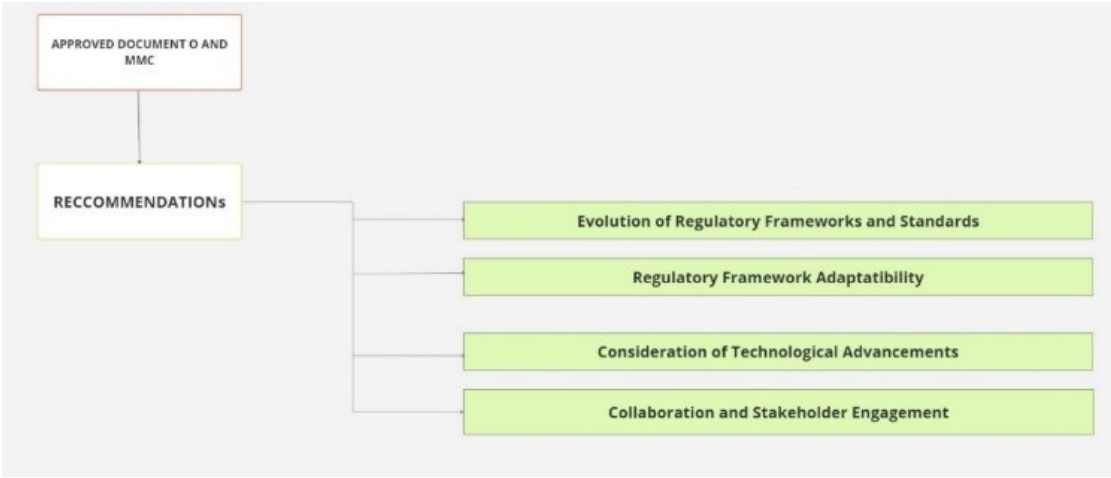


Figure 3: Overview of key themes derived for enhancing Approved Document O.

Evolution of Regulatory Framework and Standard: some interviewees advocated for flexibility and agility in regulatory frameworks to accommodate emerging trends and technologies. Furthermore, P4 highlighted the need to align regulatory frameworks with future climate projections, to create a better understanding for designers.

Regulatory Framework Adaptability: Several interviewees P2, P4 and P5 emphasized the necessity for a regulatory framework to remains consistent across different construction methods. However, they describe the need for specific adaptability consideration for lightweight structure. This emphasizes the importance of adaptability and effectiveness in regulatory standards.

Consideration of Technological Advancement: Some interviewees discussed the need for consideration of technological advancements, such as intelligent MVHR systems, to be included in regulatory frameworks.

Collaboration and Stakeholders Engagement: P6 emphasized the importance of collaboration between industry stakeholders and policymakers for the practical implementation of regulatory frameworks, this interviewee describes the struggles of stakeholders in complying with different aspect of design regulations. This aligns with P3 recommendation for enhanced collaboration to ensure the practical implementation of regulatory measures.

6. CONCLUSIONS

This study evaluated the current regulatory framework and its effectiveness in addressing overheating in buildings, especially those constructed using MMC. It began with reviewing the literature and identifying factors contributing to building overheating. These factors were categorized into climatic, design and construction., and occupancy. Furthermore, overheating mitigation strategies were examined using literature and interviews, revealing the use passive design, green solution and innovative technologies such as MVHR as effective mitigation strategies. The interviewees also highlighted that lightweight construction has a significant risk of overheating due to low thermal mass. Additionally, the assessment of Approved Document O identifying its positive impacts and challenges in terms of compliance, due to large assumptions in the dynamic thermal modelling standard and absence of consideration for MMC buildings. The study also proposed policy enhancements, emphasizing regulatory evolution, technological advancement and stakeholders' collaboration to improve overheating mitigation standards in modern buildings, contributing to occupant wellbeing and economic development. Finally, the research demonstrates the need for a comparative large-scale study between MMC and traditional construction methods to identify any significant differences in overheating risks and mitigation effectiveness, seeking to explore how the Approved Document O has addressed this risk. Limitations of the study include the small sample size of interview participants and the focus on a single regulatory document (Approved Document O). Future research should consider comparative studies across different regions and regulatory frameworks.

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EXAMINING HEALTH AND SAFETY MANAGEMENT AMONG FOREIGN CONTRACTORS IN SRI LANKA: GAPS, BARRIERS, AND IMPROVEMENT STRATEGIES

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ABSTRACT

The construction industry is one of the most hazardous sectors, with frequent workplace accidents and safety violations, particularly in developing economies. Foreign contractors play a crucial role in addressing skill shortages, introducing advanced technologies, and managing large-scale infrastructure projects beyond the capacity of local firms. This study investigates the health and safety (H&S) practices followed by foreign contractors in Sri Lanka, identifying regulatory gaps, implementation challenges, and areas for improvement. A mixed-methods approach was employed, incorporating a questionnaire survey of 40 construction professionals and semi-structured interviews with six foreign contractors. The questionnaire assessed current H&S practices, risk assessments, and regulatory compliance, while the interviews provided in-depth insights into enforcement challenges and managerial perspectives on safety policies. The findings reveal several critical gaps in H&S implementation. While foreign contractors generally maintain structured H&S policies, 28% of surveyed firms lacked formal risk assessment procedures, and 33.3% did not conduct regular safety audits, indicating inconsistencies in compliance. Top management engagement was limited, with some executives participating in safety meetings only monthly. Furthermore, 48% of organizations did not provide structured H&S training, leading to low worker awareness and adherence to safety protocols. Financial constraints emerged as a major barrier, and it effect affecting the procurement of safety equipment, training programs, and site inspections. Additionally, contractual provisions for H&S were found to be inadequate, as many firms lacked strict enforcement mechanisms. This study highlights the need for enhanced policy enforcement, increased safety training, improved communication system, and better financial allocation for H&S programs to improve workplace safety and regulatory compliance in Sri Lanka's construction industry.

Keywords: *Construction Safety; Foreign Contractors; Health and Safety (H&S); Regulatory Compliance; Risk Assessment.*

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1. INTRODUCTION

Ensuring a safe working environment is a fundamental concern for all industries, particularly in sectors where occupational hazards are prevalent (Badri et al., 2018). The construction industry is widely recognized as one of the most hazardous sectors, with high rates of workplace accidents, fatalities, and injuries (Trillo-Cabello et al., 2021). Establishing and maintaining robust health and safety (H&S) measures is crucial not only for safeguarding workers' well-being but also for optimizing workforce efficiency and reducing construction costs (Jannadi & Almishari, 2003). However, implementing safety measures in the construction sector remains a persistent challenge due to the dynamic nature of construction activities, complex work environments, and frequent changes in site conditions (Sousa et al., 2014).

Globally, the construction industry records the highest percentage of work-related accidents, including fatalities and severe injuries (Carrillo-Castrillo et al., 2017). Studies indicate that industrial accidents in construction have both social and economic repercussions, affecting not only project stakeholders but also the overall economy (Rubio et al., 2005). Despite these risks, safety management is often neglected by contractors and project owners, with cost considerations frequently prioritized over H&S compliance (Winge et al., 2019). However, in accordance with Mitchell (1995), safety is directly linked to project costs, as a proactive safety culture reduces financial losses associated with injuries, delays, insurance claims, and legal liabilities.

To mitigate risks and hazards, contractors must implement comprehensive safety measures, including fall protection systems, fire prevention strategies, structured site arrangements, and frequent safety inspections conducted by qualified personnel (Åsgård & Jørgensen, 2019). When safety standards are prioritized, contractors benefit from lower insurance costs, fewer project delays, and increased productivity, ultimately improving profit margins (Sousa et al., 2014). Moreover, a well-structured safety management system leads to higher efficiency, fewer rework incidents, and improved project timelines, ensuring better outcomes for both contractors and clients (Alkaissy et al., 2020).

Clients play a critical role in promoting H&S compliance by ensuring that contractors adhere to strict safety regulations. The inclusion of H&S requirements in construction contracts serves as an effective tool for reinforcing compliance and risk management (Alkaissy et al., 2020). Contractors with robust safety management systems are often more reliable and cost-effective choices, even when their initial bids are higher than competitors with weaker H&S policies (Winge et al., 2019). Weak enforcement of H&S regulations not only elevates risks but also inflates the final cost of construction projects, ultimately impacting the project's overall value (Winge et al., 2019).

Given the high-risk nature of construction, it is critical to investigate why safety measures are often overlooked and how regulatory frameworks can be enhanced to improve H&S standards in the industry. This study aims to address gaps in health and safety practices among foreign contractors operating in Sri Lanka's construction industry by identifying challenges, identifying current safety measures, and proposing a structured framework for improvement.

2. LITERATURE REVIEW

The construction industry is a key driver of economic growth, particularly in developing nations like Sri Lanka (Samaraweera & Gunawardhana, 2020). It provides essential infrastructure while contributing to employment and economic stability (Moavenzadeh, 1978). However, the sector is also one of the most hazardous, with frequent workplace accidents and safety violations (Shafique & Rafiq, 2019).

Construction safety refers to minimizing risks that could lead to injuries, fatalities, or property damage (Sanders et al., 2020). While absolute accident prevention is unrealistic, structured safety management systems can significantly reduce hazards. The involvement of foreign contractors in Sri Lanka's construction sector has introduced new safety standards, but their adaptation to local regulatory and cultural contexts remains a challenge (Oh et al., 2019).

2.1 FOREIGN CONTRACTORS IN SRI LANKAN CONSTRUCTION

Sri Lanka's economy has grown since the end of the war, which has led to more major infrastructure projects. This has made the government more dependent on foreign contractors and foreign workers, especially from Bangladesh, India, and China. According to industry studies, foreign companies particularly Chinese ones are well represented in Sri Lanka's construction industry. For example, the Ceylon Institute of Builders (CIOB) stated in 2018 that almost 40% of all building projects in the nation were carried out by Chinese workers, and they cautioned that this percentage would increase to 70% in the years to come (Oxford Business Group, 2019). The demand for foreign contractors in Sri Lanka has risen due to a shortage of skilled labour, increasing construction costs, and technological limitations (Maqsoom et al., 2014). Large-scale projects such as highways, power plants, and ports often require expertise and funding beyond the capacity of local firms (Jiang, 2020).

This trend is also influenced by global financial institutions such as the Asian Development Bank (ADB). ADB granted a LKR 60 billion loan in 2024 to assist the development of renewable energy and rebuild Sri Lanka's power grid, two projects that usually include foreign contractors (Asian Development Bank, 2024). Stronger economic ties with countries such as China, Qatar, Spain, and Singapore have increased foreign investments in infrastructure projects (Sethi et al., 2019).

Moreover, Foreign contractors bring modern safety practices but integrating them into local regulatory framework poses challenges (Wedagedara & Dissanayake, 2024). Collaboration between local and foreign firms is often necessary to balance international safety standards with local conditions (Bandara et al., 2018).

2.2 COST IMPLICATIONS OF HEALTH AND SAFETY

Occupational safety is not just about preventing injuries but also ensuring workers' physical, mental, and social well-being (Sinyai & Choi, 2020). The dynamic nature of construction projects increases risks, especially in environments with inconsistent safety enforcement (Liao., 2021). Effective health and safety (H&S) policies, including structured safety audits, worker training, and protective equipment are essential for reducing risks (Singh & Misra, 2021).

Construction accidents impose significant financial burdens, including medical costs, legal penalties, project delays, and loss of productivity (Hoła et al., 2017). Weak H&S management increases insurance claims, worker compensation expenses, and contract disputes (Madsen et al., 2020). Studies show that firms either pay for accidents through unexpected costs or invest in structured safety plans to reduce financial risks (Gwimbi et al., 2020). Furthermore, Amissah et al. (2019), explained that investing in risk mitigation strategies, emergency preparedness, and worker training minimizes long-term financial losses. Therefore, safety is not just a legal obligation yet a cost-effective business strategy (Kineber et al., 2023).

2.3 HEALTH AND SAFETY REGULATIONS IN SRI LANKA

While Sri Lanka has legislation to regulate workplace safety, enforcement remains weak, leading to poor compliance (Wedagedara & Dissanayake, 2024). The Factories Ordinance No. 45 of 1942 governs workplace safety but lacks industry-specific enforcement mechanisms for construction (Ministry of Labour and Labour Relations, 2014). Several global safety frameworks, such as the Occupational Safety and Health Act (OSHA, USA, 1970) and the Health and Safety at Work Act (HSWA, UK, 1974), provide structured safety management approaches (Almond & Esbester, 2019). However, Sri Lankan safety laws have been adapted from international frameworks without proper localization, reducing their effectiveness. Strengthening localized safety policies and stricter enforcement mechanisms is necessary for improving workplace safety (Kodur et al., 2020).

Effective H&S management is a core aspect of project success, requiring structured risk assessment, compliance monitoring, and worker engagement (Winge et al., 2019). The construction industry is increasingly integrating safety management into broader project frameworks due to its impact on cost control, productivity, and legal compliance (Kineber et al., 2023). A strong safety culture ensures that contractors focus on accident prevention rather than reactive responses, reducing long-term financial risks and improving site safety (Onukwulu et al., 2024). Safety must be treated as a core component of quality management, integrating project planning, training, and compliance auditing (Hettiarachchi & Coomasaru, 2019).

2.4 CHALLENGES TO MAINTAIN HEALTH AND SAFETY MANAGEMENT AMONG FOREIGN CONTRACTORS IN SRI LANKA

Due to systemic gaps, cultural misalignments, and communication difficulties, foreign contractors in Sri Lanka's construction sector confront a number of health and safety issues. Language barriers frequently make it more difficult to share instructions and conduct efficient safety briefings, which raises the possibility of accidents (Nawarathna et al., 2023; Alamouti, 2017; Weerasinghe & Ekanayake, 2012). Conflicting safety attitudes and a unwillingness to adopt practices like the usage of Personal Protective Equipment (PPE) are caused by cultural differences between foreign and local teams (Nawarathna et al., 2023; Weerasinghe & Ekanayake, 2012). Furthermore, foreign laborers face dangerous jobs and poor living circumstances, while international professionals who are not conversant with Sri Lanka's climate report feeling exhausted and performing worse (Nawarathna et al., 2023; Weerasinghe & Ekanayake, 2012). The appropriate use of safety tools offered by foreign partners is further weakened by local

staff members' lack of technical training. Lastly, unclear policies and uneven enforcement across joint ventures weaken responsibility and make risk management more difficult.

3. RESEARCH METHODOLOGY

The study employed a mixed-methods approach to comprehensively examine construction safety practices in Sri Lanka, combining quantitative data from a structured questionnaire with qualitative insights from semi-structured interviews and literature findings. The research was conducted in three stages: an extensive literature review to identify existing safety standards and gaps, data collection through surveys and interviews with construction professionals and safety experts, and data analysis using statistical and thematic methods. A purposive sampling strategy was used to ensure that participants having the relevant and in-depth knowledge of occupational health and safety in construction sector. For the questionnaire, 40 professionals were chosen based on their direct involvement in construction management, site supervision, or safety control, with representation from both local and foreign-led projects The purpose of this was to guarantee contextual relevance and document a range of real-world events. Participants in the interviews were also chosen based on their specific knowledge of international project coordination, safety rules, and compliance enforcement. Perspectives from individuals who are most knowledgeable about the regulatory challenges and compliance gaps particularly with regard to foreign contractors were to be gathered.

The collected quantitative data were analysed using descriptive statistical methods to identify trends and general patterns, while qualitative semi-structured interview transcripts were analysed using thematic analysis, allowing for the identification of key themes and recurring issues. This triangulated approach ensured a robust and nuanced understanding of the safety landscape, allowing the study to identify practical challenges and propose strategic improvements for enhancing Health and safety compliance within foreign-led construction projects in Sri Lanka.

4. DATA ANALYSIS AND DISCUSSION

The data analysis and the discussion are made while using the data collected through the questionnaire and the interviews. The findings are evaluated in relation to the study's objectives, focusing on health and safety (H&S) practices, regulatory challenges, and areas for improvement in foreign contractor projects in Sri Lanka. A total of 26 responses were received from the questionnaire survey after multiple follow-ups, while six expert interviews were conducted with professionals employed under foreign construction organizations.

4.1 ANALYSIS AND FINDINGS OF THE QUESTIONNAIRE SURVEY

The questionnaire survey was designed to assess the effectiveness of H&S regulations, current industry practices, and compliance levels among construction professionals with regard to the practices of international contractors. The responses provide insights into existing safety management systems, accident prevention measures, and challenges in implementing safety protocols. The collected data serves as a foundation for developing an improved regulatory framework for Sri Lanka's construction industry.

4.1.1 Demographic Information

The demographic section of the survey evaluated participants' professional backgrounds, experience levels, and project involvement. The findings indicate that the respondents represented a diverse cross-section of the construction industry, ensuring a comprehensive perspective on health and safety practices.

An equal number of respondents were employed under local and foreign contractors, allowing for a comparative analysis of safety practices. The majority of professionals (72%) were involved in building construction, while others worked in infrastructure, road construction, and consultancy. The questionnaire was distributed among safety officers, quantity surveyors, project managers, and engineers. The largest group consisted of safety officers and safety managers (38%), reflecting their direct involvement in construction site safety. A significant portion (60%) had less than five years of experience, while 24% had over ten years of experience. This mix ensures that the survey captures perspectives from both early-career and senior professionals. The survey revealed that 76% of professionals held bachelor's degrees, while a smaller group had postgraduate qualifications. Some professionals with diplomas or national certifications had over ten years of experience, highlighting the role of experience in safety management.

4.1.2 Health and Safety Management Practices

The second section of the survey examined H&S policies, safety meeting participation, training, risk assessments, and emergency preparedness. All surveyed organizations, except one local contractor, had internal safety management systems in place. This suggests that most companies recognize the importance of H&S management, although implementation quality may vary. All organizations conducted regular safety meetings, but their frequency varied. The majority (50%) held weekly meetings, while some foreign contractors conducted daily meetings. However, top management attendance was low, with some leaders participating only once a month. The presence of first aid kits was universal, and all organizations mandated the use of personal protective equipment (PPE). However, some professionals noted that workers had to be reminded or compelled to wear PPE, indicating gaps in safety enforcement. All organizations conducted site inspections, but methods varied. Many inspections were still performed using traditional pen-and-paper methods, which may limit efficiency and record-keeping accuracy.

The survey found that most organizations provided insurance policies for workers, except for 8.7% of local firms. The presence of insurance is critical in managing accident-related liabilities. While all foreign contractors employed qualified safety officers, 20% of local contractors did not. This shortage poses a significant risk, as qualified professionals are essential for safety compliance and hazard prevention. The results revealed that 48% of organizations did not provide structured safety training sessions, including 10% of foreign firms. Training is vital for ensuring worker safety, and the lack of training suggests a reactive rather than proactive approach to safety management. The survey showed that 72% of firms conducted risk assessments, while 28% lacked formal risk assessment processes. Without structured assessments, accident prevention efforts remain inadequate. The majority (84%) had emergency rescue plans, but 18% of local contractors did not, whereas all foreign contractors had structured response procedures.

4.2 ANALYSIS AND FINDINGS OF EXPERT INTERVIEWS

Expert interviews were conducted with six professionals currently employed in foreign construction firms, all having over five years of experience in safety management, site supervision, or project management. Given their frontline exposure to construction site safety challenges, their insights help refine the research findings and identify areas for improvement.

4.2.1 Key Challenges Identified

Interviews highlighted several critical issues affecting H&S management in foreign contractor projects in Sri Lanka. Under that, 75% of participants pointed out differences in local regulatory expectations, where foreign contractors resisted aligning their international safety standards with the less strictly enforced local regulations, often resulting in misperception and inconsistent implementation on site. Moreover, interviewees noted that language barriers posed major communication gaps, particularly in conveying safety procedures to local workers, and this was considered risky in high-hazard environments where clear understanding is important to accident prevention.

Further, interviewees were divided on whether contractual terms adequately covered H&S issues. While some professionals believed that existing contracts were sufficient, the majority argued that contracts lacked provisions for proactive safety management, leading to inconsistent enforcement. Most interviewees (83.3%) stated that funds allocated for H&S were insufficient, which negatively impacted the procurement of safety equipment, training programs, and site inspections. The lack of financial commitment to safety remains a major barrier to effective implementation.

Several interviewees were unaware of how often their organizations updated H&S policies, indicating a lack of communication and enforcement. Some stated that updates only occurred when the working environment changed rather than at regular intervals. Project managers, who are responsible for overall site safety, often lack the time or awareness to actively address H&S concerns. This disconnect between project execution and safety planning further weakens compliance. Only 33.3% of foreign firms conducted regular safety audits, while others did not prioritize this practice. Audits are crucial for identifying hazards, tracking compliance, and ensuring continuous improvement.

4.2.2 Strategies to Improve the Safety Management of Foreign Contractors

Based on the findings, a comprehensive framework was proposed to enhance health and safety (H&S) management for foreign contractors operating in Sri Lanka under the project level, organizational level, and the industry and national level. Under the findings, 78% of interviewees highlighted the importance of aligning foreign contractors' safety standards with local regulations through collaborative workshops and regular consultations with authorities. At the same time, 81% highlighted the need to conduct project-specific safety training to fill the practice gaps. To strengthen operational control, delegating H&S responsibilities across all levels of management was recommended, ensuring that safety is converted to a shared obligation. Moreover, 66% of respondents supported the implementation of digital tools for real-time monitoring and real-time coordination of safety compliance. Additionally, provisions must be needfully allocated to cover safety equipment, inspections, and training, as mentioned by 83.3% of participants who cited financial limitations as a challenge to effective H&S management.

The need to engage subcontractors and site workers to build a shared safety culture and enhance communication was also recommended by the interviewees.

Further, their recommendations included the implementation of clear contractual terms and conditions to support a safe working environment and the introduction of route safety training at the beginning of each project. Respondents also emphasized the need to update health and safety policies not only in response to emerging challenges but also whenever organizational procedures change to ensure consistency and relevance.

4.3 PROPOSED FRAMEWORK FOR IMPROVING HEALTH AND SAFETY PRACTICES

Based on the summary of findings by using the data collected through the literature review, a questionnaire and interview to improve the framework for improving Health and safety measures in foreign contractor projects in Sri Lanka is proposed. Figure 1 below, presents the framework.

This framework offers strategies to address the identified challenges faced by the foreign contractors operating in Sri Lanka at three significant levels: project level, organizational level, and industry or national level. At the project level, it proposes practical measures to enhance on-site safety practices, training, and supervision. At the organizational level, it highlights the importance of developing robust safety management systems, promoting leadership commitment, and fostering a safety-oriented work environment. At the industry or national level, it calls for greater regulatory enforcement, standardized safety protocols, and increased collaboration among stakeholders. Mutually, these strategies aim to strengthen the overall safety culture, develop regulatory compliance, and significantly reduce accidents within Sri Lanka's construction industry once they collaboratively work with foreign contractors

Moreover, the framework is particularly applicable to projects involving international construction organizations because it identifies challenges that are specific to Sri Lanka, like the need for improved incorporation of global systems into local workflows, disparities in safety standards and enforcement procedures, and communication and language barriers between local employees and foreign contractors. The foreign contractors can better adjust their operations to Sri Lanka's regulatory and cultural context by implementing practical techniques including policy alignment workshops with national agencies such as CIDA, NIOSH, digital monitoring tools, and multilingual safety briefings.

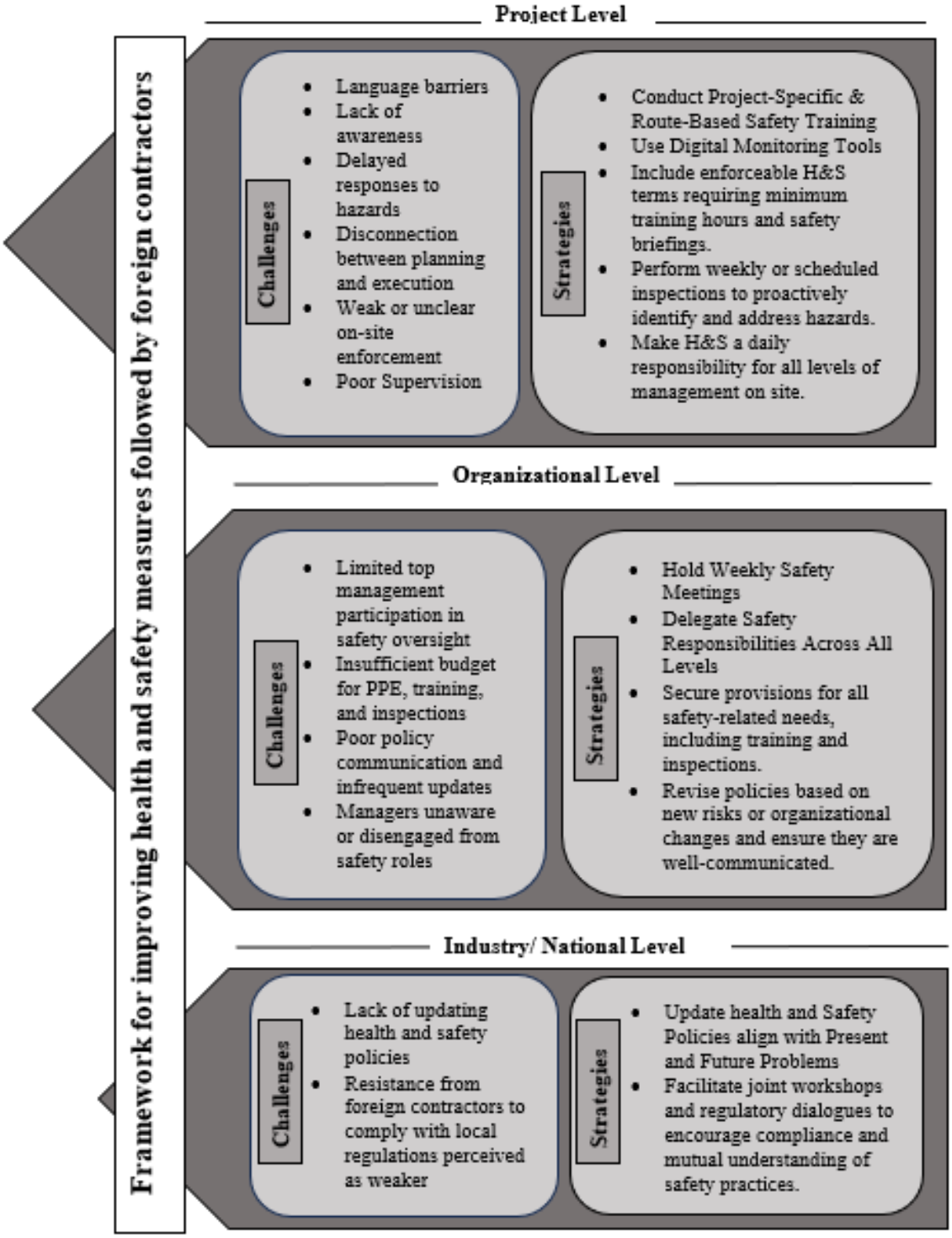


Figure 1: Framework for improving health and safety practices

5. CONCLUSION

The study confirms that foreign contractors generally have structured H&S management systems, with nearly all firms implementing internal safety policies, conducting regular safety meetings, and ensuring the use of personal protective equipment (PPE). However,

gaps remain in risk assessment practices, safety audits, and emergency planning, with 28% of surveyed firms lacking structured risk assessment procedures and 33.3% of foreign firms failing to conduct safety audits. These deficiencies highlight the need for enhanced monitoring and enforcement mechanisms to ensure sustained compliance with safety standards.

A critical issue identified was the low participation of top management in safety-related activities. While 66.7% of professionals reported that all employees attended safety meetings, top management engagement remained limited, with some organizations only involving senior personnel in safety meetings once a month. This lack of leadership involvement contributes to inconsistent enforcement of safety policies and limited investment in long-term safety improvements. The study also found that 48% of firms did not conduct structured H&S training programs, including 10% of foreign firms. Without adequate training, employees are less aware of safety protocols, increasing the likelihood of workplace accidents. The absence of well-defined training frameworks and periodic skill enhancement programs further weakens safety implementation.

Financial constraints emerged as a major barrier to effective H&S management. A significant 83.3% of interviewees indicated that funding allocated to safety measures was inadequate, affecting the procurement of safety equipment, training initiatives, and site inspections. This reflects a broader industry challenge where safety is often deprioritized in favour of cost savings, despite the long-term financial and reputational risks associated with workplace accidents. Another notable finding was the limited awareness of H&S policy updates among construction professionals. While some firms updated their policies based on project requirements, many professionals, particularly at middle management levels, were unaware of policy changes. This disconnect suggests a lack of communication within organizations, reducing the effectiveness of safety interventions.

In terms of regulatory challenges, expert interviews revealed that contractual provisions for H&S compliance are often inadequate. While some contractual clauses address safety requirements, they are not always enforced, leading to inconsistencies in implementation. The absence of strict penalties for non-compliance further weakens the impact of these provisions. Although foreign contractors generally outperform local firms in safety compliance, both groups struggle with systemic regulatory weaknesses. The study highlights that Sri Lanka's regulatory framework lacks stringent enforcement mechanisms, contributing to variable compliance levels across construction projects. While this study provides valuable insights into foreign contractor safety practices, it is limited by its sample size and geographical focus. Future research could expand the scope to include more diverse construction firms and analyze cross-country safety benchmarks.

Overall, the findings underscore the urgent need for strengthened policy enforcement, enhanced training initiatives, and greater management accountability. While some firms demonstrate strong safety practices, addressing the gaps in risk assessments, audits, and financial investment is essential for long-term safety improvements in Sri Lanka's construction sector.

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EXPLORING CIRCULAR BUILDING MATERIAL: TRANSFORMING INDUSTRIAL AND AGRICULTURAL WASTE INTO 3D PRINTABLE CONSTRUCTION MATERIAL

T. Takale[1] and V. Anagal[2]

ABSTRACT

Clothing is one of the basic needs of mankind. The textile industry produces the large amounts of fabric waste threatening the environment and contributes to a significant percentage of non-biodegradable waste. The massive amounts of textile waste dumped in landfills have led to growing environmental issues, which have forced the textile and fashion industry to adopt and practice sustainable waste management and disposal solutions. Recent research has shown that varieties of textile wastes, including pre- and post-consumer, may be treated and used successfully in building operations. This research paper aims to investigate the possibilities of using industrial textile waste and agricultural waste—specifically, textile residues of cotton fabric and cow dung that can be converted into environment friendly building materials. This research was conducted in two phases. The first phase included developing a mix using fabric waste to employ 3D printing technology. The material mix achieved in the first phase of several experiments was 3D printable. However, it was high density material and was unsuitable for light weight construction. The second phase involved to achieve a mix for lightweight blocks by replacing red soil with cow dung. The second phase achieved promising results to achieve lightweight blocks using fabric and cow dung. The findings of this study will help formulate experimentation techniques and methods to develop novel composite as well as sustainable material which could be adopted in the building construction.

Keywords: *3D Printing; Cow-dung; Compressive Strength; Sustainable Blocks; Textile Waste.*

1. INTRODUCTION

In recent decades, the building industry has experienced substantial growth, which has led to a rise in its adverse impact on the environment. Traditional and contemporary building materials consume an enormous amount of energy and virgin material resources in their manufacturing processes. Sustainable Development Goal 12 'Responsible Consumption and Production' aims to address natural resource consumption by promoting sustainable practices across the entire production and consumption cycle (United Nations, 2023). The construction sector needs to adopt sustainable consumption patterns and minimize the resource depletion by maximizing the use of recycled building

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materials. This highlights the importance of innovative building materials in minimizing the use of virgin resources and enabling the reuse of waste generated not only by the construction sector but also by other industries. The use of composite materials in construction has currently had a significant impact on achieving environmental sustainability.

Several researchers have explored different ways to incorporate industrial wastes for manufacture masonry blocks. The industrial wastes such as fly ash, textile effluent treatment plant sludge, polystyrene foam, plastic fibre, rice husk ash, wood sawdust and limestone dust, and processed waste tea have been used in the production of building materials (Mandavgane et al., 2011). To meet the urgent need for environmentally friendly substitutes, this study investigates how industrial and agricultural waste can be converted into environmentally friendly building materials. This innovative approach aims to repurpose waste streams into useful resources to minimize the ecological imprint of construction activities and promote the concepts of the circular economy within the built environment. The findings of this study will help to develop novel composite material which could be adopted in the building construction.

2. LITERATURE REVIEW

Textile waste fibres have potential application in architecture and construction industry. Reusing waste textiles for construction is one of the most durable methods of long-term recycling or prolonging the life cycle of textiles (Nistorac & Loghin, 2023). Previous studies have demonstrated that recycled textile waste can be effectively used as building material. Textile fabrics have multiple applications in construction including thermal insulation panels or blankets, as resistance components such as plates, blocks, or linear elements, or they can be utilised as heat-insulating materials or sound-absorbing materials, or even both (Nistorac & Loghin, 2023).

An increasing amount of investigation on the reuse of textile waste has been conducted in the past decade in the field of research. It is a relatively new endeavour, as the first study on the use of textile waste for construction materials was published in 2003. Since 2012, there has been a rise in interest in textile construction materials, and since 2014 a significant amount of experimental data has been released (Rubino et al., 2018). Numerous studies have been published that demonstrate how recycling textile waste materials to make new composites can address the construction industry from three angles: it reduces the environmental impact of construction, enhances some of the fundamental qualities of the composites, and lowers the cost of manufacturing (Nistorac & Loghin, 2023). Textile waste has been recycled for a variety of purposes, such as making low-grade wires, crushing it to make materials that insulate against noise and temperature changes, and using it as a filler or reinforcement for concrete (Pichardo et al., 2017).

Both the scientific community and the building industry are very interested in the fibre- and textile-reinforced mortars. These composite materials can consist of a variety of reinforcement elements, such as long or short fibres, and textiles, including woven and nonwoven fabrics, all enclosed in a cementitious matrix that can take the shape of mortar, cement paste, lime binder, or concrete. Reinforcement is primarily used to fill up cracks and improve the strength, energy absorption ability, and post-cracking behaviour of cementitious composites (Nistorac & Loghin, 2023). Cotton, one of the most widely used

natural textile fibres, is the material that goes into making blue denim jeans, the most popular article of apparel in the world. Another method for reusing textile waste is to add 16% staple cotton fibres made from denim waste to a polypropylene matrix. In experimental research, Nistorac & Loghin (2023) performed tensile and fatigue strength tests on the composites that were produced during the injection procedure in order to characterise their morphology. When compared to the pure polypropylene variant, sixty percent better outcomes were achieved. The mechanical behaviour of polymer concrete containing textile residues was investigated. The results showed that the flexural strength of polymer concrete decreases with increasing fibre concentration. However, the flexural strength values were higher than those of cement concrete (Nistorac & Loghin, 2023).

In recent years, researchers in the field of building materials have focused on using solid waste from agricultural goods as pozzolans in the production of blended mortars and concrete. Nowadays, it's common practice to add ashes from burning agricultural solid waste to concrete because of the ashes' pozzolanic action toward lime. The ash produced by burning solid waste from sugar cane is one of the most intriguing materials (Chi, 2012; Yalley & Bentle, 2009). With limited success, numerous initiatives have been undertaken to lower the growing cost of cement manufacture in developing countries. In order to create sustainable material, the construction industry must look for alternatives to traditional virgin material and give careful thought to using agricultural and industrial waste as raw materials to develop innovative construction materials. The organic matter that makes up cow dung includes fibrous material that has passed through the digestive tract of the cow as well as other liquid digestive waste that remains after fermentation, absorption, and filtration, is acidified, and is subsequently reabsorbed. The chemical composition of cow dung is cellulose, lignin, hemicellulose, salts, cells that were shed as the digester passed through the digestive tract, some urea, mucus, and other elements like carbon, nitrogen, hydrogen, oxygen, phosphorus, etc. (Magudeaswaran & Hilal, 2018). According to estimates, a cow generates 10–15 kilograms excrement per day. The cow dung emits methane gas at the rate of 40 litres per kg which accounts for huge emission of greenhouse gas in agrarian-based country like India. According to a recent assessment from the United Nations Environment Programme (UNEP) and the climate and the clean air coalition found that methane emission would be a key in the battle against climate change. Over a 20-year period, methane is 80 times more effective at warming than carbon dioxide, and it causes one million premature deaths annually. Using cow dung for manure or building purpose is an efficient way to convert waste into usable form (Sutar & Patil, 2024).

Most of the existing literature on the use of textile waste in masonry blocks focuses on incorporating it with cement as the binding material. However, studies involving the combination of textile waste with soil for 3D printing or with cow dung as a binder are largely absent. This research bridges that gap by exploring the integration of textile waste with alternative, more sustainable materials. In doing so, it contributes to the development of circular construction practices and promotes innovative approaches to material reuse.

3. MATERIALS AND METHODOLOGY

This research involves exploratory experimental study carried out in two phases. The first phase explores the application of 3D printing technology to produce the construction component using textile residues, river sand, and red soil. Since 3D printing allows for accurate material consumption and waste reduction, it is a sustainable alternative to

traditional construction processes. As this is an exploratory research, based on the findings of experiments in the stage one, the variations in the materials and mix design for developing masonry blocks were made and experiments were carried out to achieve lightweight mix design for masonry blocks. The second phase produces new masonry blocks using textile residue, cow dung powder, lime and natural rubber latex (NRL).

3.1 PHASE ONE: 3D PRINTED FABRIC MUD BLOCK

3.1.1 Materials Used in Phase 1



(a) *(b)* *(c)*

Figure 1: Material- (a) initially collected textile waste and shredded cotton fibre; (b) red soil; (c) river sand

Textile Waste

Different types of textile wastes including leftover fabric of stitched cloths, old cloths, etc., were collected initially but due to non-availability of shredding machine the shredded cotton fibres were purchased. Textile waste provides tensile strength and improves thermal insulation properties [See figure-1(a)].

Red Soil

The red soil used for experiment was procured from the nearest plant nursery. As it was rainy season, the soil was wet at the time of collection. Since the experiment required the use of fine coarse-textured soil, it was spread out to dry naturally for 2-3 days. After drying, it was thoroughly sieved to remove large stones, organic matter and other unwanted particles [See figure-1(b)].

River Sand

River sand was bought from one of the nearest construction of the college. It provides bulk to the mud mixture, making the brick larger. Natural sand or river sand constitutes as major fine aggregate in cementitious construction. Especially, masonry block production requires 70–90% sand as raw material (Sundaralingam et al., 2022) [See figure- 1(c)].

3.1.2 Methodology of Experiments in Phase 1:

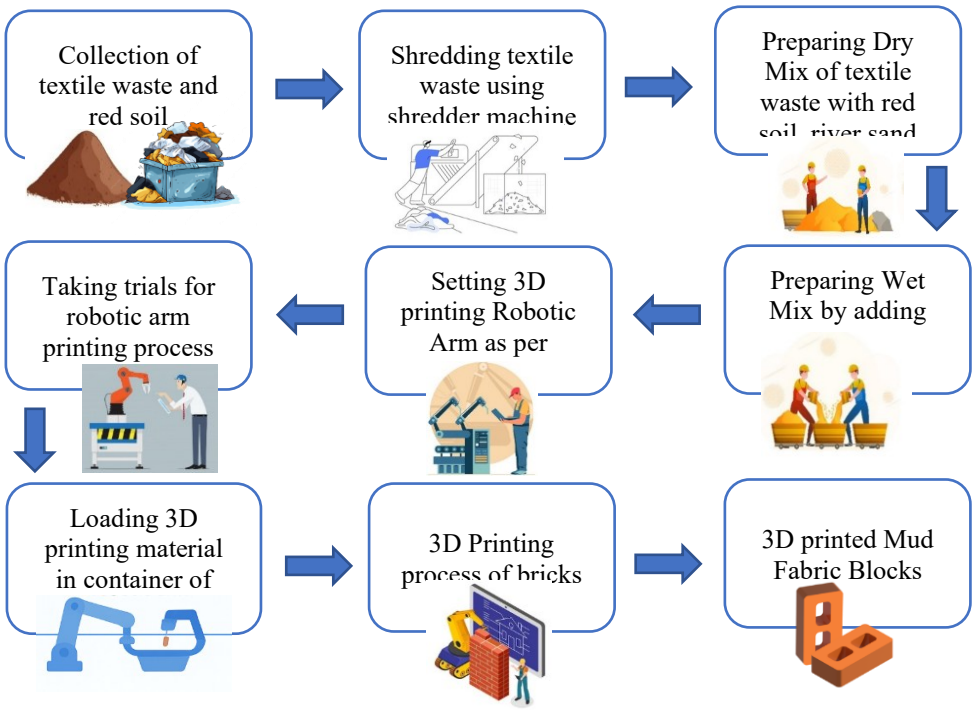


Figure 2: Process of 3D printed fabric mud block

This phase involved developing a mix design for 3D printing of masonry blocks as shown in figure 2. Initially 2-3 experiments were carried out to understand how shredded cotton needs to be used and to get the correct mix design proportions. These experiments were carried out with a household kitchen utensil which can squeeze the material into curvilinear form and had mechanism similar to the 3D printing robotic arm (See figure 3). Table 1 gives the design mix proportions in percentage for the initial experiments carried out with textile waste, red soil and river sand. The first experiment was carried out with mix-1 proportions, but the experiment failed as the cotton fibres were getting stuck through the machine. The failures of experiment 1 was due to long length of cotton strands which got stuck in hole. Taking observations from first experiment, the second experiment used cotton waste that was cut into small pieces of 1-0.5 cm so that the fabric does not get stuck in the machine. And second experiment was carried out by using design mix 2 and it became successful as the cotton waste got blended with mixture which made the mix easily applicable through machine.



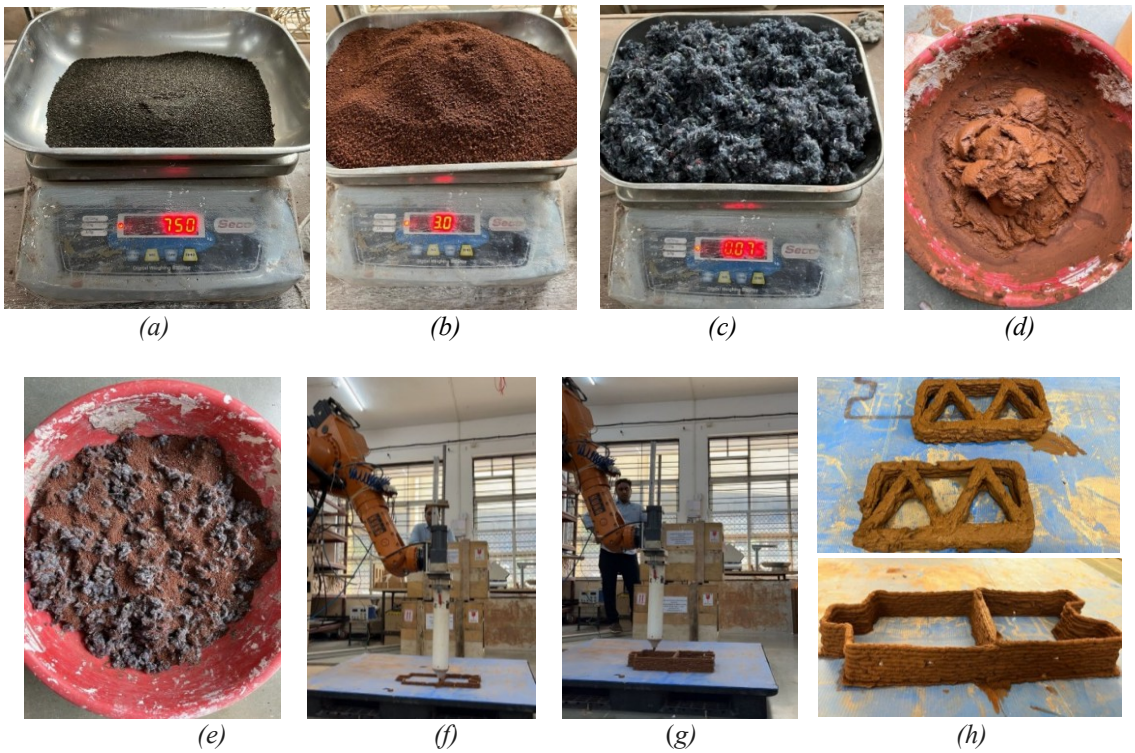
(a) *(b)* *(c)*

Figure 3: (a) preparing design mix; (b) filling design mix in machine; (c)3d printing block sample

Table 1: Design mix proportion in percentage for initial experiments of 3D printed fabric blocks.

Sr. No.	Material	Mix 1	Mix 2
1	Fabric waste	1	1.9
2	Red soil	90	78.4
3	River sand	9	19.7

After getting the right proportions of the mix, the experiment was carried out using the KUKA KR 30 robot. The design mix proportion consisted of 1.9% fabric waste, 78.4% red soil, and 19.7% river sand. A large design mix was prepared and tested with 3D printing robotic arm (See figure 4). The soil was sun dried to remove the moisture and passed through sieve number 20. The sand too was sun-dried and was passed through sieve number 20. The cotton fabric was cut to smaller lengths and was fibres were separated by hand. The material was weighed and mixed in the dry state. 1.5 litres of water was added to get the desired consistency for 3D printing. The material was mixed thoroughly with hand mixing process. The different types of drawings or scripts were produced to print the mud block with the help of computer aided design software's like rhino and grasshopper. The 3D printing process of the block required 30 minutes to print the block employing KUKA KR 30 robot. The process of experiment is illustrated in figure 4.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 4: (a) 75 gm of cotton fabric; (b) 3kg red soil; (c) 750 gm of river sand; (d) Dry design mix; (e) Wet design mix; (f) & (g) 3D Printing through KUKA KR 30; (h) 3D printed fabric-mud block

3.1.3. Discussion and Findings of Phase 1 Experiments

After conducting 3D printing experiment using a composite mixture of textile waste, red soil, and river sand, it was concluded that the textile waste is indeed 3D printable along

with red soil and suitable for other 3D printing applications like façade design. The material exhibited good consistency; however, there was need to improve the design mix cohesiveness for enhancing the 3D printing quality and mechanical performance.

Since this was an exploratory study aimed at developing a 3D-printable material, the primary focus at this stage was not on testing compressive strength. Instead, the research concentrated on examining the physical properties of the material, such as consistency, surface finish, adhesive behaviour during mixing and printing, as well as the weight and density of the printed blocks. In each experimental phase, only three blocks were produced for initial observation and basic testing. Of these, the first block was tested for compressive strength, the second for water absorption, and the third was retained for assessing surface finish and comparing design mixes.

To understand the compressive strength of material, a hollow block of dimension 300x200x150 mm was casted using a customized deign mould (See Figure 5). This casted block was naturally air-dried, baked at 300-degree temperature for one hour and was kept under shaded area for cooling to enhance its structural integrity. The compressive strength of this baked hollow block was recorded 0.34 N/mm² and the density of the same block was 863 kg/m³. Additionally, a water absorption test was carried out, obtaining a 12.5% result which indicates moderate prosperity.

Further testing involved casting a solid block of dimensions 150x150x150 mm using the same design mix. This block generated a higher compressive strength of approximately 0.91 N/ mm² as it was a solid block (See Figure 6). The density for this solid block was 1396 kg/m³ which was much higher than hollow block. The compressive strength testing of both the blocks was carried out using IS: 3495, Part-I 1992 where the block sample was compressed perpendicularly to the direction of casting. The load was applied without shock and was increased continuously at a constant rate of 14 N/mm²/min until no greater load could be sustained. The water absorption test was carried out using IS: 3495, Part-II 1992 where the sample was immersed in clean water at a temperature of 27 ± 2°C for 24 hours.

The compressive strength of both blocks was much lower than the minimum requirement specified in the IS: 1725, 1982. IS: 1725, 1982 recommends minimum compressive strength of 1.961 N/mm² and 2.942 N/mm² for soil-based blocks used in general building construction for Class 20 and Class 30.



(a) *(b)* *(c)* *(d)*

Figure 5: (a) customized mould design; (b) hollow block casted in mould; (c) block kept for sun drying; (d) compressive strength testing of block



(a) (b) (c) (d)

Figure 6: (a) mould design; (b) solid block casted in mould; (c) block kept for sun drying; (d) compressive strength testing of solid block

3.2 PHASE TWO: FABRIC COW DUNG BLOCKS

3.2.1 Materials Used for Phase 2 Experiments



(a) (b)



(c) (d) (e)

Figure 7: (a) cow dung powder; (b) textile waste; (c) lime powder; (d)Natural Rubber Latex (NRL); (e) Natural Rubber Latex (NRL) mixed with water

Cow Dung

Cow dung powder was used as the basic raw material for making blocks received from Godhan Foundation Pune. Cow dung is wealthy in minerals like Potassium, Magnesium, Sodium and Manganese and is created from natural matters. Cow dung improves workability and mould ability of mixture [See figure- 7(a)].

Textile Waste

Different types of textile wastes including leftover fabric of stitched cloths, old cloths, etc., were collected initially but due to non-availability of shredding machine the shredded cotton fibres were purchased. Textile waste provides tensile strength and improves thermal insulation properties [See figure- 7(b)].

Lime

Lime was ordered from the chemical company in Pimpri Chinchwad Pune. It is a calcium-containing inorganic mineral composed on the whole of oxides, and hydroxide, commonly calcium oxide or calcium hydroxide. Lime acts as a stabilizer to strengthen the block. It also reduces shrinkage and cracking during drying [See figure- 7(c)].

Natural Rubber Latex

It was ordered from the chemical company located at Delhi. Natural Rubber Latex (NRL) is an agricultural-based natural polymer. Natural rubber latex (NRL) is an agricultural-based natural polymer extracted directly from heveabrasiliensis (rubber tree). India being the sixth-largest producer of rubber worldwide, availability of NRL can be relied upon for making soil–cement blocks. Beneficial properties of NRL which supports soil stabilization are, miscibility with water before coagulation of latex, immiscibility after coagulation, elastomeric property, non-toxicity, compatibility with various soils and high melting point (180 °C) (Jose & Kasthurba, 2021) [See figure- 7(d)].

3.2.2 Methodology of Experiments in Phase 2:

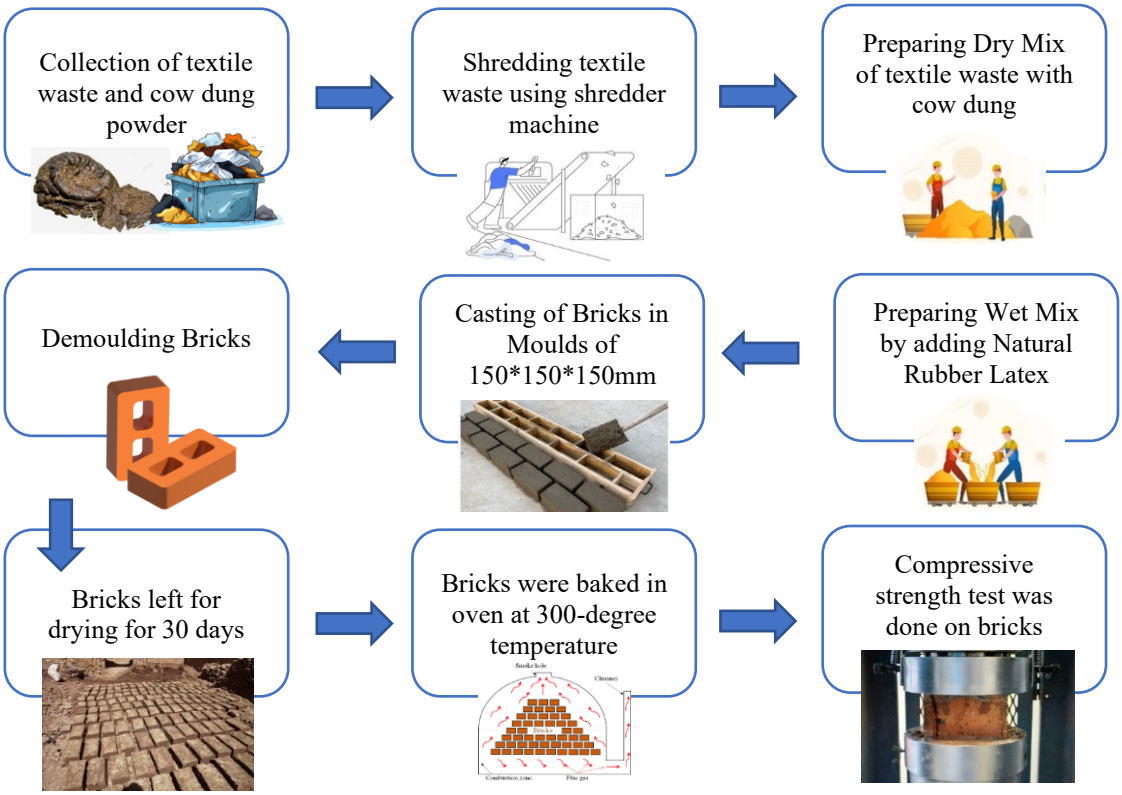


Figure 8: Process of manufacturing cow-dung fabric mud block

To address limitations identified after 3D printing experiment – specifically the low compressive strength and the excessive weight of the masonry block, a new design mix was developed along with some new materials. The primary objective was to achieve the lightweight masonry block and achieve the compressive strength in accordance with the IS codes specifications.

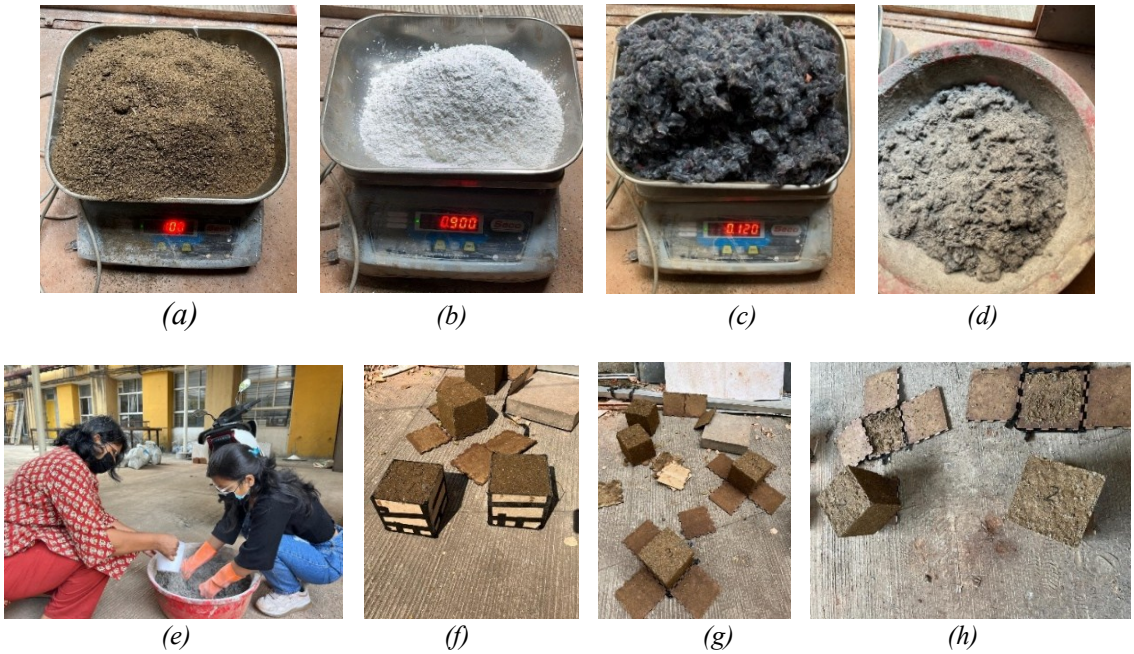
To improve the blocks mechanical properties, particularly compressive strength, there was need to use the natural adhesive. In the modified design mix, red soil was replaced

by cow dung to reduce the weight of the block, and the river sand was replaced by the lime, to reduce the weight, improve the bonding without compromising the compressive strength of the block. Furthermore, the Natural Rubber Latex was used as a biodegradable natural adhesive to improve the bonding of materials and strength of the composite material. In this phase, the experiment involved various steps as illustrated in Figure 8. Including collection of materials to casting blocks to conducting the tests to check the compressive strength of the blocks.

The process of manufacturing cow dung blocks from cow dung dry powder and textile waste involved preparation of design mix, molding, sun drying and baking of blocks. The dry design mix of cow dung powder, textile waste fibers, and lime powder was prepared and was mixed thoroughly for 10-15 min through hands. The NRL mixed was then mixed with five liters of water to the dry mix to get the required constancy of the material to cast the blocks. The blocks were casted into 150x150x150 mm size of the molds. The blocks were kept for drying around 30 days and were baked in oven at 300-degree temperature for 30 min. Table 2 indicates the new design mix proportions in percentage of cow dung, lime, textile waste fabric and natural rubber latex, the density of the blocks and their compressive strengths. Within the three design mixes prepared for the experimentation, the percentage of textile fabric waste and natural rubber latex which acts as binder were kept constant and the proportion of cow dung to lime changed in each mix by weight to evaluate the impact of cow dung on the density of the blocks and the compressive strength.

Table 2: Design mix proportion in percentage for cow dung fabric blocks.

Sr. No.	Material	Mix 1	Mix 2	Mix 3
1	Cow dung	56	61	66
2	Lime	30	25	20
3	Fabric	4	4	4
4	Latex	10	10	10



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 9: preparing design mix as per proportions: (a) cow- dung powder; (b)lime powder; (c) textile waste; (d) dry mix: (e) Adding NRL to dry mix; (f) casted cow-dung fabric block; (g) demoulding blocks; (h) drying blocks under sunlight for 30 days

3.2.3 Discussion and Findings of Experiments in Phase 2

The second phase of experimental research focused on using a modified design mix containing cow-dung, fabric waste, lime, and natural rubber latex, to develop a lightweight sustainable masonry block. The results confirmed that the textile waste, particularly shredded cotton can be combined with cow dung to produce masonry bocks.

Three design mixes mentioned in Table 2., were tested, each mix produced a solid block of dimensions 150x150x150 mm. A significant observation was noted across all three mixes that there was substantial weight reduction in blocks, with the blocks weighing 1.6 kg, 1.6 kg and 1.4 kg respectively. This reduction in weight of block reflected a decrease in material density compared to the first red soil masonry solid blocks.

However, the compressive strength tests achieved by these mixes were 0.23 N/ mm², 0.31 N/ mm² and 0.17 N/ mm² respectively as indicated in Table 3. The compressive strength testing of the blocks was carried out using IS: 3495, Part-I 1992 where the block sample was compressed perpendicularly to the direction of casting. The load was applied without shock and was increased continuously at a constant rate of 14 N/mm²/min until no greater load could be sustained. These low compressive strength values were below the minimum requirement of the IS: 1725, 1982 for the soil-based blocks. Hence, it was concluded that the complete replacement of red soil is not feasible for achieving the mechanical and structural integrity of the blocks.

Additionally, due to the use of cow dung powder, fungal growth on the surfaces of each block was observed on all three masonry blocks. Mix 2 exhibited the highest fungal growth due to prolonged wet surface exposure, followed by Mix 1. Mix 3 showed minimal presence of fungus. This outcome highlighted that there is need for pre-treatment of cow dung powder to improve the durability, minimize hydrophilic properties and improve the surface finish of the product. Fungal growth may be attributed to the weather

conditions as the experiments were conducted in rainy seasons and the blocks took a longer duration for drying.

Table 3: Test results for cow dung fabric blocks.

Sr. No.	Description	Age	Block size in mm (lxbxh)	Weight (kg)	Density (kg/m3)	Load (kN)	Compressive strength (N/mm^2)
1	Mix 1	30 days	150x143x150	1.69	514.29	5.0	0.23
2	Mix 2	30 days	150x148x150	1.60	502.84	6.9	0.31
3	Mix 3	30 days	150x142x148	1.45	455.61	3.6	0.17

4. CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

The first phase of this experimental research aimed to develop an innovative method for utilizing textile waste as a raw material for 3D printing mud blocks. The experiment confirmed that textile waste, particularly shredded cotton is compatible with red soil and river sand for 3D printing applications. The designed mixture demonstrated acceptable consistency; however, further improvement in the cohesiveness of the mix was required. One significant finding was that the textile waste, when shredded into small pieces of size between 5 mm to 10mm, resulted in a more uniform mixture. This research was successfully executed and represented a promising innovation that not only addresses the environmental impacts of conventional construction but also offers a solution to the textile industry's waste management challenges. As with all experimental research, challenges were encountered and had to be addressed. These included achieving the right consistency of the mix, ensuring the quality and uniform size of the recycled fabric fibres, and working within the limitations of the 3D printer's barrel, which had a capacity of only 3 kg. These constraints made it necessary to print a single block in two parts, thereby complicating the testing of compressive strength. Recognizing and responding to these limitations was essential for the effective execution of the research.

In the second phase of the research, an attempt was made to reduce the weight of the blocks by replacing red soil with cow dung powder and sand with lime. The cow dung formed a bond with the textile fibres when combined with lime and latex as natural binders. However, the compressive strength achieved in both phases of the experiment did not meet the standards specified in the IS code 1725, 1982 specification for soil-based blocks used in general building construction. Another major challenge in assessing the applicability of these non-conventional materials is the absence of an Indian Standard Code for sun-dried cow dung blocks. With the growing emphasis on circular construction practices aimed at reducing resource consumption, there is a clear need to develop Indian Standard Codes for alternative building materials. In both experimental phases, it became evident that micro-mixing of materials cannot be achieved through manual mixing. A mechanized mixing process is therefore essential to ensure the uniform dispersion and bonding of materials, which would improve both the mechanical performance and biological stability of the blocks.

To address the key challenges identified such as low compressive strength, excessive weight in earlier blocks, and fungal growth due to cow dung powder, a revised approach will be adopted for future research. The next phase of the research involves combining red soil with fresh cow dung and eliminating the use of cow dung powder entirely. This modification is expected to enhance the bonding characteristics, mechanical strength, and overall durability of the 3D-printed blocks. This research contributes towards the development of construction materials using industrial waste enhancing circularity in the construction industry minimizing resource consumption and depletion.

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EXPLORING PERCEPTUAL MAPPING TECHNIQUE AS AN INNOVATIVE METHOD OF REPRESENTING CONSTRUCTION COST INFORMATION

D.N.L.S. Uduwage[1], Himal Suranga Jayasena[2] and S. Piranavan[3]

ABSTRACT

Effective representation of cost information is crucial for decision-making. While traditional methods like Bills of Quantities provide essential details, their format can pose challenges for swift interpretation and comparison. This study explores perceptual mapping as an innovative complementary tool to enhance the representation of construction cost information. Adopting a qualitative methodology, data were gathered via semi-structured interviews with 16 experienced professionals comprising clients, Architects, Quantity Surveyors, Engineers in the Sri Lankan construction industry. Thematic analysis identified key insights into the applicability and benefits of perceptual mapping. The findings indicate that perceptual maps, when used in conjunction with detailed reports, significantly enhance cost data visualisation, facilitating quicker comparisons and improving decision-making efficiency. Participants recognised their value in overcoming the usability limitations of conventional formats. The study concludes that perceptual maps offer a powerful enhancement to traditional documentation by providing a clear comparative overview. This provides a clear comparative overview with notable implications for practical decision support and the theoretical understanding of information visualisation in the sector, especially when integrated with traditional documentation.

Keywords: *Construction; Cost Visualisation; Decision Support; Perceptual Mapping; Stakeholder Communication.*

1. INTRODUCTION

The construction industry is unique and complex and involves diverse stakeholders with varied project interests (Ebekozien et al., 2024). Stakeholder engagement depends heavily on the information produced and the value of their inputs during project execution. Among these, cost information is crucial for cost optimisation and effective decision-making (Safaa Eldin et al., 2024). Robson et al. (2016) emphasized the importance of cost information in addressing parties' concerns in construction. Thus, representing cost

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information understandably to various stakeholders is a vital aspect of construction projects.

The impact of cost information differs among parties; for instance, a contractor's unforeseen profit might be a client's loss. Each party's understanding depends on their role-specific information requirements (Campbell, Viza & Arnaudova, 2023). This varied interpretation is linked to mental or cognitive representations (Schack & Frank, 2021). Individuals uniquely attend to, grasp, and interpret information (Moskowitz & Gill, 2013), necessitating more attention to how cost information is represented.

Even though the preliminary and pre-tender estimates provide comprehensive cost information, the lengthy tabular presentation at times challenges swift comparison of different design options. Stakeholders, especially those without or with less technical training, find it challenging to understand the connections between design options and their impact on costs, time and performance (Love et al., 2013). This gap can slow down decision-making.

Perceptual mapping is a visual technique for comparing multi-dimensional attributes by displaying relative information from different individual standpoints (Gigauri, 2019). The technique works by having people rate items based on key attributes; these ratings are then plotted graphically to create a map that visually represents the items' perceived relationships (Gower et al., 2010). This visual representation of objects, often termed multi-dimensional scaling, aids decision-making with finer detailing and is commonly used in marketing for brand positioning (Chipoco, 2016; Gigauri, 2019). Similarly, perceptual maps in construction projects could be used for decision making based on different attributes and variables. Hence, this technique could also appropriately represent construction cost information in varied perceptions with minor detailing for successful project delivery.

Construction cost information is crucial for estimating, planning, designing, and forecasting (Rodrigues et al., 2022). Bills of Quantities (BOQ) are the most common representation, offering a general idea about construction costs, analysis, comparison, estimation, supporting bank loans, progress measurement, and tendering (Abdullahi et al., 2021). However, newer software tools for cost information incorporate Building Information Modelling (BIM). BIM represents the current industry benchmark for digital cost integration. It provides the context for many innovative approaches. BIM digitally represents a building, integrating all information types and facilitating multi-party collaboration. Discussions on 5D BIM (cost dimension) are widespread, with research extending to blockchain and digital twin technologies (Apinayan et al., 2023). This highlights the need to focus on innovative cost information representation for stakeholder benefits. Perceptual mapping is one such technique, offering multi-dimensional perceptual information on project costs relative to key comparison factors.

This study, therefore, aims to explore perceptual mapping as an effective tool to enhance traditional methods of cost information representation. The objectives are:

1. Identify the challenges stakeholders face when making swift, multi-attribute comparisons in existing cost representation methods
2. Examine the applicability of perceptual mapping technique to represent cost information
3. Analyse the benefits of integrating perceptual mapping in current documentation and technological trends.

2. LITERATURE REVIEW

This section reviews the literature on cost information representation, its issues, and the applicability of the perceptual mapping technique to construction.

2.1 EXISTING COST INFORMATION REPRESENTATION TECHNIQUES

2.1.1 Construction Cost Information

Construction is inherently uncertain, primarily due to time, cost, and quality interdependencies (Ekung et al., 2021). The cost factor is crucial for project success, particularly in addressing uncertainties (Adedokun et al., 2019). Understanding and managing cost information enhances project delivery effectiveness and predictability. Construction involves numerous parties whose roles, expectations, and contributions underscore the importance of cost information (Wang & Qiao, 2024). Cost information requirements vary in type and format throughout the project lifecycle, depending on the context and decision-making needs. Consequently, the industry has employed various representation methods for effective cost management (Gómez-Cabrera et al., 2023).

2.1.2 Cost Information Representation Methods

Historically, BOQs have been the most common cost representation method (Razali et al., 2016), evolving into a standardised tabular format. Construction parties have adapted to BOQs, with standardisation playing a role (Luyue et al., 2022). Razali et al. (2016) noted a consistent format for all parties, with information extracted for specific purposes. However, issues exist in accessing, understanding, and interpreting cost information from different perspectives, suggesting that BOQs are only one option among other potentially effective methods (Zheng et al., 2023).

Multiple cost information requirements arise at different project stages. Cost planning determines project budgets through pre-contract estimates, with BOQs as detailed outputs in later stages (Ebekozien & Aigbavboa, 2024). Other formats include bar graphs, S-curves, cost-to-complete reports, and feasibility studies, often presenting static information from a single viewpoint. BIM offers multi-dimensional modelling, incorporating cost alongside other dimensions (Sepasgozar et al., 2022). Innovative technologies such as dashboards (Gara et al., 2021), Augmented Reality (AR) (Senanayake et al., 2023), and Virtual Reality (VR) (Lee et al., 2022) are expanding communication possibilities. Thus, cost information is represented in multiple ways: tables, texts, graphs, and dashboards.

2.1.3 Innovative Representation Methods

"A mental representation is a system of symbols isomorphic to some aspect of the environment, used to make behaviour-generating decisions that anticipate events and relations in that environment" (Gallistel, 2001, p. 1). Different individuals visualise information from varied perspectives (Hebart et al., 2020). For instance, "car" evokes diverse images (Ferrari, red car, roofless car) based on an individual's history, education, experience, and other influencing factors (Luyue et al., 2022). As a psychological process, a better understanding of mental representation offers clearer perspectives (Luyue et al., 2022), connecting thinking with concept usage (Hebart et al., 2020). This underscores the need for diverse cost information representation methods to cater to the interests of different construction parties.

2.2 PERCEPTUAL MAPPING TECHNIQUE AS A COST INFORMATION REPRESENTATION METHOD

2.2.1 Perceptual Mapping Technique

Perceptual mapping, popular in marketing, compares multi-dimensional attributes from different perceptions (Gigauri, 2019). It aids comparative analysis, maps benefits, complex relationships, and the relative positioning of information (Gigauri, 2019). Applications include brand positioning, product benefit mapping, and comparative decision-making for grouping options. Najafizadeh (2012) noted its utility in displaying options relative to individual perceptions, typically using two dimensions but extendable to more. Mapping involves rating against predetermined attributes and plotting these values graphically. Figure 2 shows a multi-dimensional scaling map of beer brands based on attributes like "Heavy," "Light," and characteristics like "Popular with men". This visual placement aids selection based on varied criteria. Similarly, perceptual maps can support construction-based, cost-focused decision-making.

Figure 1 illustrates a perceptual map comparing different ceiling materials based on "Cost" and "Durability". The Timber ceiling is shown as "High Cost" and "High Durability," while the Gypsum Frame ceiling is "Low Cost" and "High Durability". The degree of durability is indicated by the dot's proximity to the attribute; thus, timber is more durable than gypsum. This exemplifies how perceptual maps can facilitate decision-making.

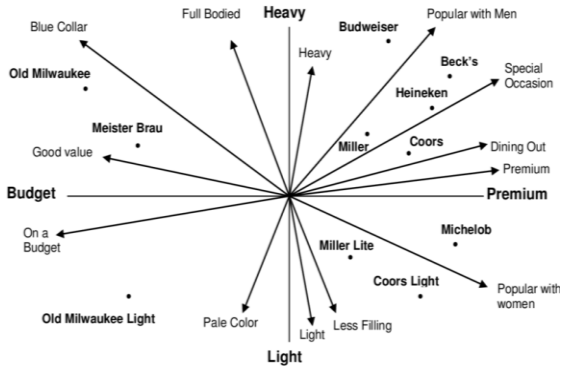


Figure 1: Perceptual Map Example 1
Source: (Cornelius et al., 2010)

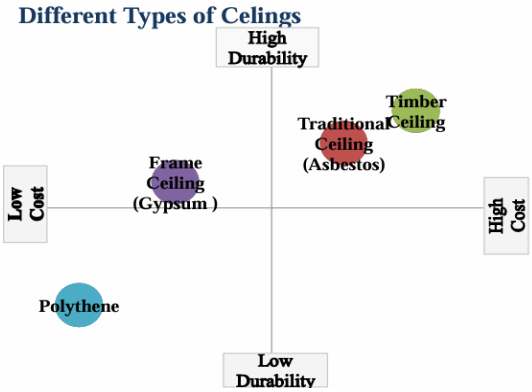


Figure 2: Perceptual Map Example 2

2.2.2 Utilizing Perceptual Maps

Perceptual maps are powerful analytical tools for comparing alternatives against defined characteristics, as seen in the ceiling type example (Figure 1). They eliminate the need to go through individual data elements for each alternative by presenting all options and their significant attributes in one diagram. Psychologically, perceptual mapping graphically interprets the mental representation of an item in the human mind. Communication to non-technical users is more comfortable with shorter reaction times, as observed in marketing.

3. RESEARCH METHODOLOGY

The research approach is interpretivism, focusing on human experiences and phenomena (William, 2024). Cost information and opinions on its representation are subjective,

warranting a qualitative methodology to interpret and generalise emergent patterns from individual experiences.

The research process began with a literature review on cost information representation and perceptual mapping. Data collection used semi-structured interviews with experts, suitable for extracting relevant information aligned with the research objectives (Saunders et al., 2019). Qualitative saturation typically occurs between nine and seventeen interviews (Hennink & Kaiser, 2022). Twenty professionals were selected via purposive sampling based on their experience, profession, designation, and experience with cost information in multiple contexts. All selected professionals were practicing in the Sri Lankan construction sector, where Bills of Quantities are standard and the norm for cost management. Accordingly, all interviewees possessed a high degree of familiarity with BOQs. Sixteen interviews were conducted, confirming data saturation. Interviews followed a guideline with spontaneous questions to maintain objective alignment. A perceptual map developed from a conventional report on partition wall material costs was tested with the interviewees. Table 1 presents the profiles of the interviewees.

Table 1: Profile of Interviewees

Professional category	Respondent No.	Area of expertise	Experience (Years)
Client	C01	Developer	18
	C02	Developer	15
	C03	Developer	12
	C04	Developer	18
Architect	A01	Senior Architect	31
	A02	Architect	12
	A03	Senior Architect	32
	A04	Senior Architect	22
Quantity Surveyor	QS01	Senior Quantity Surveyor	15
	QS02	Senior Quantity Surveyor	24
	QS03	Senior Quantity Surveyor	18
	QS04	Senior Quantity Surveyor	16
Engineer	E01	Senior Engineer	15
	E02	Senior Engineer	11
	E03	Project Manager	16
	E04	Senior Engineer	21

Manual thematic analysis was employed, focusing on identifying, analysing, and interpreting patterns of meaning ('themes') within the qualitative data relevant to research objectives (Humble & Mozelius, 2022). Interview transcripts were coded, and similar theme-based ideas were grouped and analysed from Client, Engineer, Architect, and Quantity Surveyor perspectives. Findings from the literature and data analysis were then discussed to achieve the research aim and objectives.

4. RESEARCH FINDINGS AND DISCUSSION

This section analyses findings categorised by major stakeholder groups: client, architect, engineer, and quantity surveyor. The developed perceptual map (Figure 3), tested with interviewees, formed the basis for discussion on their perceptions. The findings are discussed along with the literature outcomes to achieve the research objectives.

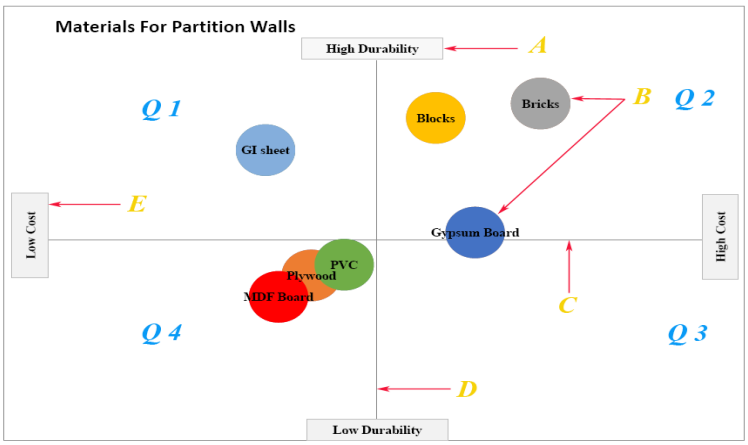
4.1 CLIENT'S POINT OF VIEW

C04 explained that perceptual maps "*can save time by depicting all the materials within one page,*" allowing anyone to "*compare two items by looking at its position in the Cartesian plain*". Perceptual maps display all items on one page, facilitating direct access for comparing several items by cost and other characteristics, simplifying selection, and saving time. C01 commented, "*when there is a new way like perceptual map, it could be used in important cost impacting decisions*", especially when clients imply changes or variations. This enhances decision-making efficiency.

C02 noted, "*Even if I find the required cost information...with current methods, I may need another method to compare those cost information with different characteristics*". Perceptual maps alleviate issues with existing methods that involve repetitive work, offering better communication, and enriched presentation. Sequential information access limits readability and understandability, causing time wastage and requiring further processing (comparison, filtering). C04 stated perceptual maps "*can show details of the compared items and the comparison process within one frame*," managing all information on one page and obviating further searches compared to reports.

4.2 ARCHITECT'S POINT OF VIEW

A02 expressed, "*By using a perceptual map I can get an idea of how these alternatives vary according to its cost and the other specific attribute*". Architects deal with many alternatives when designing, needing to assess each characteristic and cost to find the best fit. A01 found this technique "*perfect*" for such scenarios. Since all alternatives are visible on one page for comparison by cost against an attribute, selecting the best option(s) becomes easier. Users can also group alternatives before consulting a detailed report.



A = Variable Characteristic
B = Element
C = Constant Axis
D = Variable Axis
E = Constant Characteristic (Cost)
Q1 = [Low Cost, High Y] Quadrant
Q2 = [High Cost, High Y] Quadrant
Q3 = [High Cost, Low Y] Quadrant
Q4 = [Low Cost, Low Y] Quadrant

Figure 1: Developed perceptual map technique

A03 stated, "*if there is a report only, I have to go through all the pages... So, it will be time consuming. But if we have mechanism to select the areas need to be go through... it will be more efficient. In case of perceptual maps, it looks promising*". Perceptual maps use quadrants based on attributes, dividing alternatives accordingly. Users can select materials from the relevant quadrants and refer only to those in the report. A04 clarified, "*By using Perceptual Map we can eliminate materials which we don't need... if I search item with related to cost and durability; I might go for [low cost, high durability] quadrant... It will depend on user to user. But still using Perceptual Map will help to reduce the scope of selection... Then after I can get details of selected items using report*". This shows that the technique can sort/group alternatives, allowing users to analyse a selected group further with the report. A04 suggested combining both techniques for better cost information representation.

4.3 ENGINEER'S POINT OF VIEW

E04 stated, "*This technique shows the distribution of materials based on cost and other selected characteristics. We can group materials quadrant wise and can select... materials in the quadrant which suit our idea*," showing an opinion similar to C04 and A04. E04 labelled map quadrants by usefulness for material selection (see Figure 4).

According to E04, the Engineering quadrant (Low Cost, High Y) offers the best selection due to low cost and high characteristic value. The Research and Development quadrant (High Cost, High Y) materials are for research and user-dependent. Primitive quadrant (Low Cost, Low Y) materials suit temporary works, while Non-Engineering quadrant (High Cost, Low Y) materials should be discouraged. E03 added, "*As Engineers we are looking at engineering quadrant when undertaking a sustainable project execution... to*

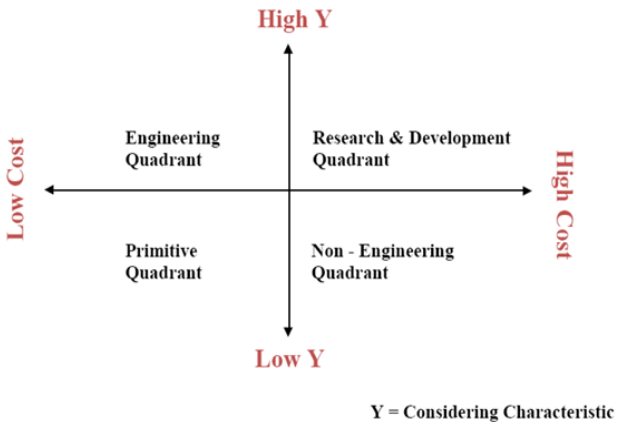


Figure 2: Diagram to depict comments of E04 interviewee

select materials in engineering quadrant, because we have the idea of saving material cost, reducing wastage and improve other related characteristics such as quality, durability etc.". Perceptual maps, with their quadrant division, allow engineers to easily identify materials in the engineering quadrant.

E04 noted that a report's efficiency is dependent and not inherently inefficient. E04 added, "*We can use Perceptual Map to sort the materials... and then can refer to the report to see further details*", aligning with A04's idea of using both techniques.

4.4 QUANTITY SURVEYORS' POINT OF VIEW

QS01 stated, "*This technique provides easy comparison between alternatives. QS can give advice the Client about characteristics of alternative material compared to Clients' money... by using this method*". Projects have estimated budgets, and this technique can depict the best alternative for that budget. QS02 suggested, "*I can use perceptual map to select few alternatives and if I cannot get best alternative... I can refer to other ways. So, I think first we must go through perceptual map and the other detailed information could be interlinked...*". Users can refer to reports if selected materials from the map conflict, an idea also shared by A04 and E04.

QS04 mentioned, "*I think we can't one hundred percent rely on the perceptual map... it is a summarised version of a cost report. To make sure reliability of any decision... we need the report... Even if the report cannot be accessed easily, the perceptual map can be accessed easily*". Both methods have limitations, but their combination can reduce these. Perceptual maps offer direct access, while reports provide more information, leading to effective and efficient results.

4.5 DISCUSSION OF FINDINGS

A common theme from interviews is the advantage of perceptual maps in enabling quick comparisons and decision-making with multiple alternatives. Table 2 presents the characteristics of perceptual maps versus conventional reports, as identified by stakeholders.

Table 2: Identified characteristics of perceptual map

Professional category	Conventional report	Perceptual map
Client	Time consuming	Time saving
	Cannot use for grouping or sorting	Can use for grouping or sorting
	Sequential access	Direct access
	Less speed of grabbing data	High speed of grabbing data
	Slow decision-making process	Quick decision-making process
	Alternative element comparison is difficult	Alternative element comparison is easy
Architect	More informative	Less informative
	Cannot use for grouping or sorting	Can use for grouping or sorting
	Alternative element comparison is difficult	Alternative element comparison is easy
Engineer	Cannot super imposed with multiple Perceptual maps	Can super imposed with multiple Perceptual maps
	Element filtering cannot be done	Element filtering can be done
	Cannot use for grouping or sorting	Can use for grouping or sorting
Quantity Surveyor	Difficult to understand	Easy to understand
	More informative	Less informative
	Descriptive format	Graphical format

The findings confirm that existing methods can lack clarity and require further processing, an issue that perceptual maps can minimise for all considered stakeholders. The interviewees identified several scenarios for using perceptual maps in projects (refer to Table 3).

Table 3: Possible scenarios of using perceptual map technique

Professional Category	Scenario
Client	Compare the cost of alternative materials against specific attribute
Architect	Compare the cost of alternative elements against specific attributes (including both materials and services)
	Group elements according to users' idea
Engineer	Grouping or Sorting elements under given criteria
Quantity Surveyor	Compare the cost of alternative elements with specific attributes (including both materials and services)

Quantity Surveyors and Architects, particularly, suggested that perceptual maps are most powerful alongside, not replacing, detailed cost reports like BOQs. The map offers a comparative overview, while the report provides detailed verification, creating a synergetic effect. This addresses the limitations of relying solely on a summarised view, aligning with the literature on mental representation: while visual tools aid perception, stakeholders need varying detail levels based on role and context. The engineer's quadrant-based analysis highlights the capacity of perceptual maps for the efficient presentation of complex information distribution.

4.6 DEVELOPMENT SUGGESTIONS

Professionals suggested development options for perceptual maps based on their perceptions of characteristics and limitations during testing.

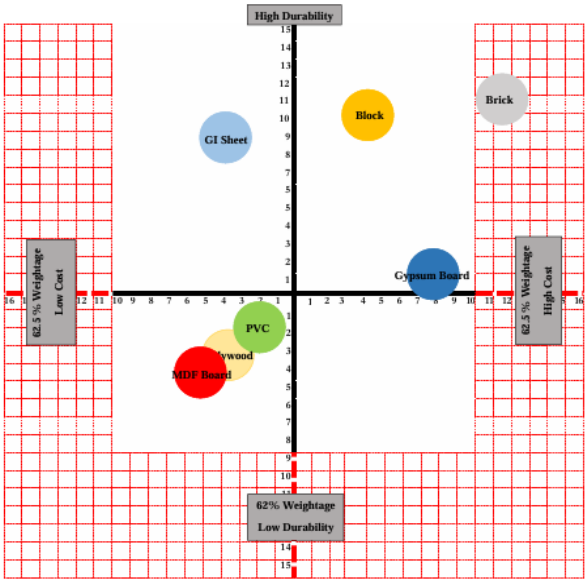


Figure 5: Developments B and C

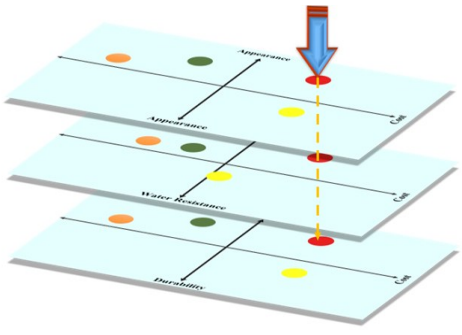


Figure 6: Super imposed perceptual map technique

1. Super-imposed method: Overlaying several perceptual maps created separately for different attributes for multi-attribute visualisation. (See Figure 5 for illustration).
2. Scaled axes: Scaling X and Y axes for quantified, accurate analysis when options within a quadrant need differentiation. (See Figure 6).
3. Weighted axes: Allowing weightages for attributes in decision-making to be applied to axes for direct visualised results. (See Figure 6).
4. Interactive linking: Linking map elements (circles) to the source report for more information, creating a dynamic cost presentation for better stakeholder decision-making.

5. CONCLUSIONS AND RECOMMENDATIONS

This study concludes that perceptual mapping is a valuable technique for enhancing the representation of construction cost information. The technique significantly improves the efficiency of comparing alternatives based on costs and other attributes, offering clearer visual communication for different stakeholders. The findings confirm that perceptual maps help overcome certain clarity and usability issues inherent in the existing formats of cost data representation. However, the research also highlights that perceptual mapping is most effective not as a standalone replacement, but as a complementary tool used alongside detailed cost reports, such as Bills of Quantities. This approach provides both a quick comparative overview and the necessary in-depth data for verification, thus ensuring robust decision support.

The implications of these findings extend to both theory and practice. Theoretically, this research contributes to understanding information visualisation and cognitive processing in complex professional domains, such as construction cost management. This demonstrates the successful adaptation of a marketing-originated tool to a new field, offering insights into how established techniques can be repurposed to address specific industry challenges. Furthermore, the emphasis on complementarity over replacement informs theories of technology integration, suggesting a nuanced path where new tools augment, rather than simply supersede, existing practices. For practitioners, the impact is tangible. Perceptual maps offer a more intuitive way to discuss and decide on cost-related matters, enhancing communication between diverse stakeholders such as Clients, Architects, Engineers, and Quantity Surveyors. This leads to more efficient decision-making, particularly when evaluating design or material alternatives. Quantity Surveyors, in particular, can leverage these maps to provide clearer, more impactful cost advice, thereby strengthening their advisory role.

To capitalise on these benefits and further address the challenge of effective cost information representation, it is recommended that Quantity Surveyors actively produce perceptual maps as a supplementary visualisation tool, especially for collaborative decision-making involving material or design alternatives. The ideal progression would be the integration of this capability into standard Quantity Surveying software, simplifying its generation and use. Exploring the synergy of perceptual maps with existing digital platforms, such as BIM environments, is also crucial for maximising data accessibility and utility.

As a qualitative study conducted with professionals in Sri Lanka, the findings of this study may have limited generalizability. Therefore, care should be taken when applying these

conclusions to different geographical or cultural setting where cost management practices may differ.

Looking ahead, further research should investigate the application of perceptual maps with a broader array of attributes beyond cost and durability. Assessing user experience across different project phases and among diverse stakeholder groups will also be vital to refine practical implementation and maximise the benefits of perceptual maps in the construction industry.

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EXPLORING THE POTENTIAL OF BLOCKCHAIN TECHNOLOGY ADOPTION IN THE SRI LANKAN CONSTRUCTION INDUSTRY: OPPORTUNITIES AND BARRIERS TO IMPLEMENTATION

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ABSTRACT

Blockchain technology promises to be a transformative solution for the Sri Lankan construction industry that has been plagued by systemic inefficiencies, corruption & fragmented workflows. Global research points out that Blockchain will make a difference to increase the transparency of documents, automate and operate contracts and optimize supply chain. However, despite being a potential in Sri Lanka, it is limited in adoption because of the technical, organizational and regulatory barriers. This research employs a qualitative approach using the research onion model to link characterizations of the benefits and challenges related to Sri Lanka, based on Systematic Literature Review (SLR) technique. Accordingly, 10 Scopus indexed papers were selected for detailed analysis followed by manual content analysis. The study found that Blockchain offers financial process efficiency e.g. lower late payments via smart contracts, transparency improvement (immutable records suppressing fraud), and corruption prevention (tamper proof e-procurement system). Despite these, implementation costs and regulatory uncertainty, as well as technical scalability issues are the challenges preventing adoption. The industry is also fragmented and has a low level of digitalization, thus making integration complex. Its implications underline both the call for pilot projects, regulatory modernization, and stakeholder education to bridge the theory to practice gap, and the fact that theoretical potential has a powerful influence on the perception of risk. Once addressed, the barriers that Sri Lankans face in its construction sector can open the doorway to adopt blockchain to have better accountability, attract foreign investment, and be in tune with the global sustainability benchmarks.

Keywords: *Blockchain Technology; Construction Industry; Procurement Efficiency; Regulatory Challenges; Sri Lanka.*

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1. INTRODUCTION

A blockchain is a form of decentralized, distributed ledger technology that creates a record of transactions in a secure, transparent and tamper-proof way across the network of computers (Chen & Bellavitis, 2020; Cong & He, 2019). Blockchain was originally set up as the backbone for things like Bitcoin, but blockchain technology has since become a widespread massive technology with uses everywhere other than purely digital currencies. Immutability, decentralization and consensus-based validation are its core features, and the data integrity, security and trust are offered by non-trust parties (Chen et al., 2024; Lashkari & Musilek, 2021) .

Blockchain has also been put to global use in finance, supply chain management, healthcare, energy, and transportation industries (Kshetri, 2021; Santhi & Muthuswamy, 2022). It serves as the underpinnings in the financial sector that support the peer-to-peer DeFi (decentralized finance) platforms, which do not have a middleman in their transactions (Vasishta et al., 2025). Therefore, Blockchain can enhance transparency, offer provenance and traceability of goods, while reducing fraud for goods in supply chains (Ming et al., 2024). Across the energy industry, blockchain is utilized in peer-to-peer energy trading and the grid (Seven et al., 2022).

While blockchain adoption in the construction industry is still emerging, it is gaining attention for addressing fragmentation, inefficiency, and distrust among stakeholders (Abdelghany, 2024; Amico & Cigolini, 2023). Key applications include smart contracts for automated payments, transparent procurement processes, secure data sharing, and improved supply chain management (Singh et al., 2024; Za'ba, 2023). Research highlights increased trust and transparency as primary benefits, though challenges like integration complexity and skill shortages persist (Abdelghany, 2024; Amico & Cigolini, 2023).

However, the Sri Lankan construction industry is a dominant force in national economic growth and prone to inefficiency, opacity and frequent disputes (Karunaratne & Abeynayake, 2023; Nitharsan & Francis, 2022). The greatest change that has the potential to transform the sector is the blockchain, as the sector transforms itself to modernize and align its practices with the best practices globally (Bandara, 2023). In this Sri Lankan context where corruption and a lack of trust permeate the political and wider society, there is relevance in its role to support streamlining contract management and reduce corruption (Nitharsan & Francis, 2022) and its ability to help engender trust among project participants (Kosala et al., 2021). The adoption of a blockchain could improve the project delivery, attract foreign investment, and set standards for accountability and performance (Bandara, 2023; Karunaratne & Abeynayake, 2023).

Despite the global momentum and clear advantages of blockchain technology, its integration into the Sri Lankan construction industry remains limited (Bandara, 2023; Karunaratne & Abeynayake, 2023). The sector continues to grapple with inefficiencies, fragmented processes, and a lack of stakeholder trust. While digital tools have been introduced, the full potential of blockchain to address these systemic issues has yet to be realized. Barriers such as technical complexity, high implementation costs, regulatory uncertainty, and limited awareness further hinder widespread adoption (Faraji et al., 2024). As such, there is a need to systematically identify both the benefits and challenges of blockchain integration in this context to inform policy, practice, and future research.

Although international research has explored blockchain's transformative potential in various industries, there is a notable lack of comprehensive, context-specific studies focused on the Sri Lankan construction sector. Most existing literature either addresses global trends or examines isolated aspects of blockchain adoption. There is a notable lack of comprehensive, context-specific studies on the practical benefits, unique challenges, and stakeholder perceptions within Sri Lanka's construction environment. This research aims to fill that gap by providing a holistic analysis of both the benefits and obstacles associated with blockchain integration in the Sri Lankan construction industry.

2. LITERATURE REVIEW

2.1 SRI LANKAN CONSTRUCTION INDUSTRY

While the construction industry globally has begun to approach blockchain technology, its entry into the construction industry of Sri Lanka is still limited. There are inefficiencies, fragmented processes and the lack of stakeholder trust to overcome in the sector (Hirusheekesan et al., 2023). Digital tools have been introduced, but blockchain has not yet fully enabled it to solve these systemic issues (Anuradha et al., 2023; Gamage et al., 2024). However, technical complexity, high implementation costs, regulatory uncertainty and lack of awareness slow down the process further (Sendanayake et al., 2024). This calls for a need for a systematic identification of both benefits and challenges in blockchain integration in this context to provide evidence to inform policy, practice and future research (Anuradha et al., 2023; Gamage et al., 2024).

Although there has been international research on blockchain's potential in transformation in different industries, there is a dearth of systematic, context-specific studies in the Sri Lankan construction (Gamage et al., 2024). Research on the practical benefits and unique challenges in Sri Lanka's construction environment is not sufficient. This research seeks to address this gap with the holistic analysis of both the benefits of adopting blockchain in the Sri Lankan construction industry and its stumbling blocks (Nitharsan & Francis, 2022).

Blockchain technology provides a strong solution to entrenched problems through decentralized transparency, automation and immutability (Sinniati & Darma, 2023). For instance, blockchain based e-procurement systems will take corruption out of the equation as they provide tamperproof records of bids and transactions, allowing the accountability of the whole duration of the procurement. One key blockchain feature that is smart contracts, facilitate automation of payment releases based on predefined milestones, thereby lowering delays and disputes endemic to Sri Lanka's project based work flows (Anuradha et al., 2023). In addition, this automation reduces the need for third party involvement by eliminating through learning, reducing administrative costs and improving efficiency. Blockchain's ledger manages to be a completely decentralized ledger, allowing real time visibility into the supply chain for stakeholders to verify material and mitigate counterfeit which is a major strength when the country itself relies on a complicated and many demarcated supply chain (Sinniati & Darma, 2023). Introduction of standardization protocols in the procurement functions on blockchain platforms could bridge regulatory gaps and develop trust among contractors, suppliers and clients. Case studies conducted in Sri Lanka show that blockchain can lead to a 15% reduction in construction costs and accelerate project timelines to conform to global best practice, proving how blockchain application in procurement can help pull the sector on

par with global best practice (Anuradha et al., 2023; Nitharsan & Francis, 2022; Sendanayake et al., 2024).

2.2 BENEFITS OF IMPLEMENTING BLOCKCHAIN TECHNOLOGY TO THE CONSTRUCTION INDUSTRY

Table 1 highlights the benefits of using Blockchain in the construction industry.

Table 1 : Benefits of implementing blockchain technology to the construction industry

Benefits	References
Transparency and Trust Enhancement	(Kiu et al., 2020; Lu et al., 2021; Pishdad-Bozorgi & Yoon, 2022; Udeh et al., 2024)
Supply Chain Management Optimization	(Azmi et al., 2022; Celik et al., 2023; Kiu et al., 2020; Qian & Papadonikolaki, 2020)
Project Monitoring and Risk Management	(Amoah & Oh, 2021; El Khatib et al., 2022; Kang et al., 2022; Liu et al., 2023; Rane & Potdar, 2021; A. K. Singh et al., 2023; Udokwu et al., 2021)
Smart Contracts and Procurement Efficiency	(Cheng et al., 2023; Heydari et al., 2024; Kiu et al., 2020; Liu et al., 2023; Özkan et al., 2021; Shang et al., 2023)
Data Security and Process Integrity	(Kiu et al., 2022; Lou & Lu, 2022; Pan et al., 2022)
Cost and Time Efficiency	(El Khatib et al., 2022; Sadeghi et al., 2022; Shu et al., 2022; Wang et al., 2022)
Dispute Resolution Acceleration	(Abeywickrama et al., 2024; Ashipala, 2025; Dincer, 2024; Kirkwood & Chaisse, 2022; Kiu et al., 2020; Olawumi et al., 2021; Son & Lien, 2022; Mohammed & Alharthi, 2022)

The benefits blockchain technology brings to the construction sector range from solving the systemic inefficiencies and creating collaboration among the stakeholders. Blockchain's immutable ledger offers transparency and trust enhancement, which helps the stakeholders to verify the authenticity of data, thus enhancing accountability (Cheng et al., 2021; Kang, 2022). This is a very important feature for Supply Chain Management Optimization, where blockchain makes it possible to track materials from origin to site in real time, reducing counterfeits and delays, and complying with sustainability standards (Bakhtiarizadeh et al., 2022; Cheng et al., 2021). Blockchain is interconnected with Internet of Things (IoT), in terms of integration with Project Monitoring and Risk Management, to enable real time progress updates and early detection of deviations before they occur and take proactive action in case of risk mitigation (Cheng & Chong, 2022; Kang, 2022). The Smart Contract and Procurement Efficiency improves the workflows by automating the payments upon the agreed conditions (e.g., the milestone completions), minimizing the time and cost associated with the procurement cycle (Weerapperuma et al., 2023; Ye et al., 2022; Yu et al., 2024). By having blockchain's decentralized architecture, Data Security and Process Integrity are ensured as encrypted records prevent malicious hacking and alterations of sensitive project data (Kang, 2022; Ye et al., 2022). Together, these features contribute to cost and time efficiency by eliminating manual work, rework, and disputes. Studies show that these features can lead to saving 15 to 20 % in a project budget (Yu et al., 2024). Blockchain's ability to leave an auditable trail of actions, contracts, and communications facilitates fast dispute

resolution , and reducing litigation costs (Cheng et al., 2021). By addressing these aspects, blockchain puts itself at the centre of the modernization of the ways of construction in the entire world.

2.3 CHALLENGES OF IMPLEMENTING BLOCKCHAIN TECHNOLOGY IN THE CONSTRUCTION INDUSTRY

The adoption of blockchain technology in the construction industry faces multifaceted challenges across technical, organizational, legal, and operational domains. Table 2 shows the challenges of implementing blockchain technology to the construction industry.

Table 2 : Challenges of implementing blockchain technology to the construction industry

Challenge category	Specific challenges	Reference
Technical	Scalability and performance issues	(Khan et al., 2021; Perera et al., 2020; Rahman et al., 2022; Sanka & Cheung, 2021)
	Integration with existing systems	(Plevris et al., 2022; A. K. Singh et al., 2024; Waqar et al., 2024)
	Data privacy and security concerns	(Teisserenc & Sepasgozar, 2021; Wenhua et al., 2023)
	Lack of standardization	(Teisserenc & Sepasgozar, 2021; Xu et al., 2023)
Organizational (Attributes)	Resistance to change ***(non-payment are part of the inherent culture in the construction industry)***	(Gurgun et al., 2022)
	Lack of skilled personnel	(Elbashbishy et al., 2022; Khuc et al., 2024; A. K. Singh et al., 2023)
	High initial implementation costs	(Gamage et al., 2024; Su et al., 2023; Waqar et al., 2024)
	Unclear return on investment	(Khuc et al., 2024; A. K. Singh et al., 2024; Waqar et al., 2024)
Legal and Regulatory	Regulatory uncertainty	(Khuc et al., 2024; A. K. Singh et al., 2024; Zhuk, 2025)
	Lack of legal frameworks	(A. K. Singh et al., 2024; Zhuk, 2025)
	Smart contract enforceability	(Gamage et al., 2024; Zhuk, 2025)
Industry specific	Fragmented nature of construction industry	(Aasen & Klakegg, 2023; Elbashbishy et al., 2022; Plevris et al., 2022)
	Low digitalization level	(Aasen & Klakegg, 2023; Gamage et al., 2024; A. K. Singh et al., 2024)

Challenge category	Specific challenges	Reference
	Complex supply chains	(Plevris et al., 2022; A. K. Singh et al., 2023; Wu et al., 2022)
Cultural and Social	Lack of trust in new technology	(Aasen & Klakegg, 2023; Elbashbishy et al., 2022; A. K. Singh et al., 2023)
	Limited awareness and understanding	(Gamage et al., 2024; Khuc et al., 2024; A. K. Singh et al., 2024)
Operational	Difficulty in managing large volumes of data	(Elbashbishy et al., 2022; Elsaeidy, 2024; Waqar et al., 2024)
	Energy consumption concerns	(Plevris et al., 2022; Su et al., 2023)
	Interoperability issues	(Elbashbishy et al., 2022; Plevris et al., 2022; Waqar et al., 2024)
	Lack of proven use cases	(A. K. Singh et al., 2024; Waqar et al., 2024)

Scalability and performance issues tend to be technical barriers since blockchain's computationally heavy tasks cannot process large-scale real-time data, and integration of blockchain with legacy systems such as Enterprise Resource Planning (ERP) and Building Information Modelling (BIM) tools has a lack of interoperability with decentralized ledgers (Khuc et al., 2024; Plevris et al., 2022). Current data privacy and security concerns, however, exist because blockchain's transparency conflicts with the requirements of confidentiality for sensitive contracts, as well as the issue of a lack of standardization, making cross-platform compatibility difficult (Khuc et al., 2024; Plevris et al., 2022). The entrenched practices of entrenched cultures, such as the non-payment cultures and misgivings regarding automation, are compounded by huge initial costs of infrastructure and low rate of investment relative to investment, which makes them not attractive (Gamage et al., 2024; Khuc et al., 2024). Smart contracts further face legal and regulatory uncertainty, which is not addressed by most existing frameworks with respect to smart contract enforceability and liability in decentralized systems. Coordination tends to be more difficult in industry-specific hurdles such as fragmentation, low digital maturity and complex multi-tiered supply chains that place limits on the potential of blockchain to expedite workflow. Cultural resistance is driven by a lack of awareness about the beneficial aspects that blockchain offers and doubt on its reliability primarily by traditional stakeholders. One of the main issues with blockchain is operational ones: for instance, it is energy intensive and requires energy consensus in its blockchain, as well as interoperability with blockchain and IoT/BIM (Plevris et al., 2022).

3. METHODOLOGY

This study's data collection process involved the utilization of Scopus database, a comprehensive repository of peer reviewed academic literature, to collect relevant research papers following SLR technique. The search string "Construction" AND

"Blockchain" AND "Sri Lanka" was applied to filter studies specifically addressing blockchain adoption in Sri Lanka's construction sector. Ten articles were selected for this study based on inclusion criteria that include relevance to the study's objectives, publication in English, and empirical or theoretical insight on applying blockchain technologies. Topics selected for the worked papers ranged from smart contracts to supply chain transparency to regulatory challenges and thus made up a foundational dataset for analysis. The manual content analysis approach was used for data analysis. Key themes such as "benefits," "challenges," and "implementation strategies" were identified through manual content analysis process, with findings cross-validated to ensure consistency.

Rationale for Filter Selection

The search strategy employed Title, Abstract, and Keywords as search fields to ensure relevance and precision, capturing studies explicitly addressing blockchain applications in construction. The publication year range (2019–2025) prioritizes recent advancements in blockchain technology while accommodating pre-2023 studies to establish foundational trends. The subject/research area filters (Blockchain, Construction, Sri Lanka) focus the scope on context-specific challenges and opportunities, addressing the gap in localized research. Document types were limited to articles and conference papers to prioritize peer-reviewed, empirically validated insights while excluding non-academic sources. Language restrictions (English) ensure accessibility and academic rigor, given Sri Lanka's reliance on English-language technical documentation. This filtering approach minimizes noise from irrelevant disciplines (e.g., fintech) and ensures alignment with the study's objectives of analysing blockchain's viability in Sri Lanka's construction industry.

Table 3 shows the inclusion criteria of the secondary data collection.

Table 3 : Inclusion criteria.

Categories	Filters
Search fields	Title, Abstract, Keywords
Publication year	From 2019 to 2025
Subject/Research area	Blockchain. Construction, Sri Lanka
Document type	Articles, conferences
Language	English

Figure 1 presents the flow diagram of the study selection.

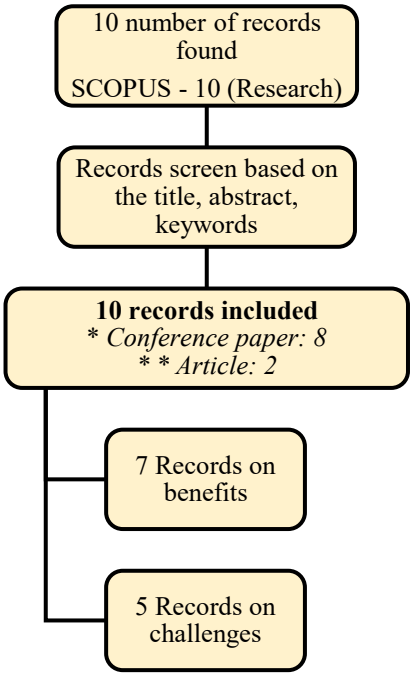


Figure 1: Flow diagram of the study selection.

4. DATA ANALYSIS

4.1 BENEFITS OF IMPLEMENTING BLOCKCHAIN TECHNOLOGY TO THE SRI LANKAN CONSTRUCTION INDUSTRY

The data for seven key studies have been analysed and a strong consensus on the transformative benefits for Sri Lanka's construction industry has emerged from the analysis. Table 4 shows the analysis of benefits of implementing blockchain technology to the Sri Lankan construction industry.

Table 4 : Benefits of implementing blockchain technology to the Sri Lankan construction industry

Benefit category	Specific benefits	References						
		1	2	3	4	5	6	7
Contract Management	Streamlined contract execution, reduced disputes, and automated compliance tracking.	✓	✓	✓		✓	✓	✓
Financial Processes	Faster transactions, reduced late payments, and minimized third-party intermediation.	✓	✓	✓	✓	✓	✓	✓
Transparency and Trust	Immutable records enhancing stakeholder trust and reducing fraudulent activities.	✓	✓	✓	✓	✓	✓	✓
Corruption Mitigation	E-procurement systems reducing bribery and bid-rigging in public projects.	✓	✓	✓	✓	✓	✓	✓
International Trade	Simplified cross-border transactions and reduced documentation delays.	✓	✓	✓	✓	✓	✓	✓

Benefit category	Specific benefits	References						
		1	2	3	4	5	6	7
Security and Data Integrity	Encrypted, tamper-proof ledgers for secure financial and contractual data.	✓	✓	✓	✓	✓	✓	✓

Sources : 1 : (Karunaratne & Abeynayake, 2023), 2 : (Bandara, 2023), 3 : (Nitharsan & Francis, 2022) , 4 : (Weerakoon & Chandanie, 2021), 5 (Kosala et al., 2021), 6 : (Abeywickrama et al., 2024), 7 : (Gamage et al., 2024)

All studies consistently acknowledged Financial Processes as the most universal benefit of blockchain, as it makes it possible to speed up transactions, minimize late payments, as well as decrease the need for third party intermediaries arranged through smart contracts. Also, papers had supported both Transparency and Trust and Security and Data Integrity beyond all papers, reflecting blockchain's ability to record to immutable ledgers and encrypted ledgers and to thus deter fraud and engender stakeholder confidence. Researchers emphasized that blockchain's great potential for streamlining e-procurement systems and smooth cross-border transactions would effectively tackle Sri Lanka's persistent problems of bid-rigging and bureaucratic delays and unanimously supported Corruption Mitigation and International Trade. Six studies supported the use of Contract Management for automating compliance tracking and reducing disputes, but one study did not specifically cover this area. The results collectively suggest that blockchain may help overcome systemic inefficiencies in Sri Lanka's construction sector, most critically in high stakes fields like public procurement sector and foreign cooperation. At the same time, near universal agreement across studies means that future pilot projects for targeting these theoretical benefits, in real world applications, are needed.

4.2 CHALLENGES OF IMPLEMENTING BLOCKCHAIN TECHNOLOGY IN THE SRI LANKAN CONSTRUCTION INDUSTRY

Five key studies on the analysis of challenges for the installation of blockchain technology in Sri Lanka's construction industry demonstrate systemic issues within technical, organizational and socio-cultural areas of implementation. Table 5 presents the analysis of challenges of implementing blockchain technology in the Sri Lankan construction industry.

Table 5 : Challenges of implementing blockchain technology in the Sri Lankan construction industry

Challenge category	Specific challenges	References				
		1	2	3	4	5
Technical	Scalability and performance issues	✓	✓		✓	✓
	Integration with existing systems	✓	✓	✓		✓
	Data privacy and security concerns	✓	✓		✓	✓
	Lack of standardization	✓	✓	✓		✓
Organizational	Resistance to change	✓	✓		✓	✓
	Lack of skilled personnel	✓	✓	✓	✓	✓
	High initial implementation costs	✓	✓	✓	✓	
	Unclear return on investment	✓	✓		✓	✓

Challenge category	Specific challenges	References				
		1	2	3	4	5
Legal and Regulatory	Regulatory uncertainty	✓	✓	✓	✓	
	Lack of legal frameworks	✓	✓	✓	✓	✓
	Compliance issues	✓	✓	✓	✓	
	Smart contract enforceability	✓	✓		✓	✓
Industry-Specific	Fragmented nature of construction industry	✓	✓	✓		
	Low digitalization level	✓	✓	✓	✓	✓
	Complex supply chains	✓	✓	✓	✓	
	Project-based structure	✓	✓		✓	✓
Cultural and Social	Lack of trust in new technology	✓	✓	✓	✓	✓
	Limited awareness and understanding	✓	✓	✓	✓	✓
	Resistance from traditional stakeholders	✓	✓		✓	✓
Operational	Difficulty in managing large volumes of data	✓	✓	✓		✓
	Energy consumption concerns	✓	✓		✓	✓
	Interoperability issues	✓	✓	✓	✓	
	Lack of proven use cases	✓	✓	✓	✓	✓

Sources: 1 : (Bandara, 2023),2 : (Gamage et al., 2024), 3 : (Weerakoon & Chandanie, 2021), 4 : (Kosala et al., 2021), 5 : (Karunaratne & Abeynayake, 2023)

Technical challenges such as scalability issues (cited in 4 out of 5 studies) and integration with legacy systems (cited in 4 out of 5 studies) highlight the sector's struggle to adapt blockchain to existing workflows, particularly in a context where digital maturity is low (noted universally as "Low digitalization level" across all studies). Among the cited in 4 out of 5 studies that identified high initial costs and unclear Return on Investment (ROI), there was organizational resistance; and the lack of skilled personnel is acknowledged generally. Theoretically, there is a dearth of tailored policies to guide the adoption of blockchain (all studies) and the lack of a legal framework (cited in 4 out of 5 studies), while smart contract enforceability (cited in 4 out of 5 studies) marks a gap in Sri Lanka's judicial system. The sector suffers from structural inefficiencies (cited in 3 out of 5 studies; industry specific barriers such as fragmentation and complex supply chains) displayed through industry fragmentation (cited in 3 out of 5 studies) due to the project-based structure of the sector (cited in 3 out of 5 studies) that is not conducive of long term blockchain integration. Generally, distrust in technology and awareness is low (universal) feeding into culture of distrust—and is typical of traditional stakeholders who are sceptical of digitization. Practically, there are limitations of energy consumption concern (cited in 3 out of 5 studies), interoperability issues (cited in 4 out of 5 studies) and unproven use cases (all studies), which instil a scepticism in blockchain's feasibility. Clearly, Bandara (2023) and Karunaratne and Abeynayake (2023) tell us these findings point to the fact that, apart from technological solutions, Sri Lanka's blockchain adoption challenges need to be addressed with regulatory modernization, needs training the workforce and pilot projects to show their validity.

5. CONCLUSION

Upon synthesis of 10 selected studies specific to Sri Lankan context, this study concludes 6 benefits of using Blockchain, and 23 specific challenges the industry face while implementing Blockchain. 23 challenges were categorised into six categories as Technical, Organizational, Legal and Regulatory, Industry-Specific, Cultural and Social, and Operational. This study indicates how great the opportunity is for blockchain technology to be integrated in the construction industry of Sri Lanka. On the benefits side, the possibility that blockchain could help desk into which it has already been deployed speeds of transaction time, reduce late payments, and significantly increase transparency, reduce human error, and higher levels of trust and security is widely acknowledged by all studies considered, and these can be used to mitigate corruption, improve international trade, to automate contract management. However, challenges analysis shows that, in addition to technical barriers (such as scalability, interoperability), organizational resistance (due to high costs, lack of skills), and legal regulatory voids (impossible smart contracts) systemic barriers reduce the likelihood of adoption: the digital maturation of the industry is low, the culture in which is sceptical or not, and all the operational difficulty that comes with the way of energy efficient on data management. Most critically, the absence of proven use cases is essentially inevitably near universal. To unlock the potential of blockchain, it is recommended to further research via multi-pronged strategy: Collaborative pilot projects to show ROI, regulatory modernization to address compliance gaps, and targeted training programs to have technical expertise.

The study's methodological design is intentionally focused to ensure precision and relevance, though this specificity creates clear boundaries for its scope. By concentrating exclusively on the Scopus database and using a narrow search string—"Construction" AND "Blockchain" AND "Sri Lanka"—the research guarantees that all selected articles directly address the core topic within the specified context. Therefore, this research has a limitation inherent in the selection criteria adopted. This deliberate approach, however, means that relevant literature from other academic databases or papers using related but different keywords may not be included. Similarly, the timeframe of 2019 to 2025 was strategically chosen to capture the most recent advancements in a rapidly evolving technological field. While this provides a valuable snapshot of the current state of research, it also establishes an opportunity for future studies to build upon this work by employing a broader search strategy across more databases and a longer historical period to map the evolution of the topic.

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FINANCIAL AND SOCIO-ECONOMIC IMPACTS OF IMPLEMENTING ACTIVE DESIGN PRINCIPLES IN SOUTH AFRICAN OFFICE BUILDINGS

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ABSTRACT

The drive towards sustainable construction increasingly demands a balance between socio-economic, financial viability, cultural relevance, and user satisfaction. Limited empirical research exists on the financial and socio-economic impacts of active design principles in South Africa, especially from the perspective of Quantity Surveyors. This study aimed to establish a foundational understanding of the financial and socio-economical impacts associated with the implementation of active design principles to improve built environment sustainability, cost management and workplace wellness. An exploratory, case-study approach was adopted, involving interviews with purposively selected participants. Key findings identified four significant phenomena: health and wellness in construction, financial factors, socio-economic factors, and barriers and limitations. One notable limitation included the limited implementation of active design principles in the South African Construction industry. This study highlights the importance of integrated stakeholder collaboration and recommends the industry-wide adoption of active design principles to enhance user value. This study also emphasizes the emerging role of Quantity Surveyors in driving innovative sustainable concepts in the construction industry. It is beneficial for built environment stakeholders as it provides valuable insights and empirical evidence regarding the implementation of active design principles and the resulting health and financial outcomes. This study offers a unique opportunity to support built environment sustainability through social, economic, and health benefits and is among the first to compare actively designed and conventional buildings in South Africa, providing novel insights into how Quantity Surveyors can influence sustainability through workplace wellness and socio-economic value creation.

Keywords: *Active Design; Cost Management; Quantity Surveying; Socio-economic Sustainability.*

1. INTRODUCTION AND BACKGROUND

Poor health and physical inactivity are escalating global issues that present a multitude of obstacles to the overall well-being and enjoyment of life and are increasingly affecting low-and middle-income countries such as South Africa (Mahmood & Arulkumaran, 2013; Malambo et al., 2017). Research shows that the built environment contributes

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significantly to sedentary lifestyles through inactive indoor settings and disconnected urban planning (Rossouw et al., 2016; Marsh et al., 2016). Given that the average adult spends over 1,700 hours annually in office settings, workplaces present critical opportunities for health-enhancing design interventions (Marsh et al., 2016).

A possible way offered in the literature that can be used to mitigate problems associated with socio sustainability is the application of the concept of active design, an evidence-based approach to architecture and urban planning that encourages physical activity and healthier behavior through spatial layout (McCormack & Shiell, 2011). Active design is an evidence-based approach to planning, architecture and construction that encourages physical activity and healthy living through the built environment. It encompasses strategies such as walkable communities, accessible stairwells, active transportation infrastructure and the strategic placement of shared amenities to promote movement and user wellbeing (Price & Fenton, 2015; Engelen et al, 2016). Socio-ecological models of physical activity theorize that individual physical activity levels are influenced by policy, physical and socio-cultural environments, and individual personalities (Sawyer et al., 2017). Active buildings aim to subtly nudge users towards movement through intentional placement of amenities and communal spaces, enhancing both user well-being and building efficiency (Khairuddin et al., 2021). Active Design further complements sustainable construction practices by integrating environmental health into building design, reducing energy demands, and supporting eco-friendly urban infrastructure (Gul et al., 2020).

From a social sustainability viewpoint, there is growing research on the impact of current interior environments on individual health (Marsh et al., 2016). Construction Consultants concentrate on four strategies to promote healthier lifestyles among the general public, specifically *active recreation, active buildings, alternative methods of transportation, and improved availability of nutritious food* (Opoku et al., 2024; Zulu et al., 2023). This paper highlights the cost and socio-economic implications of implementing active design principles in office spaces to increase the triple bottom line, namely *social* - improved employee health and wellbeing, *economic* - reduced absenteeism, higher productivity and higher building value and *environment*, less energy use and greener, more sustainable environments from the perspective of Quantity Surveying (QS). While the socio-economic benefits of active design are often discussed in health or planning contexts, this study uniquely frames the conversation around the strategic role of the QS as financial manager in construction projects. The role of the QS is critical in assessing feasibility, managing costs and ensuring value-for-money.

This study explores the socio-economic and financial implications of implementing active design in South African office buildings, focusing on user well-being and employee productivity. By comparing an actively designed office building with a conventional office counterpart, this study aims to provide empirical insight into the socio-economic benefits of active design. Office buildings were specifically selected for this study due to their relevance in modern sedentary lifestyles and the high proportion of daily time spent indoors by working employees. In South Africa, professionals spend over 1,700 hours per year in office settings (Marsh et al., 2016), making these spaces ideal for investigating how spatial design can promote physical activity, wellness and productivity. Furthermore, office buildings offer a practical entry point for piloting active design interventions due to their standardized operations and measurable outcomes. This paper highlights *active buildings* but acknowledges *alternative transportation* which includes the creation of safer and more user-friendly walking and cycling paths. The findings

presented in this paper will offer valuable insights to guide clients on the adoption and implementation of active design principles for effective project cost management and provide insights into the benefits of implementing these principles towards workplace wellness.

2. LITERATURE REVIEW

2.1 ENVIRONMENTAL BENEFITS OF ACTIVE DESIGN

Active design aligns closely with environmental sustainability goals through the reduction of energy consumption and promotion of resource-efficient buildings. Increased natural ventilation, the use of daylight, and reduced reliance on elevators or lifts via the increase usage of stairs contribute to lower carbon emissions and utility costs (Price & Fenton, 2015; Heidari et al., 2016). Research by Price and Fenton (2015) further states that the incorporation of active circulation routes and green communal spaces enhances user wellness and environmental performance, especially in office environments. These strategies complement broader green building goals and reinforce the environmental pillar of the triple bottom line.

Less resilience on elevators leads to less energy use which creates green spaces and reduces the environmental impact. Furthermore, attention must be given to building shape and design (Gordeljevic, 2018). Climate, layout, and orientation all have an impact on the design of building circulation areas, which contribute to employee activity (Gordeljevic, 2018).

Sustainable design presents a challenge for developers and built environment stakeholders to think innovatively. Its objective is to reduce detrimental impacts on the environment, create healthy and productive spaces, and minimize waste (Kibert, 2016). Sustainable development refers to a form of development that fulfills current needs while safeguarding the ability of future generations to meet their own needs (Strydom, 2013). The overarching concept of sustainability encompasses economic, socio-political, and environmental aspects (Kibert, 2016). Sustainable development creates an opportunity for the construction industry to move forward, towards optimal sustainability whilst considering the current economic, socio-economic and environmental concerns (Strydom, 2013). Green design and construction focus on the reduction of social and environmental impacts on the built environment whilst improving the quality of life for the building occupants (Cole, 2019). Sustainable infrastructure thus incorporates the interconnection between community and health, providing a system to control benefits from the mitigation of urban heat to increased physical activity (Heidari et. al., 2016). Social sustainability and green building practices align focus on the implementation of construction practices to build buildings that will last longer, be more efficient, reduce operating costs, increase the productivity of employees and contribute to healthy living (Kubba, 2010). Studies indicate that green spaces can have significant impact on health benefits including reduced stress levels, improved cognitive function, and increased mental health (Heidari et al., 2016; Nugroho et al., 2020; Ahmad, 2023).

The construction industry is still in the early stages of filling the gap between building design, construction, and health (Bernstein & Russo, 2014; Engelen et al., 2016; Khairuddin et al., 2021). There are limited studies and information available regarding active design buildings, hence the opportunity presents itself to study built environment sustainability through social, economic, and health benefits.

2.2 ACTIVE DESIGN AND EMPLOYEE PRODUCTIVITY

More companies are embracing workplace wellness through architecture (Emmit, 2014). The New York center for active design defines the concept as the transformation of health research findings into design solutions that strengthen the contribution of architecture to improve public health and wellbeing (Khairuddin et al., 2021).

The South African workplace is experiencing an increase in non-communicable chronic diseases (NCCD) (Cole, 2019). The growth of NCCDs is likely to be caused by the rapid economic and social changes that include urbanization and dramatic changes in individual lifestyle (Gordeljevic, 2018). The incorporation of active design principles can be used to combat the effect of these NCCDs on individuals. Research indicates that the average employee spends about five hours and forty-one minutes per day sitting (Khairuddin et al., 2021). This not only decreases productivity levels, but also increases diseases such as diabetes, depression, heart diseases and obesity (Emmit, 2014). Although many organisations offer health and wellness programs to their employees, a more active strategy must be created through workplace design (Cole, 2019). The workplace provides a useful setting for promoting physical activity as there is a broad and captive audience and existing social structures provide a framework around which to build interventions (Ahmad, 2023).

Heidari et al., (2016) explains that there are many ways to promote healthy behavior and environments within office buildings that can subconsciously influence employees to be more active. Designing a workplace that gives access to movement, ventilation, daylight, and interaction through communal working lounges, standing desks and outdoor circulation paths gives employees freedom and control over the time they spent at work (Nugroho et al., 2020).

Horwitz et al., (2013) claims that workplace wellness can be a win-win situation as it improves both employees' health and employers' bottom lines. An unhealthy workplace and unhealthy lifestyle lead to work-related stress which, in return, leads to an increase in turnover, litigation, absenteeism, health insurance claims, presenteeism, short- and long-term disability, depression and accidents and to a decrease in employee satisfaction and commitment (Khairuddin et al., 2021). Research shows that stress can contribute to 19% of absenteeism cost (Hassard, et al., 2014). About 4.5% of all South Africans are absent on any given day due to work related stress (Nugroho et al., 2020). Presenteeism on the other hand can cost employers up to four times more than absenteeism (Vänni, et al., 2016). Presenteeism can be explained as employees attending work while being sick when it is justifiable to stay at home (Kawalec & Malinowski, 2015).

To succeed in the creation of active spaces, human factor research must be considered (Harrigan, 2014). Architects are challenged to conduct human factor studies in the context of design, while QSs have to shift their traditional focus from cost-estimation, financial control and contractual administration to include a more strategic role in shaping the built environment (Smallwood, 2015; Fonarrow et al., 2015). Designers have a direct and indirect influence on construction projects; hence the architect and interior designer should put the project in context in terms of project objectives reflecting the current situation, client needs, developing events and the future whilst comparing possible actions to feasibility and resources available (Smallwood, 2015). Active design requires early-stage planning, feasibility assessments and cost-justification to ensure successful integration (Sawyer et al., 2017).

2.3 COST CONSIDERATIONS AND FINANCIAL BARRIERS IN ACTIVE DESIGN IMPLEMENTATION

Implementing active design principles in construction often presents financial challenges. While long-term socio-economic benefits are increasingly acknowledged, the initial capital costs are perceived as financial risks and remain a concern for developers and project stakeholders (Abidin & Azizi, 2016; Shen et al., 2018). Cost related factors influencing the implementation of active design strategies include awareness, knowledge, financial, technical and government support (Kasim, et al., 2018). These factors are particularly relevant in the South African context where limited benchmarking data and industry research are available. Abidin and Azizi (2016) highlights that building for health creates healthy, comfortable, and economically prosperous places for employees and families. As cost is seen as one of the leading barriers to the implementation of active design strategies it is pertinent to understand the cost elements to recommend ways to reduce this cost and make active designed buildings feasibly presentable (Abidin & Azizi, 2016). Research shows that early-stage planning, spatial reconfiguration, and the integration of walkable layouts, stair prominence and green spaces can increase initial capital expenditure compared to conventional office buildings (Kasim et al., 2018). However, active designed buildings have been found to generate higher rental income, higher occupancy rates, longer economic lives, and high profits over a longer period of time for investors (Taemthong & Chaisaard, 2019).

From a Quantity Surveying perspective, these cost dynamics highlight the importance of robust feasibility assessments and value management. Quantity Surveyors are well-positioned to guide clients through feasibility studies, cost-benefit analysis, and life-cycle costing whilst quantifying indirect financial gains such as reduced absenteeism and increased employee productivity (Goh & Sun, 2016; Manewa et al., 2021).

3. METHODOLOGY

The exploratory nature of this study together with the limited existing empirical research on active design in South Africa leaned towards a qualitative case study research approach to explore and comprehend participants' perceptions and reactions towards the topic of active design within the construction sector, which is relatively new and not well understood. A two-way case study approach was employed, focusing on two modern office buildings in the Gauteng province in South Africa. This method allowed for an in-depth, context-rich understanding of how active design is implemented and perceived in real-world scenarios, capturing both cost and socio-economic dimensions through end-user experiences. The study was limited to two contrasting case studies, one with implemented active design principles (Building A, a national bank) and one conventional office building without active design implementation (Building B, conventional office building). The decision to limit the study to two cases was based on feasibility, the depth of analysis required and the goal of capturing rich, focused insights rather than broad generalizations. This aligns with the purposive logic of case study research, where fewer cases allow for deeper contextual and thematic analysis (Rodríguez-Labajos et al., 2021).

Building A, the FNB WesBank Headquarters situated in Johannesburg, South Africa, is a flagship commercial development with approximately 66,000m2 rentable space and was completed in 2020. This development integrates numerous active design features, including interconnected circulation routes, outdoor wellness areas, landscaped courtyards and on-site amenities that promote movement, social interaction and user

comfort. Building B, by contrast, is a medium-sized conventional office building situated in the Woodmead Office Park, also in Johannesburg, South Africa. It comprises approximately 10,000m2 office space and houses various professional tenants. The building follows a traditional layout, comprising a combination of open- and private office spaces, it has limited communal spaces and movement-enhancing design features. While the study acknowledges the differences in scale and user volume between the two buildings, both serve comparable commercial office functions and are located within similar urban and climate conditions. This allows for comparative exploration of how active design features influence occupant well-being and socio-economic perceptions.

The research conducted further interviewed a total of eighteen (18) participants from the case studies to obtain their input on the comprehensive understanding of the financial and socio-economic impact of implementing developing active design principles in construction. A combination of structured and semi-structured interviews was conducted. The participants were selected through a combination of purposive and snowball sampling until a saturation point was reached. These sampling strategies were important to maintain the high standard of knowledge from participants required to obtain valuable data. The participants were all users of the respective buildings. Additionally, five (5) industry experts were purposefully selected and interviewed to contribute to the overall understanding of active design implementation in the construction industry. Table 1 below presents the demographic and professional breakdown of the participants.

Table 1: Empirical study data

	Building A (Case Study)	**Building B (Case Study)**	**Other (Expert)**
Case Studies	Active Design - Bank	No Active Design - Conventional Office Building	N/A
Profession/ Field of Work	Financial / Other	Quantity Surveying	Quantity Surveying/ Construction related
Designations/ Role level	4 x Employers, 3 x Employees	4 x Employers, 9 x Employees	Employees
Interviewees	7	12	5
Interviewee ID's	A1, A2, A3, AS4, AS5, AS6, AS7	B1, B2, B3 BS4, BS5, BS6, BS7, BS8, BS9, BS10, BS11, BS12	C1, C2, CS3, CS4, CS5
Interviewee age group	3 x Participants per the following age group: 30 – 40	3 x Participants per the following age groups: 30 – 40; 40 – 50	2 x Participants per the following age group: 20 – 30
	4 x Participants per the following age group: 20 -30	4 x Participants per the following age group: 20 – 30	2 x Participants per the following age group: 30 – 50
		1 x Participant per the following age group: >60	1 x Participant per the following age group: 40 - 50
Interviewee gender	Female x 2 Male x 5	Female x 3 Male x 9	Female x 1 Male x 4

Expert participants were selected using purposive sampling to ensure representation across areas of construction, cost management and sustainable building practices. Participants were mainly identified based on their professional roles (Quantity Surveyors, Construction Related roles such as Construction Managers, Architects, etc., Financial Officers, etc.) and role levels (employees/employers) within the companies. These distinctions were useful for interpretation of responses in light of varying perspectives between end-users and decision- makers and to understand how different professional lenses shape attitudes towards active design implementation and cost feasibility. The study recognizes that demographic factors such as age and gender may influence personal health perspectives, and therefore a mix of ages and genders was achieved among both experts and users to enrich the diversity of perspectives.

Thematic analysis was used to analyze the data. The main analytical approaches employed in this study included revisiting the collected data and examining and categorizing the data to achieve the study objectives. The study also utilized techniques such as applied pattern matching and explanation building to analyze the data, codes were used to identify key points of data, concepts were developed to group similar codes, categories were formed to generate theory, and theory was used to explain the research topic. Participant codes were developed based on the buildings (A and B), expert interviewees were coded with a C, and distinction has been made between semi-structured (A, B, C) and structured interviews (AS, BS. CS).

4. RESULTS

4.1 PRESENTATION AND DISCUSSION OF RESULTS

Interviews were guided by semi-structured and structured questions aligned to the study objective. The four main themes explored included: awareness and understanding of active design principles, perceived health and productivity benefits of the built environment, financial implications and cost-related barriers, and social and cultural acceptance of active design features. Due to the qualitative nature of the study and space constraints, this paper presents the key emergent themes from the interview data rather than individual responses or per-case breakdowns.

Four major themes emerged from the thematic data analysis, namely, 1. Health and Wellbeing; 2. Financial Factors; 3. Socio-Economic Implications; 4. Barriers and Limitations. These themes align with the interview structure and study objectives and were further developed and explained as phenomenon.

Phenomenon 1: Promoting health and well-being through the construction industry. The initial concept explored various factors that affect and contribute to the overall health and well-being of individuals occupying buildings, including both employees and employers. Participants from Building A reported improved comfort, movement, and reduced fatigue and stress levels followed by an increase in productivity due to designated walking routes, natural light and stairwell prominence while participants from Building B reported discomfort in long sitting periods, lack of regulated fresh air and minimal exposure to natural light. Participants from Building B further noted that implementation of active design principles could improve employee morale and employee/employer relationships. All respondents expressed a keen interest in learning more about the effects of active design on their personal health and well-being, underscoring their value for personal wellness. The study also revealed that individuals who prioritize a healthy and active

lifestyle are more likely to be interested in learning about active design and its potential impact on employee health and well-being.

Phenomenon 2: Financial factors related to implementation. A key objective of this research was to identify the financial factors connected to the implementation of active design in the construction field. Theme 2 revolved around understanding the costs associated with implementing active design strategies in construction. It also explored whether the benefits of active design principles outweighed the costs and established a link between active design implementation and cost control. Experts highlighted a lack of financial awareness regarding active design returns among clients. Building A employers felt that the space they created justifies investment through increased motivation, productivity and business performance and decreased absenteeism and presentism. Participants from Building B had limited exposure to the impact of active design principles due to limited implementation and portrayed hesitance in the effect on business performance. They indicated that it might have some effect on business performance but should be closely monitored as some employees may take advantage of the concept which can have a negative effect on productivity. Experts indicated that early-stage cost-planning and ROI analysis for wellness design is still rare in South Africa. The findings align with existing literature, highlighting both direct and indirect cost implications of active design implementation. The study identified four key findings directly related to the financial impact of applying innovative active design principles in construction: knowledge, feasibility, implementation, and success factors. The empirical study revealed that Quantity Surveyors have limited knowledge about active design, that a healthy workplace can reduce company turnover, enhance the company's brand, and increase employee productivity. The empirical study also uncovered a lack of awareness among Quantity Surveyors when it comes to active design. Additionally, the study reinforces the conclusions reached by Abidin and Azizi (2016) that cost is a major obstacle in implementing active design. However, it was also found that the adoption of active design strategies in the construction industry could be feasible if effective cost management strategies are utilized. The findings highlight that successful implementation of active design strategies in construction relies on factors such as knowledge, feasibility, and cost management.

Phenomenon 3: Socio-economic response to the implementation of active design principles in the construction industry. The third theme focuses on the socio-economic aspects of the study. The study reveals that the application of innovative active design strategies in construction has a noticeable and valued socio-economic impact. It was observed that the implementation positively enhances employee relationships, employee/employer dynamics, employee performance and productivity, workforce positivity, self-confidence, education, and the environmental effects of buildings. Building A users reported increased social interaction, improved morale and higher satisfaction with shared spaces (lounges, cycling facilities, etc.). These features were also linked to improved team dynamics and self-confidence. Building B respondents reported disconnection from others and perceived their office space as purely functional. Expert interviews revealed that socio-economic outcomes of design are not generally considered in value management processes.

Phenomenon 4: Barriers and limitations to Active Design adoption. The fourth theme revolves around the factors that impact the implementation of active design strategies in the construction sector. A major limitation was identified as the lack of awareness among industry experts regarding the concept of active design and effective cost management

strategies. Responses from Building B users highlighted cost-related hesitancy, the absence of implementation guidelines and conservatism. Experts highlighted the need for training and evidence-based case studies to support increased adoption.

5. CONCLUSION AND RECOMMENDATIONS

This study identified the link between wellbeing and the built environment as a growing topic of interest. The literature proposes the incorporation of active design as a possible way to mitigate health problems associated with the lack of physical activity. It is evident that individual physical activity levels are influenced by policy, physical and socio-cultural environments, as well as individual personalities.

The results demonstrated that active design implementation in the South African construction industry can be feasible if optimal knowledge and cost management systems are applied. The study further found that the implementation of active design strategies can have a positive effect on socio-economic sustainability including employee relationships, employee/employer relationships, employee performance and productivity, positivity amongst the workforce, self-confidence, education, and the effect of buildings on the environment. The study however concludes that despite the potential of active design, there are inherent barriers that limits implementation in the South African construction industry. These include limited knowledge amongst industry experts on the topic as well as limited available research in the South African context. This study therefore recommends that the implementation of active design principles should be generalized as an industry norm. It is also recommended for clients invest in in-depth feasibility studies and cost analysis for optimisation of the benefits of the implementation of active design principles in construction.

The positive socio-economic impacts of implementing active design, such as enhancing employee and employer relationships, improving performance and productivity, boosting morale within the workforce, and increasing self-confidence, provide a compelling argument for QSs to expand their traditional roles. By adopting a more innovative mindset, QSs can make significant contributions and add value to the process through involvement in the early design phase and by implementing cost management principles and practices based on well-informed insights. By aligning their technical expertise with sustainability and wellness goals, QSs can become key enablers in delivering buildings that are cost-effective, socially responsive and future-proof. The research emphasizes a significant gap in the potential contribution of QSs to promote sustainable construction practices through active design. It is, however, crucial to enhance training and expand expertise in this field of active design and the role of construction to foster a superior and healthier built environment. This study contributes to the limited empirical literature on active design by offering comparative insights into its financial and socio-economic impacts in the South African context. It also highlights the evolving role of Quantity Surveyors in supporting health-oriented design through cost planning and feasibility analysis.

One potential constraint of this study is that the case studies were conducted exclusively in the Gauteng Province, which means that the findings may not necessarily apply to other regions or provinces. As a result, it is advisable for future research to include case studies from various areas and provinces in South Africa in order to determine if similar results can be obtained.

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FROM POLICY PRESENCE TO ENFORCEABILITY: EVALUATING WATER CIRCULARITY IN THE INDIAN CONSTRUCTION FRAMEWORKS

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ABSTRACT

With increasing water scarcity and accelerating urbanization in India, embedding circular water practices within the construction sector has become a critical imperative. This study undertakes a comprehensive evaluation of how Indian policies, standards, regulations, and green certifications address principles of water reuse and circularity across the building lifecycle. Using a structured assessment framework centred on eight key Construction Water Principles (CWPs) —such as water demand reduction, greywater reuse, rainwater harvesting, and lifecycle-based water planning—the research assesses each document based on three parameters: Presence (whether a principle is acknowledged), Strength (the technical clarity and detail), and Enforceability (the existence of legal and institutional mechanisms). These parameters are scored on a standardized scale to allow comparative analysis. The findings indicate that while several national frameworks exhibit strong recognition and moderate technical guidance, there is a consistent shortfall in legal enforceability and accountability. Critical gaps persist in areas such as dual plumbing mandates, construction-phase reuse, and integrated infrastructure planning. The study demonstrates that policies often remain symbolic in nature, with limited translation into implementable actions. To address these issues, the research proposes a replicable and scalable evaluation model that can help policymakers, regulatory bodies, and practitioners diagnose gaps and align regulatory instruments with circular water goals. Ultimately, the framework aims to shift focus from policy recognition to practical execution, advancing water sustainability in India's construction ecosystem.

Keywords: *Building Construction; Policy Evaluation; Regulatory Gaps; Sustainable Construction; Water Circularity.*

1. INTRODUCTION

Water is a finite and indispensable resource, and less than 1% of the Earth's freshwater is accessible for human use (World Green Building Council, 2023). The intensifying

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global water crisis has led to an urgent rethinking of water use strategies, especially in the construction sector where water demand is significant and recurrent across all project stages. As cities grow and climate change intensifies, the imperative to shift from linear water use models to circular approaches has become paramount (United Nations, 2018). Water circularity refers to the design and operation of water systems that minimize extraction, maximize reuse, and close the loop on wastewater streams. In the context of the built environment, this includes strategies such as greywater and blackwater reuse, rainwater harvesting, demand reduction, dual plumbing, and lifecycle-based water planning. Globally and in India, several policies, codes, standards, guidelines, and certification frameworks attempt to address these themes. However, there exists a notable lack of cohesion, consistency, and enforceability in how water circularity principles are integrated across these instruments.

The construction industry accounts for roughly 15% of global freshwater withdrawals (World Green Building Council, 2023), yet water circularity in the built environment remains largely overlooked in policy and practice, particularly in India. The Indian building and construction sector is governed by a fragmented mesh of documents ranging from national codes (e.g., IS standards, National Building Code), environmental regulations (e.g., EIA Notification), sectoral guidelines (e.g., CPCB/SPCB), and voluntary certifications (e.g., GRIHA, IGBC, LEED India). Internationally, frameworks such as LEED USA, BREEAM (UK), Green Star (Australia), CASBEE (Japan), and regulatory initiatives like Israel's Water Efficiency Law or Singapore's ABC Waters Programme have attempted to embed circularity. Yet, despite the presence of multiple instruments, the sector still lacks a systematic, comparative evaluation framework to assess how comprehensively and effectively water reuse and circularity principles are being addressed. Without a structured tool to diagnose and compare the strengths and gaps across these diverse frameworks, policymakers, practitioners, and researchers are left with fragmented insights and limited strategic direction.

To address this need, this study proposes a structured evaluation methodology based on a triadic framework of Presence, Strength, and Enforceability (P-S-E), applied to eight carefully chosen Construction Water Principles (CWPs). These CWPs reflect the most critical domains within the circular water paradigm applicable to the built environment: water demand reduction, greywater and blackwater reuse, rainwater harvesting and recharge, construction-phase water circularity, dual plumbing and infrastructure integration, reuse-ready storage systems, water quality for safe reuse, and lifecycle-based water planning. The triadic lens helps capture three key dimensions: whether a principle is recognized (Presence), how technically robust the articulation is (Strength), and whether it is supported by legal or institutional enforcement mechanisms (Enforceability). Each dimension is scored from 0 to 3, offering a quantifiable yet nuanced view of each document's performance.

2. LITERATURE REVIEW

The integration of water circularity into policy frameworks is a relatively recent yet expanding field of research. Traditionally, water governance studies have focused on supply-side management and centralized infrastructure planning (Gleick, 1998). However, the global shift towards sustainable urban development and the limitations of conventional water systems have prompted a growing body of literature emphasizing decentralization, resource recovery, and reuse (United Nations Environment Programme - UNEP, 2016). Circular water strategies in buildings offer multiple benefits: reducing

dependence on freshwater sources, minimizing wastewater discharge, and enhancing resilience against climate-induced water stress (Dobbs et.al., 2011). Nonetheless, the success of these strategies depends largely on the supporting regulatory and policy environment, a theme echoed across environmental governance literature (Ostrom, 2009).

Policy effectiveness in environmental domains is often evaluated using multidimensional frameworks. Howlett and Cashore (2009) argue that "policy content" is the foundational layer in evaluating a policy's capacity and intent. Without formal recognition of a principle, it remains outside the sphere of policy attention. In this context, the Presence parameter in this study ensures that circular water principles are at least acknowledged in the regulatory narrative (TERI University, 2017). Similarly, the technical robustness or Strength of a provision determines whether it can be operationalized. Ostrom (2009) and Rogers et al. (2000) emphasize that clearly defined and measurable policy directives are essential for effective implementation and accountability. Vague or symbolic references fail to drive institutional change or influence design and construction practices.

Enforceability, the third pillar, is often the weakest link in policy frameworks, especially in the Global South. The United Nations Environment Programme – UNEP (2019) report on Environmental Rule of Law identifies poor enforcement as a major challenge, even where policies exist on paper. The Organisation for Economic Co-operation and Development (2020) adds that monitoring capacity and legal clarity are crucial to achieving environmental outcomes. Cashore et al. (2004) distinguish between voluntary and mandatory regimes, highlighting that enforceable standards are more likely to produce tangible results. In the domain of green building, global certifications like LEED, BREEAM, and Green Star incorporate enforcement indirectly—through third-party verification, performance tracking, and credit-based incentives. However, regulatory codes often lack such operational tools, especially in India where implementation mechanisms vary across states and municipalities.

Several studies have attempted to assess water-related policies, but most adopt qualitative or thematic analysis. For instance, studies evaluating the EIA Notification (2006) or National Building Code (2016) focus on policy gaps or sectoral limitations. Others explore the alignment of green certifications with sustainability goals. Yet, there is little consensus on a unified assessment method. This study's P-S-E framework builds on existing approaches used in policy content analysis (Scholz & Wang, 2006) and Regulatory Impact Assessment (RIA) tools by OECD and the European Union. These frameworks underscore the need to evaluate not just the existence of a regulation, but also its clarity and enforceability. The P-S-E methodology distils these insights into a concise, replicable tool specifically tailored for water circularity.

The choice of eight CWPs is based on a synthesis of contemporary literature and best practices in sustainable water management. In a CE, water is treated as a closed-loop resource, meaning it can be reused and recycled within the system (Bouziotas et al., 2023). Municipal sources are already strained, borewell extraction accelerates aquifer depletion, and tankers often rely on informal or illegal extraction, undermining local water equity (World Bank, 2016). Water flow in building construction can be made more sustainable by integrating systems that recycle greywater, harvest rainwater, and reuse treated wastewater for non-potable purposes (Gonzalez et al., 2021). By adopting innovative technologies and integrating water recycling, the construction sector can play a significant role in mitigating water scarcity and environmental degradation (Frijns et al., 2024). Water demand reduction is universally acknowledged as a first step in

conservation (Gleick, 1998). Greywater and blackwater reuse are gaining momentum, especially in water-stressed regions, supported by case studies from Singapore, Israel, and California (World Bank, 2016). Rainwater harvesting and recharge have been mandated in several Indian states, yet implementation remains uneven. Construction-phase water use is often ignored, although it constitutes a significant share of project-stage consumption. Infrastructure provisions such as dual plumbing and reuse-ready storage are prerequisites for enabling future reuse, aligning with lifecycle-based planning perspectives advocated in Integrated Water Resource Management frameworks (Global Water Partnership Technical, 2000).

The integration of water quality standards is essential for safe reuse, yet in India, guidelines like IS 3025 and CPCB norms often remain non-binding. Lifecycle-based planning, a core tenet of circular economy thinking, is largely absent in conventional water codes. This fragmented landscape demands an evaluation tool that can holistically assess how policies, standards, and certifications address each of these principles. By combining thematic relevance (CWPs) with policy analysis parameters (P-S-E), the framework proposed in this study seeks to fill this methodological gap. It enables cross-comparative analysis between Indian and global instruments, identifying patterns, strengths, and lacunae.

In conclusion, there is a critical need for a structured, evidence-based evaluation method to know how well water reuse and circularity principles are embedded in the regulatory ecosystem of the construction sector (Ministry of Environment & Forests, Government of India, 2010). As water scarcity becomes a central challenge for cities and buildings alike, the ability to diagnose policy gaps and recommend strategic reforms is more important than ever. The P-S-E evaluation method, aligned with eight CWPs, offers a promising methodology to achieve this goal. It is grounded in established literature on policy analysis, environmental governance, and sustainability metrics. Moreover, it provides practical utility for researchers, policymakers, and green building professionals aiming to advance water circularity in both Indian and global contexts.

3. METHODOLOGY

This study employs a structured, criteria-based evaluation framework to assess the comprehensiveness and effectiveness of water-related policies, standards, codes, and certifications that influence the construction and operation phases of buildings. The methodology is grounded in eight CWPs derived from key dimensions of sustainable and circular water management. These principles were selected based on international best practices, Indian green building standards, and interdisciplinary literature on IWRM, environmental governance, and circular economy transitions (Rogers et al., 2000; United Nations Environment Programme - UNEP, 2019; Ellen MacArthur Foundation, 2017).

3.1 SELECTION OF CWPS

The eight CWPs used for evaluation reflect both conventional and advanced water circularity strategies applicable to the built environment, as illustrated in Figure 1. These principles were developed after an extensive review of international frameworks such as UNEP's Circularity in Water Management (United Nations Environment Programme - UNEP, 2016), the EU Circular Economy Action Plan, and sustainability rating systems like LEED v4.1, BREEAM, Green Star, and Singapore's ABC Waters Programme. Additional inputs were drawn from scholarly research on urban water circularity, lifecycle-based infrastructure planning, and decentralized reuse systems.

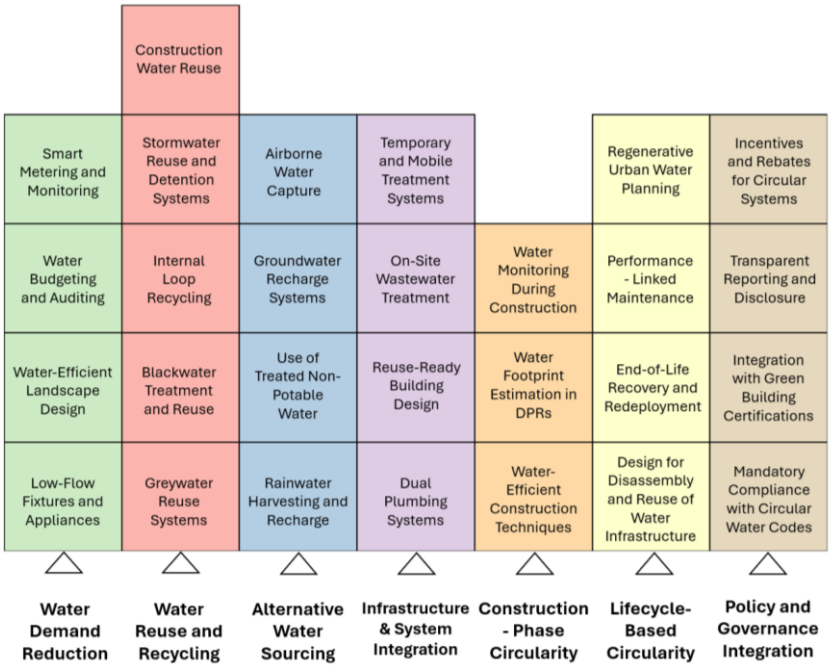


Figure 1: Circular water principles in the built environment
Source: Author

The formulation of these principles was guided by the need to evaluate not just water-use efficiency but also systemic infrastructure readiness, regulatory alignment, and construction-phase circularity—elements often overlooked in conventional water frameworks. The resulting eight CWPs include:

1. Water Demand Reduction – minimization of water consumption through design, fixtures, and behaviour change mechanisms.
2. Greywater & Blackwater Reuse – collection, treatment, and reuse of wastewater streams for non-potable or landscape applications.
3. Rainwater Harvesting & Recharge – on-site storage and infiltration systems to reduce runoff and augment groundwater.
4. Construction-Phase Water Circularity – strategies for water reuse, treatment, and management during the construction process.
5. Dual Plumbing & Infrastructure Integration – provision of parallel pipelines for potable and non-potable water flows to enable reuse.
6. Reuse-Ready Storage Systems – built infrastructure (e.g., tanks, reservoirs) that supports future water reuse scalability.
7. Water Quality for Safe Reuse – specification of quality parameters, treatment thresholds, and health safety for reused water.
8. Lifecycle-Based Water Planning – long-term, integrated planning of water systems across the building's lifecycle, including adaptive strategies for climate resilience.

These CWPs were curated to span both end-use efficiency and upstream planning and governance, thereby offering a comprehensive framework to evaluate Indian policies on water circularity. Full mapping of documents against these principles is detailed in subsequent sections, while justification tables are provided in the Annexure.

3.2 EVALUATION DIMENSIONS: PRESENCE, STRENGTH AND ENFORCEABILITY

Each document, be it a regulation, code, standard, or voluntary certification, was assessed across the eight CWPs using three evaluation dimensions:

1. Presence (P): Whether a particular principle is mentioned, recognized, or acknowledged in the document.
2. Strength (S): The technical clarity and depth of guidance provided, including any quantitative standards or engineering protocols.
3. Enforceability (E): The legal authority, mechanisms for compliance, and extent to which non-adherence is subject to monitoring or penalties.

These evaluation dimensions—Presence, Strength, and Enforceability (P–S–E)—were chosen based on well-established policy assessment models, such as the Regulatory Impact Assessment (Organisation for Economic Co-operation and Development, 2009), Scholz and Wang's (2006) policy content analysis frameworks, and environmental certification criteria used in LEED, BREEAM, and Green Star. Together, these dimensions offer a multidimensional lens for evaluating regulatory instruments, one that balances conceptual acknowledgment (Presence), technical specificity (Strength), and implementation potential (Enforceability). This approach is especially suited to the evaluation of environmental policy instruments, which must be assessed not just on their intent but on their depth and likelihood of real-world impact (Cashore et al., 2004; Howlett & Cashore, 2009).

3.3 SCORING FRAMEWORK

Each policy or standard was scored on a 0 to 3 scale for each of the three evaluation dimensions across all eight CWPs, with a total of 24 scores per document. The scoring scale is interpreted in Table 1 given below.

Table 1: Score interpretation of the dimensions for CWP evaluation

No.	Dimension	Score	Score interpretation
1.	Presence (P)	0	Not Addressed
		1	Weakly or Implicitly Addressed
		2	Moderately Addressed with Some Specific Guidelines
		3	Clearly and Explicitly Addressed with Detailed Guidelines
2.	Strength (S)	0	Weak or Not Specified
		1	Weakly Mentioned or Suggestive
		2	Moderately Strong with Some Technical Detail
		3	Technically Strong and Detailed
3.	Enforceability (E)	0	Not Enforceable (no legal backing or monitoring)
		1	Weakly Enforceable (voluntary or advisory only)
		2	Moderately Enforceable (some legal basis, limited enforcement)
		3	Strongly Enforceable (legally mandated with monitoring, penalties)

This quantitative rubric facilitates comparability across heterogeneous instruments—ranging from mandatory national codes like the National Building Code (NBC 2016) to voluntary certifications like GRIHA or LEED India, as well as operational guidelines from CPWD, CPCB, and various State-level DCRs and ULB policies.

Building on the evaluation dimensions discussed above, the study adopts a structured P–S–E scoring framework to enable systematic comparison across policy documents. This framework is grounded in established literature on policy evaluation and regulatory governance. It draws directly from the OECD's Regulatory Impact Assessment (RIA), which emphasizes the need to assess policy content for coverage, technical detail, and institutional enforceability (Organisation for Economic Co-operation and Development, 2009).

The tripartite structure is also aligned with Scholz and Wang's (2006) framework that distinguishes between the existence of a policy, its technical substance, and its administrative credibility. Furthermore, this scoring method reflects practice-oriented evaluation models embedded in green building certifications such as LEED, BREEAM, and Green Star, where criteria are scored based on presence, quality of guidance, and compliance assurance. Theoretical reinforcement comes from governance scholars like Cashore et al. (2004) and Howlett and Cashore (2009), who argue for integrated assessment of policy instruments based on content, capacity, and legitimacy.

Recent contributions in the urban water governance literature also support this approach, suggesting that the success of circular water frameworks depends not only on innovation in design but on enforceability, institutional alignment, and implementation tracking.

3.4 DATASET SELECTION

The documents selected for evaluation were categorized into Indian and global instruments. The Indian set includes five categories: (1) National Policies and Frameworks such as the National Water Policy (2012) and EIA Notification (2006); (2) BIS Standards and Codes like IS 456:2000, IS 1172:1993, and NBC 2016; (3) Regulatory Guidelines including those issued by the CPCB, SPCBs, and the CPWD Manual; (4) Local Government Instruments such as Urban Local Body (ULB) policies and Development Control Regulations (DCRs); and (5) Voluntary Green Building Certifications including GRIHA, IGBC, and LEED-India. These documents together represent the multi-tiered regulatory landscape shaping water-related decision-making in the Indian construction sector.

The global set includes instruments like LEED (USA), BREEAM (UK), Green Star (Australia), BEAM Plus (Hong Kong), CASBEE (Japan), ABC Waters (Singapore), and Israel's water reuse policy framework. These were selected based on their prominence in sustainability literature, adoption in urban water resilience case studies, or citation in global water governance reports (World Bank, 2016; United Nations-Habitat, 2020).

3.5 DATA COLLECTION AND CODING

Each policy and regulatory document was independently reviewed and scored by two researchers with expertise in sustainable construction, urban water systems, and Indian regulatory frameworks. They were selected for their familiarity with both technical standards and institutional contexts. In developing the coding framework, a broader panel of experts—including green building professionals, urban planners, and legal scholars—were consulted through interviews and informal feedback. While their insights helped

refine the Circular Water Principles (CWPs) and scoring rubric, the two lead researchers conducted the primary scoring due to their overarching understanding and consistency.

Documents were evaluated across three dimensions—Presence, Strength, and Enforceability (P–S–E)—for each of the eight CWPs. Scores were based on explicit references, inclusion of technical details, and the use of compliance-oriented language (e.g., "shall," "must"). A detailed coding guideline was developed, piloted on a sample of policies, and refined before full application to ensure consistency.

Discrepancies in scoring were infrequent but typically arose in the Strength and Enforceability dimensions. For instance, a performance target without technical depth could be interpreted differently depending on emphasis. Similarly, unclear implementation mechanisms (e.g., in state DCRs) led to varied enforcement scores. These differences were resolved through iterative discussions referencing the rubric and comparable examples until consensus was reached.

To enhance transparency, a justification matrix was created for each score assigned. These justifications are document-specific and based on direct textual evidence, technical annexures, and regulatory phrasing. For example, a Strength score of "2" was only given if a document showed moderate but incomplete technical detail related to a specific CWP.

While summary heatmaps are presented in the main text (Figures 2 and 3), the full justification tables are available in the Annexure. This enables readers to trace the reasoning behind each score and supports replicability of the method. The approach balances comparative synthesis with analytical depth, ensuring that the scoring process remains robust, transparent, and grounded in documented evidence.

3.6 ANALYSIS APPROACH

The scores were then aggregated and visualized using matrix heatmaps and comparative tables. Descriptive statistics (averages, standard deviations) were calculated for each CWP across all documents. Cross-sectional comparisons were conducted between Indian and global frameworks to highlight strengths, gaps, and opportunities for policy transfer or harmonization.

Special attention was paid to patterns of low Presence but high Strength or Enforceability (indicating niche technical interventions not widely mainstreamed), high Presence but low Enforceability (indicative of symbolic policy with limited follow-through), and consistently low scores across all dimensions for a principle (signalling critical lacunas).

This enabled both a horizontal evaluation (within a document across all CWPs) and a vertical evaluation (for a single CWP across all documents).

3.7 LIMITATIONS AND SCOPE

This evaluation is limited to textual policy analysis and does not assess on-ground implementation or stakeholder perceptions. Furthermore, the enforceability dimension is inferred from legal phrasing and mandates but does not include field verification or implementation of enforcement practices.

Nevertheless, this structured P-S-E scoring model allows for systematic benchmarking and policy diagnosis. It serves both as a comparative tool and as a basis for future work on policy enhancement, especially as circular water practices gain traction under climate resilience and urban sustainability agendas.

4. RESULTS AND FINDINGS

4.1 PATTERN ANALYSIS OF INDIAN POLICIES, REGULATIONS, STANDARDS AND CERTIFICATIONS FOR CWP IN CONSTRUCTION

In the real-world implementation of circular water practices in the Indian construction sector, it is essential to dissect the scope, strengths, and gaps in existing regulatory frameworks and institutional actors. The extended analysis below evaluates major national codes, standards, and policy instruments—against key Circular Water Principles (CWPs). The following Table 2 is essential as it maps the alignment of key Indian policies and regulations with each of the eight CWPs, offering a snapshot of the current policy landscape. It highlights both the areas of regulatory endorsement and the gaps in comprehensive adoption, helping to justify the need for a structured assessment framework that can evaluate presence, strength, and enforceability across these principles.

Table 2: Alignment of key Indian policies and regulations with eight CWPs

No.	CWP Principle	Indian Policies and Regulations Endorsing It
1	Water Demand Reduction	NBC 2016, IS 456, EIA, GRIHA/IGBC, CPCB (guidance)
2	Greywater & Blackwater Reuse	NBC 2016, IS 456, EIA, GRIHA, CPCB, SPCBs
3	Rainwater Harvesting & Recharge	NBC, National Water Policy, GRIHA/IGBC, DCRs, ULBs, EIA, CPCB
4	Construction-Phase Water Circularity	IS 456 (partial), EIA (partial), CPCB (stronger), GRIHA (partial), SPCBs (compliance)
5	Dual Plumbing & Infra Integration	NBC 2016, GRIHA, DCRs, EIA
6	Reuse-Ready Storage Systems	IS 3370, NBC, CPCB (partial)
7	Water Quality for Reuse	IS 3025, IS 456, CPCB
8	Lifecycle-Based Water Planning	GRIHA, LEED, EIA, CPCB (early-stage C&D water reuse pilots)

By comparing principles horizontally across policies, it becomes easier to pinpoint patterns of redundancy, fragmentation, and policy silence. For example, while rainwater harvesting is consistently addressed, construction-phase water reuse is frequently neglected across otherwise progressive codes. The mapping thus acts as both a compliance checklist and a policy integration matrix, offering a strategic view of the degree to which water circularity has been embedded—or omitted—within India's building and urban regulatory frameworks, as seen in Figure 2. This structured comparison lays the groundwork for identifying not just individual document gaps, but system-level misalignments in policy intent versus execution.

An analysis of Indian regulations reveals a mixed pattern in the integration of CWPs. On the positive side, green building rating systems such as GRIHA, IGBC, and LEED India, along with the EIA Notification (2006), consistently score high in both Presence and Strength. These frameworks provide detailed, technically sound provisions on aspects like water reuse, rainwater harvesting, and demand reduction. Similarly, guidelines issued by the Central Pollution Control Board (CPCB) and various State Pollution Control Boards (SPCBs) show stronger enforceability—particularly in areas related to wastewater reuse and quality standards—indicating a relatively robust regulatory mechanism for environmental water management.

CW Principle	Water Demand Reduction			Greywater & Blackwater Reuse			Rainwater Harvesting & Recharge			Construction-Phase Water Circularity			Dual Plumbing & Infrastructure Integration			Reuse-Ready Storage Systems			Water Quality for Safe Reuse			Lifecycle-Based Water Planning		
Level	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E
National Water Policy (2012)	2	2	0	2	1	0	3	2	1	1	1	0	1	0	0	1	1	0	1	1	0	2	2	0
NBC 2016	3	3	2	2	2	1	3	3	3	1	1	1	2	1	1	2	2	1	1	1	1	1	1	1
IS 456:2000	2	2	1	2	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IS 3370:2009	1	1	0	1	1	0	2	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
IS 2065:1983	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IS 1172:1993	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0
IS 3025 Series	0	0	0	1	2	0	1	0	0	0	0	0	0	0	0	0	0	0	3	3	2	0	0	0
CPWD Manual	1	1	1	0	0	0	1	2	2	2	2	1	1	1	1	2	2	1	1	1	1	1	1	1
GRIHA/ IGBC/ LEED -India	3	3	1	3	3	1	3	3	1	3	3	1	3	3	1	3	3	1	3	3	1	3	3	1
EIA Notification (2006)	3	3	3	3	3	3	3	1	2	1	1	2	0	0	0	1	1	0	1	1	0	1	1	1
DCRs (State-wise)	2	2	2	2	2	2	3	2	2	1	1	1	1	1	0	1	1	1	0	0	1	0	0	0
ULB Policies	2	2	2	2	2	2	2	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0
CPCB Guidelines	2	2	2	3	3	2	3	2	1	1	1	0	0	0	0	1	1	0	3	3	3	1	1	1
SPCBs Guidelines	2	2	2	3	3	3	2	1	1	1	1	0	0	0	0	1	1	0	2	2	2	1	1	1

Legend	Presence Score (P):	Strength Score (S):	Enforceability Score (E):
	0 = Not Addressed	0 = Weak or Not Specified	0 = Not Enforceable (no legal backing or monitoring)
	1 = Weakly or Implicitly Addressed	1 = Weakly Mentioned or Suggestive	1 = Weakly Enforceable (voluntary or advisory only)
	2 = Moderately Addressed with Some Specific Guidelines	2 = Moderately Strong with Some Technical Detail	2 = Moderately Enforceable (some legal basis, limited enforcement)
	3 = Clearly and Explicitly Addressed with Detailed Guidelines	3 = Technically Strong and Detailed	3 = Strongly Enforceable (legally mandated with monitoring, penalties)

Figure 2: Matrix mapping for Indian policies and regulations against eight CWPs based on Presence, Strength and Enforceability
Source: Author

However, substantial gaps are evident. Many Bureau of Indian Standards (BIS) codes, such as IS 456, IS 3370, IS 2065, IS 1172, and IS 3025, suffer from low enforceability scores (mostly 0s and 1s), suggesting that these standards, while occasionally technically sound, lack binding mechanisms for implementation. Further, for more advanced water practices such as reuse-ready storage systems and dual plumbing infrastructure, both Presence and Strength are typically minimal or absent. These topics often score between 0 and 1, indicating a lack of recognition or technical guidance. Local-level policies, such as those formulated by Urban Local Bodies (ULBs) and embedded in Development Control Regulations (DCRs), show poor and inconsistent enforcement, with scores in the 0–1 range, pointing to significant decentralization and governance challenges in implementation.

4.2 Pattern Analysis of Global Best Practices for CWP in Construction

Globally, several leading policies and certification frameworks have mainstreamed CWPs as integral components of sustainable development in the built environment. These frameworks go beyond traditional water efficiency to incorporate closed-loop systems, lifecycle reuse, and infrastructure-level resilience. Green building certifications and national initiatives exemplify how CWPs are translated into enforceable design and operational strategies. These systems provide detailed technical guidance, mandatory

performance metrics, and post-occupancy accountability, setting a high benchmark for water circularity in urban construction. The comparative Figure 3 outlines the key features of each framework that align with CWPs and illustrates the scope and ambition with which global best practices address water reuse, rainwater harvesting, stormwater management, and non-potable water infrastructure. This sets a reference point for evaluating the relative maturity and implementation potential of India's evolving regulatory ecosystem.

When compared to Indian counterparts, global policies and standards show much stronger integration of CWPs across the board. International certification systems such as LEED (USA), BREEAM (UK), Green Star (Australia), BEAM Plus (Hong Kong), and CASBEE (Japan) demonstrate consistently high scores in both Presence and Strength, typically ranging between 2 and 3. These systems incorporate comprehensive checklists, performance criteria, and technical detailing, ensuring that water-related design strategies are thoroughly embedded into the building lifecycle.

CW Principle	Water Demand Reduction			Grey/ Blackwater Reuse			Rainwater Harvesting			Construction Phase Reuse			Dual Plumbing Readiness			Reuse-Ready Storage Systems			Water Quality for Safe Reuse			Lifecycle-Based Water Planning		
Level	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E	P	S	E
LEED v4.1 (USA)	3	3	1	3	3	1	3	3	1	1	1	0	2	2	1	2	2	1	3	3	1	3	3	1
BREEAM (UK)	3	3	1	2	2	1	3	2	1	1	1	0	2	2	1	2	2	1	3	3	1	3	3	1
EU Circular Economy Plan	2	2	2	2	2	2	2	1	1	1	0	0	1	1	0	1	1	0	2	2	2	3	3	2
ABC Waters (Singapore)	2	2	2	2	2	2	3	3	2	0	0	0	1	1	1	1	1	1	2	2	2	2	2	2
Israel Water Policy	3	3	3	3	3	3	2	1	1	0	0	0	1	1	0	1	1	0	2	2	2	2	2	2
Sponge City Program (China)	2	2	2	2	2	2	3	3	2	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1
BEAM Plus (Hong Kong)	3	3	1	2	2	1	3	2	1	1	1	0	2	2	1	2	2	1	2	2	1	3	3	1
Delta Programme (Netherlands)	2	2	2	2	2	2	2	2	2	0	0	0	1	1	0	1	1	0	2	2	3	3	3	3
CASBEE (Japan)	2	2	1	2	2	1	2	2	1	0	0	0	1	1	0	1	1	0	2	2	1	3	3	1
Green Star (Australia)	3	3	1	3	3	1	3	3	1	2	2	1	2	2	1	2	2	1	3	3	1	3	3	1

Legend	Presence Score (P):	Strength Score (S):	Enforceability Score (E):
	0 = Not Addressed	0 = Weak or Not Specified	0 = Not Enforceable (no legal backing or monitoring)
	1 = Weakly or Implicitly Addressed	1 = Weakly Mentioned or Suggestive	1 = Weakly Enforceable (voluntary or advisory only)
	2 = Moderately Addressed with Some Specific Guidelines	2 = Moderately Strong with Some Technical Detail	2 = Moderately Enforceable (some legal basis, limited enforcement)
	3 = Clearly and Explicitly Addressed with Detailed Guidelines	3 = Technically Strong and Detailed	3 = Strongly Enforceable (legally mandated with monitoring, penalties)

Figure 3: Matrix mapping for global best practices against eight CWPs based on Presence, Strength and Enforceability
Source: Author

Beyond certification systems, leading national frameworks such as the Israel Water Policy, the Delta Programme (Netherlands), and China's Sponge City initiative stand out for their strong performance across all three metrics. These policies emphasize water reuse, flood resilience, and integrated planning, with enforceability mechanisms that are both structured and impactful. Singapore's ABC Waters Programme is particularly noteworthy for achieving high scores across the board, thanks to its emphasis on landscape integration, long-term planning, and stringent monitoring.

Nevertheless, even some global systems exhibit gaps, particularly in enforceability. For example, CASBEE and the EU Circular Economy Action Plan show weaker legal backing for advanced reuse strategies, scoring low in enforceability for niche principles such as construction-phase water circularity and reuse-ready infrastructure. This points to a global challenge in bridging innovative design concepts with legal mechanisms for compliance.

4.3 COMPARATIVE GAP ANALYSIS AND KEY LACUNAE

A comparative analysis between Indian and global regulatory frameworks reveals significant shortcomings in how Indian systems address Circular Water Principles

(CWPs). While global frameworks (e.g., Singapore, Israel, Netherlands) show uniform integration of circular strategies across building lifecycles, Indian policies remain fragmented. Except for GRIHA and IGBC, Indian regulations display weak coverage of CWPs, especially during the construction phase. The most evident disparity lies in enforceability—Indian instruments typically score between 0 and 1, whereas global policies range from 1 to 3, backed by institutional mandates and penalties. Technical strength is evident in NBC 2016 and the EIA Notification, but this is inconsistent across IS codes and silent on emerging areas like dual plumbing or reuse-ready infrastructure. Urban local governance in India further suffers from decentralization, resulting in fragmented DCRs and uneven policy enforcement at the municipal level.

Key lacunae include the lack of legal mandates and monitoring, leading to weak ground-level implementation even where water-related clauses exist (e.g., IS 456, NBC). Indian regulations are not integrated with urban planning or climate resilience frameworks, limiting systemic transitions to circularity. Moreover, infrastructure readiness is rarely mandated provisions for dual plumbing, greywater lines, or rainwater storage are absent in most codes. Construction-phase water circularity is also largely unaddressed, despite being a high-consumption phase. These limitations collectively hinder India's ability to mainstream circular water practices in its built environment.

5. CONCLUSION AND RECOMMENDATIONS

This study identifies critical gaps and misalignments in how Indian policies, codes, and standards address Circular Water Principles (CWPs) in the built environment. Through a structured evaluation across the dimensions of Presence, Strength, and Enforceability, the analysis reveals that while circularity is increasingly acknowledged in policy texts, significant inconsistencies exist in technical clarity and implementation mechanisms.

It is important to note a methodological limitation: the "Enforceability" dimension was inferred from the legal language, mandates, and institutional jurisdiction present in the documents, rather than verified through field-level assessment. As such, the enforceability scores represent theoretical enforceability—what *should* be enforced based on textual provisions—not what is *actually* enforced on the ground. This distinction is critical and underscores the need for future studies to incorporate empirical validation of policy enforcement and compliance practices, particularly at the level of urban local bodies (ULBs), state departments, and regulatory authorities.

To address the identified policy gaps and transition toward a more circular and resilient water paradigm, several strategic directions are proposed. First, legal enforceability must be strengthened across relevant instruments, especially those under the Bureau of Indian Standards (BIS), National Building Code (NBC), and EIA frameworks. Embedding mandatory provisions, backed by compliance audits and penalties, is essential. Second, comprehensive integration of CWPs into IS codes and building guidelines should be carried out through coordinated and harmonized revisions. Third, adoption of global best practices—such as Israel's compliance-driven mandates or Singapore's infrastructure-linked planning tools—can inform scalable solutions for India. Fourth, mandatory infrastructure readiness, such as dual plumbing systems, greywater lines, and rainwater recharge pits, should be incorporated into building approval processes across all jurisdictions. Fifth, dedicated circularity guidelines for construction-phase water use—currently a blind spot—must be developed to address temporary reuse systems, curing water recycling, and runoff management. Lastly, institutional coordination among

ministries (e.g., Water Resources, Urban Development, Housing, Environment) and municipal authorities is essential to unify regulatory efforts under a circularity-oriented governance framework.

While these directions emerge from this analysis, they require further empirical testing through the study of actual projects, programs, and their outcomes. Future research should focus on ground-level enforcement, stakeholder capacity, and regulatory performance, to refine and validate policy strategies for water circularity in the Indian built environment.

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8. ANNEXURE 1: Justification table for CWP scoring framework

CWP	Water Demand Reduction					
Level	**P**	**Justification**	**S**	**Justification**	**E**	**Justification**
National Water Policy (2012)	2	Acknowledges water as an economic resource and promotes efficiency, but lacks detailed sector-specific guidelines for buildings.	2	Promotes water efficiency across sectors and recommends technologies for conservation, but lacks detailed implementation methods or technical benchmarks for construction.	0	High-level strategic framework with no legal binding or enforceable mandates on water efficiency.
NBC 2016	3	Strong emphasis on low-flow fixtures, water-efficient appliances, and water budgeting in building design.	3	Provides detailed technical guidance on low-flow fixtures, water budgeting, efficient landscaping, and water-saving plumbing designs. Appendices include fixture flow rates and design considerations.	2	Enforceability depends on whether state or city authorities adopt NBC provisions in local bye-laws; partial enforcement in Tier-1 cities.
IS 456:2000	2	Indirectly contributes through control of water-cement ratio and optimized curing, but does not address end-use demand.	2	Recommends reduced water use for concrete curing and mixing; indirectly supports water conservation in construction through water-cement ratio control and minimal usage practices.	1	Applied in structural engineering contexts; water-saving practices during construction are not independently enforced.
IS 3370:2009	1	Focused on structural storage; no provisions for demand reduction but indirectly supports water conservation through secure storage.	1	Offers technical specifications for storage tanks, indirectly enabling water conservation through containment, but does not address end-use reduction methods.	0	Focuses on storage tank design; no enforceable provisions regarding demand reduction or usage behavior.
IS 2065:1983	2	Provides water supply design standards and sizing, but based on outdated norms and without reduction focus.	1	Provides design sizing for pipelines, but the norms are outdated and not based on modern efficiency goals or reduced water consumption logic.	0	Outdated and not incorporated in regulatory approvals; no enforceable clauses on efficiency.
IS 1172:1993	1	Provides per capita consumption norms, but does not emphasize reduction or efficiency; norms are outdated.	1	Lists per capita water demand standards but does not guide efficiency improvements; norms are excessive compared to modern benchmarks and lack adaptive context.	0	Still used for plumbing design, but its norms are not binding in terms of water-saving compliance.
IS 3025 Series	0	Focuses entirely on water quality testing; no content related to demand reduction.	0	Entirely focused on water quality testing methods; does not contribute to demand reduction practices or plumbing efficiency.	0	Testing standards only; no direct linkage to regulatory implementation of water-saving measures.
CPWD Manual	1	Estimates construction water demand but does not promote reduced consumption or specify efficient methods.	1	Includes general estimates of construction-phase water requirements, but lacks technical suggestions for conservation techniques or alternate construction practices.	1	Binding only for government construction projects under CPWD; no enforcement mechanism outside of CPWD jurisdiction.
GRIHA/ IGBC/ LEED -India	3	Clearly encourages low-flow fixtures, metering, water budgeting, and efficient landscape design as rating criteria.	3	Highly detailed guidance for achieving water efficiency, including specific fixture types, irrigation strategies, and water budgeting approaches backed by performance metrics.	1	Voluntary rating systems; water efficiency measures are only enforced in participating certified projects.
EIA Notification (2006)	3	Mandates water balance charts, estimation of fresh and recycled water demand, and justification of source.	3	Strong in technical clarity—mandates submission of water balance charts, fresh and recycled water demand justification, and incorporates demand reduction via reuse systems.	3	Enforceable via Environmental Clearance for large projects; requires water budgeting, reuse targets, and periodic compliance submissions.
DCRs (State-wise)	2	Varies by state; many require water-efficient fixtures but lack uniformity or detail in mandates.	2	Varies significantly across states; where present, some include fixture efficiency and metering guidelines, but the depth of technical detail differs by region.	2	Many state-level DCRs now require water-efficient fixtures or plumbing standards during plan approvals; enforcement varies by municipality.
ULB Policies	2	Some urban local bodies promote audits, metering, and rebates for water-efficient fittings, though fragmented.	2	In cities with advanced building regulations (e.g., Pune, Delhi), ULBs issue guidelines for low-flow fixtures and water-efficient landscaping, though not always standardized.	2	Urban local bodies can enforce water-saving fixtures and metering through building permissions and plumbing inspections.
CPCB Guidelines	2	Encourages reduction in water use and reuse in construction-related environmental management practices.	2	Encourage efficient water use and reference good practices, but lack exhaustive design-level detailing. Often generalized and applicable at macro scale.	2	Integrated into EC processes via MoEF&CC and monitored indirectly through SPCBs; enforceability is medium-strength.
SPCBs Guidelines	2	Support efficiency during environmental clearances; however, demand reduction is not always explicitly mandated.	2	Offer moderate-level guidance on reducing water consumption in EC-compliant projects and suggest good practices for water efficiency, especially in large developments.	2	Enforceability stems from their role in monitoring EC compliance conditions, including water consumption and efficiency targets.

* This table is only a sample table for Indian policies evaluated for one CWP for the purpose of understanding of the reader. Such tables were generated for all CWPs for all policies and guidelines studied (Indian and International) during the process of data analysis and research.

Hemantha, H.H.A.P., Perera, R.A.B.U.N. and Uduwage, D.N.L.S., 2025. Global research trends in carbon capture and utilization technologies for cement production: A Bibliometric analysis. 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. 773-786. DOI: https://doi.org/10.31705/WCS.2025.58. Available from: https://ciobwcs.com/papers/

GLOBAL RESEARCH TRENDS IN CARBON CAPTURE AND UTILIZATION TECHNOLOGIES FOR CEMENT PRODUCTION: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

The cement industry is a significant contributor to global Carbon Dioxide (CO_2) emissions, necessitating the adoption of Carbon Capture and Utilization (CCU) technologies to mitigate environmental impacts. This study conducts a bibliometric analysis of CCU technologies for cement production, with a focus on research trends, influential publications, key authors, and emerging themes. Using Scopus as the data source and VOSviewer for network visualization, the study maps the intellectual structure of CCU research and examines global collaboration patterns. The study highlights the disparity in CCU research between developed and developing nations, emphasizing the need for more inclusive and regionally relevant studies. The findings provide insights for policymakers, industry professionals, and researchers to align the cement sector with global decarbonization trends. Recommendations are made for integrating CCU into the construction industry, considering economic, regulatory, and technological challenges.

Keywords: *Bibliometric Analysis; Carbon Capture and Utilization; Cement; VOSviewer.*

1. INTRODUCTION

Carbon Capture and Utilization (CCU) technologies have become increasingly important in addressing the environmental impact of the cement industry, which is a major contributor to global Carbon Dioxide (CO_2) emissions (Hanifa et al., 2022). Cement production is carbon-intensive due to processes such as calcination and high-temperature combustion (Agrawal et al., 2024). With urbanization driving demand for cement, the need for sustainable solutions has never been more critical (Huang et al., 2017). CCU offers a promising approach by converting CO_2 into useful products, such as concrete aggregates, fuels, and chemicals, thus contributing to the circular economy (Ghiat & Al-Ansari, 2021). This aligns with global efforts, such as the Paris Agreement, to mitigate

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climate change while fostering industrial sustainability (Aggarwal, 2024). However, the scalability, economic viability, and technical efficiency of CCU methods remain key areas of research (Hanson et al., 2024).

The global research landscape on CCU technologies in cement production has expanded significantly over the past two decades, with countries like China and the United States at the forefront of research and investment (Dziejarski et al., 2023). However, developing nations, including Sri Lanka, have been slower to adopt these technologies despite the importance of the cement industry to their infrastructure (Danieli et al., 2025). Sri Lanka's reliance on both imported and locally produced cement highlights the need for sustainable production techniques (Fernando et al., 2024). While global research is robust, Sri Lanka-specific studies on CCU remain limited, indicating a need for more localized investigations into the feasibility and applicability of these technologies in the country (Nasvi, 2021).

Therefore, this study aims to analyze global and regional research trends in CCU technologies for cement production by identifying key contributors, influential publications, major research institutions, and examining the evolution of research themes and keyword patterns within the field. By focusing on Sri Lanka, the study addresses the gap in region-specific knowledge and encourages international collaboration. This collaboration is essential for overcoming technical, financial, and regulatory barriers and promoting the sustainable transformation of Sri Lanka's cement sector. To achieve this aim, the following objectives are formulated.

- To analyse the global and regional research trends in CCU technologies for cement production.
- To identify key contributors, influential publications, and major research institutions in the field of CCU technologies.
- To examine the evolution of research themes and keyword trends in CCU for cement production.

2. LITERATURE REVIEW

Cement production is a vital industrial activity that plays a significant role in global carbon emissions, highlighting the need for a thorough understanding of its environmental impact and possible mitigation measures (Barbhuiya et al., 2024). The manufacturing process consists of multiple stages, including raw material extraction, calcination, and the final grinding of clinker with additives (Hanifa et al., 2022). A key source of emissions arises during calcination, where limestone (Calcium Carbonate) is subjected to high temperatures, resulting in the formation of lime (calcium oxide) and the release of CO_2 (Agrawal, 2024). On average, the production of one ton of cement clinker generates approximately 0.9 tons of CO_2, contributing to an estimated 5% to 8% of global anthropogenic CO_2 emissions (Barbhuiya et al., 2024). Additionally, the cement industry is highly energy-intensive, accounting for around 12% to 15% of total industrial energy consumption, further amplifying its carbon footprint (Barbhuiya et al., 2024).

The environmental impact of cement production goes beyond CO_2 emissions, as the process also releases other carbon-containing greenhouse gases (CO, CH_4, HFC_s, PFC_s) and pollutants, negatively affecting air quality and contributing to climate change (Imboden et al., 2014). Lifecycle assessments of cement production indicate that a significant share of greenhouse gas emissions originates from the extraction and

processing of raw materials, with research highlighting that raw material production is a major contributor (Dahanni et al., 2023). Additionally, the cement industry is frequently associated with biodiversity loss and habitat destruction due to quarrying activities (Imboden et al., 2014). Direct emissions from energy use and limestone calcination make up roughly 60% of total emissions, while indirect emissions from electricity and heat production account for another 40% to 50% (Sousa & Bogas, 2021).

2.1 CEMENT INDUSTRY IN SRI LANKA

In Sri Lanka, the cement industry is a key driver of infrastructure development, but it also faces significant challenges concerning environmental sustainability (Madhuwanthi & Somachandra, 2019). Sri Lanka has been making efforts to incorporate more sustainable approaches in cement manufacturing, such as utilizing alternative fuels and raw materials to lower carbon emissions (Usón et al., 2013). Studies suggest that the adoption of alternative fuels can substantially decrease emissions while also offering economic advantages (McLaughlin et al., 2023). Additionally, the feasibility of CCU technologies is being considered as a strategy to mitigate emissions from the cement industry (Monteiro & Roussanaly, 2022). As Sri Lanka's cement sector continues to expand, maintaining a balance between economic development and environmental stewardship is essential, ensuring that the industry supports national growth objectives while minimizing its environmental footprint (Ministry of Environment and Natural Resources, Sri Lanka, 2007).

At present, Sri Lanka has not yet implemented full-scale CCU facilities within its cement industry. However, several preliminary initiatives and feasibility studies have been undertaken to assess the country's readiness and potential for carbon capture deployment. The government, in collaboration with academic institutions and international environmental agencies, has started exploring CCU pathways more aligned with Sri Lanka's economic and technological landscape. Pilot projects focusing on low-cost carbon capture technologies such as chemical absorption using amine-based solvents, mineral carbonation using industrial by-products, and the integration of solid sorbents have been evaluated in academic and research contexts (Fernando et al., 2024).

2.2 OVERVIEW OF CO_2 CAPTURE TRANSPORT, STORAGE AND UTILIZATION

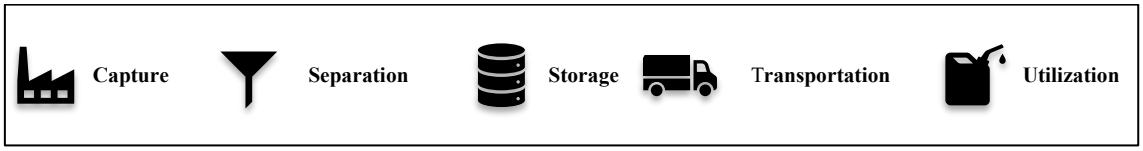


Figure 1: CCU process

Carbon emissions are a major contributor to climate change, primarily generated by industrial activities such as cement production, power generation, and steel manufacturing (Belaïd, 2022). CCU is a key strategy to mitigate these emissions by capturing CO_2 at the source, transporting it to appropriate locations, and either storing it safely or utilizing it for value-added applications (McLaughlin et al., 2023). Figure 1 illustrates the process of CCU technologies, providing a visual representation of how carbon dioxide is captured from industrial sources, transported, and either stored permanently or converted into useful products through various utilization pathways.

Table 1 presents a comprehensive categorization of the key technological domains associated with CCU systems. It outlines the primary categories that must be considered in the implementation of CCU frameworks, highlighting the multiple options available for each stage of the process.

Table 1: CCU process different options
Source: (Hanson et al., 2024)

Category	Options
CO_2 Capture	Industrial Separation, Post-combustion capture, Oxy-fuel combustion capture, Pre-combustion capture
Separation	Solvents (Absorption), Membranes, Solid sorbents, Cryogenic
CO_2 Storage (Sequestration)	Deep Saline Aquifers, Depleted Oil & Gas Reservoirs, Basalt & Mineralization Storage, Ocean Storage (Under Research)
CO_2 Transport	Pipeline Transport, Ship Transport, Truck and Rail Transport
CO_2 Utilization	Products Providing Permanent Storage, Products Potentially Providing Long-Term Storage Intermediates for Products, Products Providing Short-Term Storage and Utilizing CO_2 in the Conventional Production Process, Products Providing Short-Term Storage and Utilizing CO_2 in Nonconventional Processes, Utilization of CO_2 for Renewable Fuel Production

3. RESEARCH METHODOLOGY

This section explains how the literature was extracted and the types of analysis used to scrutinize it.

3.1 MATERIAL EXTRACTION

In this study, Scopus was selected as the primary data source for bibliometric analysis due to its comprehensive coverage of peer-reviewed literature. Scopus provides advanced search functionalities that allow for precise filtering based on keywords, publication years, document types, and citation metrics (Powell & Peterson, 2017). By using Scopus, this study ensures the inclusion of authoritative and up-to-date research on carbon capture and utilization technologies in cement production, supporting a robust bibliometric analysis (Elsevier, 2024). The query below was developed to extract the material related to this study from Scopus.

Table 2- Literature extraction

Criteria	Description
Sources website	Scopus
Years	2015 January to 2025 February
Searching terms	"Carbon Dioxide", "Carbon Capture", "Cements", "Carbon Capture and Utilization", "Carbon", "Carbon Capture and Storage", "Adsorption", "Cement Industry", "Cement", "Carbon Storage", "Construction Industry", "Carbon Utilization", "CCS", "CCUS", "Cement Production"
Inclusions Criteria	All Open Access Final Articles

Criteria	Description
Exclusion Criteria	Other languages Articles, Books, Proceeding Papers, Review Articles, Book Chapters, Letters, Editorial materials, Early Accesses
Sample size	5984

In the search query, a focused selection of academic articles published between 2015 and 2025 was utilized to explore the latest developments in carbon capture and utilization technologies within the context of cement production. 17 specific keywords (Carbon Dioxide, Carbon Capture, Cements, Carbon Capture And Utilization, Carbon, Carbon Capture And Storage, Adsorption, Cement Industry, Cement, Carbon Storage, Concrete, Concretes, Construction Industry, Carbon Utilization, CCS, CCUS, Cement Production) were strategically chosen to capture a broad yet relevant range of literature, ensuring comprehensive coverage of the subject area. The application of these keywords resulted in the retrieval of 5,984 articles, which formed the dataset for the bibliometric analysis. To maintain the quality and relevance of the analysis, only English-language articles categorized as final stage publications were included, ensuring the study focused on peer-reviewed, finalized research that reflects the most recent high-quality academic work in the field. All materials were downloaded on March 12, 2025, thereby ensuring the timeliness and consistency of the dataset. This stringent selection process resulted in a robust and up-to-date sample that supports the comprehensive bibliometric analysis of carbon capture technologies in cement production.

To analyse and visualize the structure and evolution of research related to CCU technologies in cement production, this study adopted a bibliometric analysis approach, which offers a systematic and quantitative means of evaluating scholarly literature (Donthu et al., 2021). Bibliometric analysis was selected for its ability to reveal trends, intellectual structures, and collaboration dynamics within a specific research domain (Aria & Cuccurullo, 2017). It provides critical insights into the development of the field, key contributors, and influential research clusters, thereby establishing a foundation for deeper content analysis and decision-making in subsequent stages of the research (Zupic & Čater, 2015).

The analysis was conducted using VOSviewer, a specialized software tool designed for constructing and visualizing bibliometric networks. Its advanced capabilities in handling large datasets and generating interpretable graphical maps made it particularly suitable for this study (van Eck & Waltman, 2014). The techniques selected for this study are closely aligned with its core objectives, ensuring a comprehensive and systematic understanding of the research landscape surrounding CCU technologies in cement production.

To achieve objectives, 'Collaboration Network Analysis' through bibliometric coupling of countries and regions is employed. This method reveals the geographical distribution of research efforts, highlighting which nations or regions are actively contributing to CCU research in the cement sector. Additionally, co-authorship analysis among authors uncovers patterns of academic collaboration, providing insights into how research networks are formed and how knowledge is shared across institutions and borders. In addressing the objective of identifying key contributors, influential publications, and major institutions, Density Visualization based on citation intensity plays a crucial role. This technique emphasizes highly cited works and prolific authors or institutions, allowing the study to pinpoint where and by whom impactful research is being produced.

Citation density also serves as a proxy for academic influence and recognition within the field.

To examine the evolution of research themes and emerging research areas, 'Overlay Visualization' is applied to the bibliometric coupling of sources. This enables a temporal view of how research interests and focal points have shifted over time, identifying transitions in dominant themes and the emergence of novel areas of inquiry. Furthermore, 'Word Cloud Analysis' of author keywords visually distils the most frequently used terms, highlighting prevalent topics and signalling upcoming research directions based on recent keyword trends.

4. RESULTS AND DISCUSSION

This section presents the findings derived from the literature and discusses the analytical techniques employed to interpret and evaluate the data.

4.1 CHRONOLOGICAL DISTRIBUTION OF SCIENTIFIC LITERATURE

Figure 2 presents the number of academic publications related to CCU technologies in cement production from 2015 to 2025. The main purpose of this graph is to show how research interest in this specific field has changed over time. The graph shows the annual number of publications, which helps to understand the level of academic attention given to CCU technologies in the cement industry. From the results, it is clear that the number of publications has been increasing steadily over the years. In 2015, there were 106 publications, and this number gradually grew each year, reaching 994 publications in 2023. This steady rise shows that research interest in this area has been growing consistently.

A significant increase is observed in 2024, with 1,635 publications, the highest number during the entire period. This suggests that CCU technologies in cement production have become a major topic of interest recently, possibly due to global climate concerns and advancements in carbon capture methods. However, in 2025, the number of publications drops to 510. It is important to note that this figure reflects data only up to February 2025. If the current publication rate continues consistently throughout the year, the extrapolated total for 2025 would be approximately 3,060 publications, almost double the number recorded in 2024. Therefore, the lower figure observed at this stage should not be interpreted as a decline in research interest but rather as a reflection of the early point in the publication calendar.

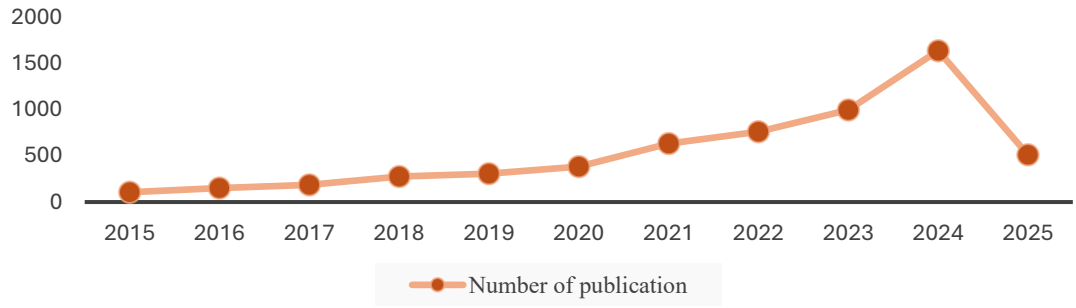


Figure 2: Number of publications in years

Overall, the data indicates a growing academic interest in CCU technologies in the cement industry between 2015 and 2024. This trend reflects the increasing importance of developing low-carbon solutions for one of the world's most emissions-intensive industries and directly supports the first objective of this study. Further analysis of the content of these publications can help identify the main focus areas, emerging themes, and gaps in the existing research.

4.2 INTERNATIONAL RESEARCH COLLABORATION- A BIBLIOMETRIC COUPLING ANALYSIS OF COUNTRIES AND REGIONS

Bibliometric coupling is a method used in bibliometric analysis to identify relationships between countries, authors, or institutions based on shared references in their publications. As per Figure 3, bibliometric coupling by country was used to understand how different nations are contributing to the research on CCU Technologies for cement Production. The purpose of this analysis is to identify leading countries in the field, understand patterns of international research efforts, and highlight global collaboration trends.

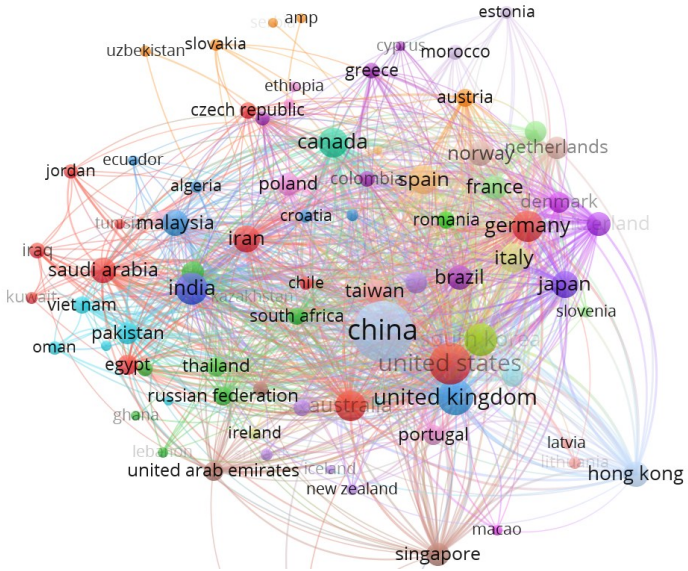


Figure 3: Countries/regions collaboration network (minimum 20 documents)

Table 2: Top 5 countries based on the number of publications

Rank	Country	Documents	Citation
1	China	2269	50845
2	United State	564	18893
3	United Kingdom	305	15994
4	South Korea	271	6348
5	India	236	5040

According to the results presented in Table 02, a total of 146 countries have published at least one article on this topic. This demonstrates a broad global interest in CCU technologies and a shared recognition of the need to address carbon emissions in cement production. Among all countries, China is the leading contributor, with 2,269

publications. It also has the highest citation count of 50,845, which reflects both the volume and influence of its research. The United States ranks second, with 564 publications and 18,893 citations, showing its strong presence in this area. The United Kingdom comes third, contributing 305 publications and receiving 15,994 citations.

4.3 Analysing Citation Intensity through Bibliometric Density Mapping

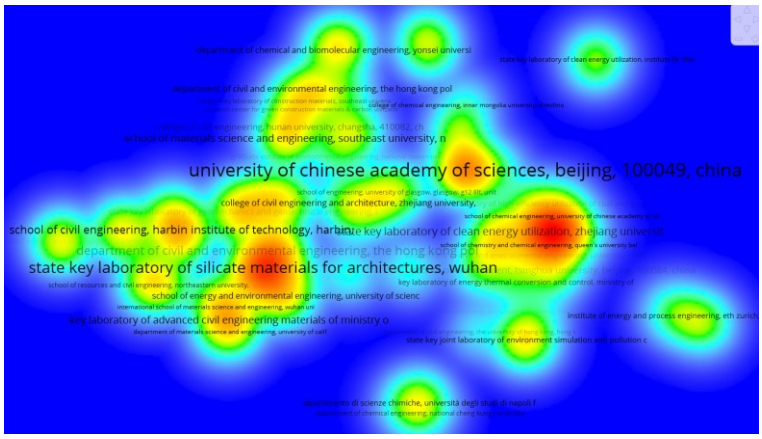


Figure 4: Citation intensity of density visualization clusters in institutional cooperation (minimum 5 documents)

Figure 4 presents a density visualization of citation intensity among research organizations engaged in carbon capture and utilization (CCU) technologies for cement production. This visualization highlights not merely the presence of collaboration but the academic impact of institutions, based on how frequently their work is cited. Warmer colours (red) indicate high citation concentrations, signifying institutions whose publications are widely referenced, whereas cooler regions (green and yellow) denote comparatively lower citation intensity.

From the analysis, several institutions emerge as key contributors. Notably, the University of Chinese Academy of Sciences appears in one of the densest red zones, suggesting its central role in high-impact CCU research. Similarly, Tsinghua University's School of Environment and School of Energy and Power Engineering demonstrate strong citation intensity, underscoring their reputation in environmental and industrial carbon studies. Other influential institutions include the State Key Laboratory of Clean Energy Utilization**, the** Department of Civil and Environmental Engineering and the School of Materials Science and Engineering, which collectively form visible clusters of academic recognition. These findings reflect a concentration of impactful CCU research in East Asia, particularly China, consistent with broader publication trends in the field.

4.4 Ranking of Research Institutions by Publication Output

According to Table 3, Chinese organizations emerge as pioneers in this field, reflecting their strong commitment to reducing carbon emissions from the cement sector—one of the country's most emission-intensive industries. Leading the list is the Chinese Academy of Sciences, which has contributed 53 publications and received 1,125 citations, indicating both high output and significant academic impact. The Wuhan University of Technology (Silicate Material for Architecture) follows with 41 documents and 1,274 citations, demonstrating a strong specialization in materials research relevant to CCU

technologies. Another prominent contributor is the Hong Kong Polytechnic University, with 30 publications and a higher citation count of 1,606, indicating substantial influence in the academic community.

Table 3: Top 5 institutions based on the number of publications

Rank	Organization	Documents	Citations	Country
1	Chinese Academy of Science	53	1125	China
2	Wuhan University of Technology (silicate material for architecture)	41	1274	China
3	Hong Kong Polytechnic University	30	1606	China
4	Harbin Institute of Technology	26	1009	China
5	Zhejiang University	24	476	China

In total, 12,994 organizations worldwide have contributed to research in this domain, highlighting the global scale of institutional involvement and collaboration. Table 4 provides a summary of the top 5 institutions based on the number of publications, offering insight into the key research leaders in the development of carbon capture and utilization technologies for cement production. These findings suggest that China's research institutions play a leading role in shaping the scientific advancements in CCU technologies. Their prominent presence in both publication volume and citation impact illustrates their strategic focus on sustainable technologies and positions them as global leaders in this critical area of environmental innovation.

4.5 BIBLIOMETRIC COUPLING OF SOURCES- A TEMPORAL OVERLAY PERSPECTIVE

Figure 5 and Table 4 present the results of a Bibliometric coupling of source analysis, which was conducted to identify the most influential academic journals contributing to the field of CCU Technologies for Cement Production. This type of analysis is important because it helps determine where research is being published, which journals serve as key platforms, and how scholarly communication is structured within the field. Understanding the distribution of publications across journals is valuable for recognizing reputable sources, tracking the dissemination of knowledge, and guiding researchers toward impactful publication venues. The analysis reveals that research in this area is highly interdisciplinary, with publications appearing in a total of 864 different journals. This wide distribution reflects the diverse nature of CCU research, which spans environmental science, materials engineering, construction, and energy systems.

Among the sources, the Journal of Cleaner Production stands out as the leading journal, having published 378 documents related to CCU in cement production. This journal focuses on sustainability, cleaner production, and environmental management, making it a suitable outlet for research in low-carbon cement technologies. The second most prominent journal is Construction and Building Materials, which has published 359 articles. This indicates a strong connection between CCU technologies and advancements in construction materials, especially in efforts to reduce the carbon footprint of traditional cement and concrete. The Journal of Carbon Dioxide Utilization also plays a significant role, contributing 196 publications specifically focused on innovative methods for

capturing and converting CO_2 into useful products. This aligns directly with the core objective of the research domain.

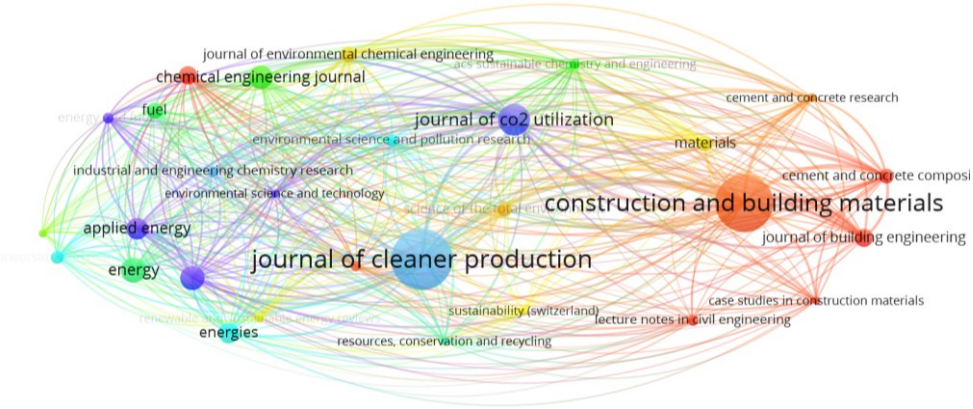


Figure 5: Overlay visualization of source journals(minimum 15 documents)

Overall, the source analysis highlights the interdisciplinary and evolving nature of CCU research within the cement industry. The concentration of publications in a few key journals suggests the presence of specialized platforms that are shaping the academic conversation and influencing research directions in sustainable cement production.

Table 4: Top 5 most cited journals with Cite score and impact factor

Rank	Source	Documents	Citation	Cite Score	Impact factor
1	Journal of Cleaner Production	378	13723	20.4	9.8
2	Construction and building materials	359	5945	13.8	7.4
3	Journal of carbon dioxide utilization	196	6272	13.9	7.2
4	Energy	155	3371	15.3	9.0
5	International Journal of Greenhouse Gas Control	133	1433	10.0	6.7

4.6 AUTHOR COLLABORATION NETWORKS- A CO-AUTHORSHIP ANALYSIS

Figure 6 presents the results of a co-authorship author network analysis, which was conducted to identify the most influential researchers and collaborative relationships in the field of CCU Technologies for Cement Production. This type of analysis focuses specifically on co-authorship patterns, revealing how researchers are connected through joint publications.

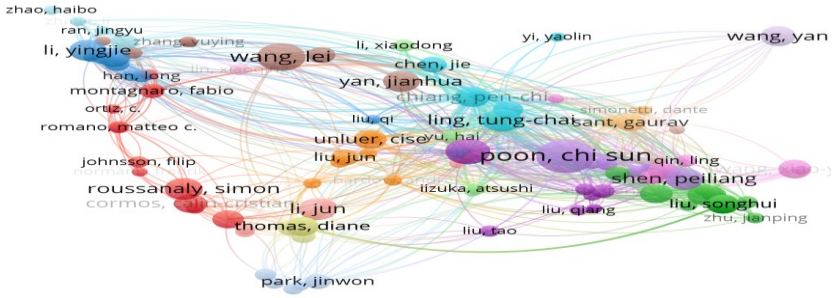


Figure 6: Network visualization map of authors (minimum 10 document)

The visualization map in Figure 6 illustrates the collaborative networks among authors by mapping out the relationships formed through co-authored research articles. Authors who frequently collaborate are grouped into clusters, and the strength of their connections is represented by the proximity and thickness of the linking lines.

Table 5: Top 5 authors based on number of publications

Rank	Author	Documents	Citation	Country
1	Poon, Chi Sun	35	1209	China
2	Wan, Lei	29	708	China
3	Wang, Tao	27	999	China
4	Ling, Tung-Chai	24	1142	China
5	Shen, Peiliang	23	216	China

According to Table 5, 21,416 authors have contributed to research in this field, highlighting the extensive global collaboration in advancing CCU technologies for cement production. Among the top contributors, Poon Chi Sun stands out with 35 publications and 1,209 citations, emphasizing advancements in sustainable construction materials.

4.7 KEYWORD ANALYSIS THROUGH WORD CLOUD VISUALIZATION

Figure 7 presents a word cloud view of author keywords from publications in the field of CCU Technologies for cement production. The word cloud technique is used to visually represent the frequency of terms or keywords in the literature, with the size of each word reflecting its importance or frequency. This technique is particularly useful for identifying prominent research topics, trends, and areas of focus within a large body of literature. It allows for an intuitive, quick understanding of what has been central to the research discussions and helps highlight emerging concepts or themes. In this study, the word cloud organizes the author keywords by their first appearance in the literature, showcasing the development of research topics since 2015 and directly supports the third objective of this study.

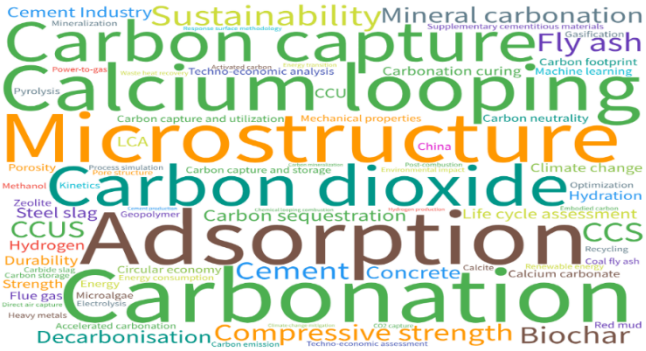


Figure 7: Word cloud of author keyword

The integrated bibliometric techniques employed in this study have collectively offered a comprehensive understanding of the global research landscape on CCU technologies in cement production. Collaboration network analysis has effectively identified the geographical distribution of research and the extent of academic partnerships across countries and institutions, reflecting the collaborative nature of advancements in this

domain. Citation-based density visualization has highlighted the most influential authors, institutions, and publications, thereby uncovering the intellectual pillars shaping the field. The overlay visualization of bibliometric coupling among sources has provided a temporal perspective, tracing the evolution of scholarly focus and the emergence of novel research directions over time. Additionally, word cloud analysis of author keywords has illuminated dominant research themes and recurring concepts, offering a snapshot of both current priorities and potential future trends.

5. CONCLUSIONS

This study conducted a comprehensive bibliometric analysis to examine global and regional research trends in technologies within the cement industry, an essential sector in reducing industrial CO_2 emissions. The results mainly show global patterns, with most high-impact research coming from developed regions such as Europe, North America, and East Asia. In comparison, research from developing countries is limited, indicating a gap and pointing to the opportunity for these countries to increase their involvement in CCU development.

Although this study used only the Scopus database and English-language articles, which means that some local or non-indexed studies may not have been captured, it still provides useful knowledge that can help other countries develop their own CCU research and policies. These global findings can guide governments, researchers, and industries in making informed decisions, investing in cleaner technologies, and planning for low-carbon construction. To advance in this area, countries will need to strengthen local expertise, increase public awareness, and build partnerships with international research organizations. Future research should consider using additional databases and combining different methods to gather broader and more locally relevant information. This approach can better support climate action and help achieve long-term sustainability goals.

As CCU technologies are primarily adopted in developed countries, these findings underscore the potential for developing countries like Sri Lanka to leverage such technologies in the cement sector. A national plan should be established with clear policy direction, financial incentives, and collaboration among government agencies, the private sector, and academic institutions.

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GREEN ADAPTIVE RE-USE OF BUILDINGS IN SRI LANKA

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ABSTRACT

Sustainability has emerged as a key component of the construction industry, and it is now incorporated into all aspects of building administration, construction, and design. In terms of sustainability, adaptive reuse of buildings and green building concepts can be considered superior alternatives to modern construction. Many past research studies have been carried out on the green building concept as well as the adaptive reuse of buildings in the construction industry. However, there is a lack of research related to the integration of green building concept with adaptive reuse of buildings. Thus, the aim of this research is to investigate the applicability of green building concepts to the adaptive reuse of buildings. Qualitative research approach was used to fulfil the objectives of this study. Semi-structured expert interviews were used to collect data and case studies were used to validate the findings which were obtained through expert interviews. To analysis the data, manual content analysis was used. During the expert interviews, factors considered in green adaptive reuse of buildings were identified. Through case studies, those findings were validated. Factors were categorised into nine (09) categories namely economic, environmental, social, functional, technological, legal, architectural, physical, and political. As there are less studies related to green adaptive reuse of buildings, the outcomes of the study can be used as a basis for future studies.

Keywords: *Green Building; Sustainable Construction; Green Adaptive Re-Use; Sri Lanka.*

1. INTRODUCTION

The construction industry's activities immensely contribute to the waste generation and negatively impact on sustainability (Yildirim & Turan, 2012) due to excessive energy and material use, solid waste creation, greenhouse gas emissions, external pollution, harm to the environment, and resource depletion (Chan et al., 2009). Sustainable construction practices have become crucial for obtaining social, economic, and environmental benefits from the sector (Alaloul et al., 2021). Green building techniques, such as energy-efficient HVAC systems, renewable energy sources, and sustainable materials, can be combined with adaptive re-use of buildings to further reduce energy consumption and waste (Maulina et al., 2022). Green building is an environmentally responsible approach to design, construct, and operate buildings, with the goal of creating energy-efficient structures that use renewable resources and minimize environmental impact while promoting healthy indoor environments (Saravanan, 2011; Nadeeshani et al., 2021). Further, green buildings improve resource efficiency through

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improved design, construction, operation, maintenance, waste collection, and recycling (Ragheb et al., 2016). The concept of green building comprises various elements and components that are intertwined to form the green building concept (Samer, 2013).

Adaptive re-use of existing structures is a well-established concept that extends the economic, environmental, and social functions of buildings, materials, and components (Misirlisoy & Günçe, 2016; Conejos et al., 2011). Adaptive re-use involves the transformation of a non-functional component into a new item that can be used for a different purpose (Bertino et al., 2021). This process involves upgrading the performance of the building to suit modern standards and changing user requirements while retaining as much of the original building as possible (Laefer & Manke, 2008). The technique provides the building with an innovative use while preserving its historical and cultural significance (Douglas, 2006). However, current adaptations rely on subjective methods and the intuition of practitioners, which can limit objective measurement (Tam & Hao, 2019).

There are number of research studies that have been carried out on the green building concept in the construction industry (Alsulaili et al., 2020; Ding et al., 2018; Hwang et al., 2017; Sharma, 2020; Liu & Lin, 2016). Further, research has been carried out on the adaptive re-use of buildings in the construction industry as well (Aigwi et al., 2021; Misirlisoy & Günçe, 2016; Tam & Hao, 2019). However, limited attention has been paid on integrating green building concepts and the adaptive re-use of buildings.

The construction industry in Sri Lanka is a fast-growing industry, which highly contributes on the economy of the country (Illankoon et al., 2022). Therefore, maintaining the productivity of the Sri Lankan construction industry is vital for the development of Sri Lanka (Manoharan et al., 2020). However, Nawarathna et al. (2019) stated that the development in the construction industry paves the way for the generation of environmentally hazardous outputs. Further, high solid waste generation (Kaluarachchi, 2018) and high energy consumption (Nadeeshani et al., 2021) can be identified as barriers that are being faced by the building construction in Sri Lanka. Therefore, sustainable construction practices should be adapted to mitigate the barriers and establish environmental, economic, and social sustainability in the country (Athapaththu & Karunasena, 2018). Green building concepts (Weerasinghe et al., 2021) and adaptive re-use of building concepts (De-Silva et al., 2019) can be introduced as modern and practical sustainable practices in the construction sector in Sri Lanka. According to the current situation of Sri Lanka, adaptive re-use of buildings will promote to minimize building redundancy in next year's rather than demolition and replacement of the existing buildings. Further, encouraging adaptive re-use of buildings can have various economic, socio-cultural, and historical benefits and the green building concept will add dynamic value to the adaptive reuse of buildings. Hence identifying the applicability of green building concepts to adaptive re-use of buildings would yield many benefits to the Sri Lankan construction industry. Accordingly, this study investigates the applicability of green adaptive re-use of buildings within the Sri Lankan context.

The aim of this study is to investigate the applicability of green building concepts to the adaptive reuse of buildings in Sri Lanka. To achieve this aim, the study first explores how green building concepts can be integrated within adaptive reuse projects in the Sri Lankan context. It then identifies the key factors influencing such integration by conducting expert interviews. Finally, it validates and refines these identified factors through in-depth case studies of selected green adaptive reuse projects.

2. LITERATURE REVIEW

2.1 ADAPTIVE RE-USE OF BUILDINGS

Repurposing existing buildings for new purposes while maintaining its structure and character is known as adaptive re-use (Bullen & Love, 2011). This technique is seen as sustainable since it adheres to the values of environmental preservation, cultural heritage preservation, and conservation (Balliana et al., 2016). According to studies, adaptive reuse extends a building's life by meeting contemporary needs, lowering waste from demolition, and lowering the need for new construction (Foster, 2020). In urban settings, where historic buildings are challenged by urbanization and functional obsolescence, adaptive reuse works especially well (Davies et al., 2024). In order to preserve historical and cultural value while pursuing sustainable development goals, important frameworks like Campbell's Planner's Triangle emphasize the necessity of striking a balance between social, economic, and environmental goals in reuse projects (Campbell, 2016). Additionally, the viability and sustainability of reuse programs are regularly evaluated using multi-criteria decision-making techniques (De-Feo et al., 2018).

2.2 GREEN ADAPTIVE RE-USE OF BUILDINGS

Adaptive reuse and green building techniques combine to form a hybrid approach with a sustainability focus (Spina, 2021). Green adaptive reuse addresses the environmental effects of both construction and operation by incorporating renewable energy technology, sustainable materials, and energy-efficient retrofitting into repurposed structures (Jane, 2025). This strategy is praised for fostering sustainability and preserving cultural heritage (Pai et al., 2025). By lowering resource consumption and extending the life cycle of existing structures, research shows how important green adaptive reuse is in promoting circular economies (Foster, 2020). High upfront expenditures, legal restrictions, and the technical challenges of incorporating contemporary green technologies into older buildings are some of the obstacles (Chan et al., 2017).

2.3 APPLICABILITY OF GREEN ADAPTIVE RE-USE BUILDINGS TO SRI LANKA

Sri Lanka's rich architectural legacy and escalating environmental issues present a special setting for green adaptive reuse (Wijesiri et al., 2022). The nation's traditional and historic colonial structures offer chances for green-minded adaptive reuse (Uekötter, 2010). However, implementation is frequently hampered by issues like low public awareness, insufficient policy frameworks, and budgetary limitations (Crosby, 1996). Sri Lanka may encourage green adaptive reuse by embracing internationally accepted sustainability standards and utilizing the cultural significance of its legacy (De-Silva et al., 2019). Stakeholder participation, professional training programs, and laws encouraging adaptive reuse should be the main goals of initiatives to accomplish sustainable urban growth while protecting architectural history (Yung & Chan, 2012).

2.4 FACTORS TO BE CONSIDERED IN GREEN ADAPTIVE RE-USE OF BUILDINGS

Integrating the green concept with the adaptive re-use of buildings is not an easy task, where it demands proper coordination, planning, and management is needed for succeeding in the integration (Wijesiri et al., 2021). Therefore, there are various factors to be considered when implementing a green adaptive re-use project (Vafaie et al., 2023).

Among those, the pioneering factors to be considered in green adaptive re-use of the building are the structural integrity (Wijesiri et al., 2021), architectural features of the building including the building layout and orientation (Celadyn, 2019), economic factors such as initial cost,

return on investment (ROI), and maintenance cost (Rockow et al., 2019), resource efficiency (Eray et al., 2019), innovative techniques (Celadyn, 2019; Conejos et al., 2011), occupancy comfort (Dewiyana et al., 2016), compliance with existing laws and regulations, and flexibility in future modifications and disassembly requirements (Rockow et al., 2019).

3. METHODOLOGY

The study required to gather the insight on green adaptive re-use of buildings within the context of Sri Lanka. Hence, the study incorporated the qualitative research approach in developing an in-depth inquiry on the two concepts, adaptive re-use of buildings and green building construction. The data collection was implemented in two phases as detailed below.

3.1 PHASE 1: EXPERT INTERVIEWS

Survey strategy can be identified as the most effective way to collect data since it explores the depths of what people think (Punch, 2014). Hence, the survey strategy was facilitated as the initial data collection strategy to identify and comprehend the current factors associated with green adaptive re-use of buildings in Sri Lanka. Table 2.1 elaborates the respective respondent profile incorporated in conducting the survey. A purposive sampling method was used to select the experts who possess substantial experience in both adaptive reuse and green building practices.

Table 1: Respondent profiles for expert interviews

Respondent Code	Profession	Designation	Industry Experience	Experience in Adaptive Reuse of Buildings
E1	Architect	Director/ Consultant	20	12
E2	Architect	Director/ Consultant	20	16
E3	Architect	Director/ Consultant	20	12
E4	Architect	Director/ Consultant	20	15
E5	Quantity Surveyor	Consultant	22	14
E6	Quantity Surveyor	Consultant	20	14
E7	Engineer	Director	23	12
E8	Engineer	Director	25	14
E9	Facilities Manager	Consultant	10	08
E10	Facilities Manager	Consultant	08	06

3.2 PHASE 2: CASE STUDY

Phase 02 of the data collection incorporated a case study approach to investigate the current applicability of the green adaptive re-use concept to the buildings in Sri Lanka. Accordingly, two building construction projects which have incorporated the said concept were selected.

3.2.1 Description of Case Study – 1

Case 1 is one of the major green adaptive re-use of buildings projects done in Colombo city. It is the first real estate project initiated in Sri Lanka. The structure ended up in 152m in height and consisted of two 39 story towers connected by a four-story retail block. The total cost of construction of the building was $130 million and was opened on the 12th of October 1997. With over 750,000 sq. ft. of office and retail space, the building currently holds more than 120 local, international, and multinational brands which makes in Sri Lanka are most demanding commercial dwelling. After fifteen years of opening the building management team decided to renovate their building with green concepts. Currently, this building has been successfully adaptively re-used with applying green building concepts. They have initiated the Energy and water management.

3.2.2 Description of Case Study – 2

This building is a public library building in Sri Lanka. The main building and its interior layout had been scientifically planned in the 1970s by an internationally renowned UNESCO consultant architect. In January 2017, this library building was allocated Rs 500 million by the department of budget to upgrade the national library of which Rs 400 million was for refurbishing with green concepts the present building and constructing an additional building while Rs 100 million was for furniture. Rainwater havering systems, Solar power systems, Indoor air quality systems are the main green concepts to be proposed.

Table 2: Case study respondent profile

Description	Interview Code	Profession	Experience
Case 1	C1A1	Consultant Architect	24 years
	C1E1	Maintenance Engineer	15 years
	C1QS1	Quantity Surveyor	10 years
Case 2	C2A1	Consultant Architect	15 years
	C2E1	Maintenance Engineer	22 years
	C2QS1	Quantity Surveyor	10 years

4. FINDINGS AND ANALYSIS

4.1 FACTORS CONSIDERED IN GREEN ADAPTIVE REUSE OF BUILDINGS: EXPERT INTERVIEW FINDINGS

Various factors have been identified by the experts regarding the green adaptive reuse of buildings. For obtaining the experts' opinion and validation process, those identified factors were categorised into nine (9) main categories named economic, environmental, social, functional, technological, legal, architectural, physical, and political.

4.1.1 Physical Factors

Most of the respondents emphasised the importance of having the proper building orientation in making green adaptive buildings. E2 strengthened the fact by stating that "*proper building*

orientation enables penetration of natural daylight into the building and also it allows buildings to have natural ventilation". As per E5, this enables higher energy performance and upgrades the indoor building quality. Further, having a properly insulated building envelope is considered as a factor to be considered in green adaptive buildings by the respondents E2, E3 and E8. According to E8, possessing properly insulated building envelope engages in providing a precious temperature level and also minimises the energy usage. E1 identified structural integrity as an important attribute that is required to be considered while delivering green adaptive buildings. The respondent stated that "*while considering all other major physical factors, it is required to ensure the structural integrity of the particular building that shall enable the structural soundness and safe building environment*". Building materials is another attribute to be considered while delivering adaptively reuse of buildings. According to E10, it is more beneficial to have eco-friendly practices during the construction. The author further said that attaining eco-friendly construction is accelerated through the use of sustainable materials having low embodied energy and a higher durability. The incorporation of flexible design strategies is another physical factor highlighted by E7. The respondent stated that the "*use of modular construction in a building allows future changes with lesser effort on demolition and reconstruction*". Additionally, respondents identified several other factors that is ideal to be considered in case of an adaptive reuse of a building such as required workmanship, reuse age of the building, operational convenience, size of the building, and the available green space.

4.1.2 Economic Factors

Most of the respondents highlighted the possibility of acquiring financial incentives and rebates when implementing green adaptive reuse of buildings. E1 identified the availability of financial options such as loans, mortgages, or other financing options as another significant economic factor to be considered when considering the green adaptive reuse of buildings. As stated by the respondent "*the financial options offer favourable conditions to the building stakeholders such as favourable terms and conditions, and the interest rates*".

E8 stated that "*when considering green adaptive reuse of buildings, it is beneficial to account several factors such as initial cost on investment, operational and maintenance expenses, return on investment, and revenue generated*". Further, the respondent emphasised the importance of conducting a cost-benefit analysis in evaluating the financial implications of launching a green adaptive reuse of buildings. In relation to the response made by E8, E2 mentioned that green adaptive reuse of buildings is capable of making a significant financial benefit when the initial cost of building is comparatively lesser than the operational and maintenance cost.

Further, E6 stated *"...evaluating the building value is a mandatory factor to be considered when delivering a green adaptive reuse building. It is a well-known factor that this type of building has a higher sales prices or the rental fees due to the improved quality of living inside the building*". In addition, E2 highlighted that these buildings are capable of making energy savings as the buildings incorporate energy-efficient design strategies and also the tendency to integrate renewable energy into the building, which ultimately leads to an economic benefit.

4.1.3 Environmental Factors

Ensuring a favourable indoor environmental quality is another vital factor raised by many respondents including E2, E4, E6, E7, and E10. E4 stated that *"...controlling the amount of indoor pollutants, optimising the ventilation supply, and maintaining the thermal comfort are required to be considered when ensuring quality indoor environment*".

As highlighted by another factor to be considered in the green adaptive reuse of buildings is the reduction of resource consumption and resource conservation. E9 suggested the use of low embodied energy materials, material recycling, and minimised material wastage. As per E7, another mode to implement resource conservation having energy efficient design strategies which shall reduce the energy consumption. Further, the respondent emphasised that the water conservation also shall be implemented through sustainable water management practices.

4.1.4 Social Factors

As highlighted by most of the respondents, occupant comfort is an important social factor to be considered when delivering green adaptive reuse buildings. E3 stated, *"…increased occupant comfort is a good attribute that shall be considered when deciding the rental or selling fees*". Moreover, the safety and security of the occupants are required to be made confirmed mandatorily. This shall lead to make highly satisfied occupants.

Education and awareness of the occupants on the value of green adaptive reuse of buildings is important as it promotes this type of building construction by eradicating most of the misconceptions in the minds of the occupants.

4.1.5 Functional Factors

As per all the respondents, functional factors are crucial in ensuring the attainability of the requirements of the occupants and the surroundings. Flexibility is a main attribute that is required to be considered in these types of buildings, where it enables future changes without huge disturbance. E7 stated that *"…the required changes to a building are easily viable when the building possesses features such as modular sections, and also the multi-purpose spaces*". Operational efficiency is said to be another factor to be considered when delivering these types of buildings. This enables the operation of the building with less use of resources and less maintenance requirement. E1 stated, *"…operational efficiency shall be optimised with the integration of modern technology*".

4.1.6 Technological Factors

E3 mentioned that "…*the adaptability of buildings is compulsory to be considered when delivering green adaptive reuse buildings*". E10 suggested to use of innovative technological solutions as it is vital in delivering a green adaptive reuse building. These chosen technologies shall ensure the use of low embodied energy and low toxic material, as well the recycled materials.

4.1.7 Architectural Factors

E10 stated that "*accessibility is one of the major architectural factors to be considered in green adaptive reuse of buildings due to the consideration of vital factors such as better ergonomic designs, accessibility to all sort of people including disabled community and elderly people*". Further, E5, E7, and E8 identified optimization of the building envelope as a factor to be included under this category whereas E5 identified it as a mode of ensuring the comfort of building occupants.

4.1.8 Legal Factors

Most of the respondents identified environmental regulations as a crucial legal factor to be considered when delivering a green adaptive reuse building. As per E5, complying with legal requirements avoids unnecessary legal and financial risks for a project. Moreover, zoning regulations are required to be strictly followed as it avoids many legal issues. Also, complying with regional development policies were further emphasised by E4, E8, and E10. Further, E3

emphasised the importance of complying with green building rating systems in achieving green adaptive reuse of buildings.

4.1.9 Political Factors

As per most of the respondents, fulfilling the political factors has become crucial, as the political support is essential in streamlining the project approvals and acquisition of incentives provided by the government for the implementation of green building initiatives. E3 emphasised that the political leaders and policymakers are public figures who shall pioneer in publicising the green adaptive re-use of buildings and acquiring public support in the respective building practice. According to E5, collaboration among the stakeholders engaged in a project such as government, political leaders, community organisations, and other stakeholders, especially a project that gets more local and international attraction, demands higher collaboration among the stakeholders in getting successful project output.

4.2 FACTORS CONSIDERED IN GREEN BUILDING ADAPTIVE REUSE OF BUILDINGS: CASE STUDY FINDINGS

The findings of the expert interviews were validated through two case studies which have incorporated the green adaptive reuse concept in those buildings. Based on the findings of the case studies, the findings of expert interviews were subjected to addition, deletion, alteration, or else the data was kept with no change. Table 3 illustrates the factors to be considered in green adaptive reuse of buildings.

Table 3: Factors to be considered in green adaptive re-use of buildings

	Factors (Expert Interview Findings)	Modifications made through Case Studies	Factors (After Validation with Case Study Findings)
Physical factors	Proper building orientation (Geometry)	No Change	Proper building orientation (Geometry)
	Properly insulated building envelope	No Change	Properly insulated building envelope
	Structural integrity	No Change	Structural integrity
	Building materials	No Change	Building materials
	Flexible design strategies	No Change	Flexible design strategies
	Workmanship	No Change	Workmanship
	Reuse age of the building	No Change	Reuse age of the building
	Operational convenience	No Change	Operational convenience
	Size of the building	No Change	Size of the building
	Green Space	No Change	Green Space
	Building location	Added	Building location
	Historic value of the building	Added	Historic value of the building
	Site amenities	Added	Site amenities
	Prevailing Climate	Added	Prevailing Climate

	Factors (Expert Interview Findings)	Modifications made through Case Studies	Factors (After Validation with Case Study Findings)
Economic factors	Financial incentives and rebates	Altered	Financial options (Including Tax incentives/ loans/ grants etc.)
	Financial options		
	Initial cost on investment	Altered	Initial cost
	Operational and maintenance expenses	Altered	Operational and maintenance costs
	Return on investment	No Change	Return on investment
	Building value	No Change	Building value
	Revenue generated	Altered	Profitability
	Construction material cost	Added	Construction material cost
Environmental factors	Indoor environmental quality	No Change	Indoor environmental quality
	Reduction of resource consumption		
	Use of low embodied energy materials	Altered	Resource conservation
	Material recycling		
	Minimised material wastage		
	Energy efficient design strategies	No Change	Energy efficient design strategies
	Environmental sensitivity	Deleted	-
	Water conservation	No Change	Water conservation
	Site and community	Added	Site and community
	Use of greenfield sites	Added	Use of greenfield sites
	Site layout, space gain and change and building character	Added	Site layout, space gain and change and building character
Social factors	Occupant comfort	No Change	Occupant comfort
	Occupant safety	No Change	Occupant safety
	Education and awareness	No Change	Education and awareness
	Social value	Added	Social value
	Compatibility of newly introduced uses with existing	Added	Compatibility of newly introduced uses with existing
	Identity	Added	Identity
	Access to facilities	Added	Access to facilities
Functional factors	Client's requirements	No Change	Client's requirements
	Flexibility	No Change	Flexibility
	Disassembly	Deleted	Considered under Flexibility
	Operational efficiency	No Change	Operational efficiency
	Building maintenance	Deleted	Operational efficiency ensures less resource usage and less maintenance requirement
	Structural Grid	Added	

	Factors (Expert Interview Findings)	Modifications made through Case Studies	Factors (After Validation with Case Study Findings)
Technological factors	Adaptability	No Change	Adaptability
	Innovation	No Change	Innovation
	Construction time period	Added	Construction time period
	Existing Building type	Added	Existing Building type
Architectural factors	Accessibility	No Change	Accessibility
	Optimisation of the building envelop	No Change	Optimisation of the building envelop
Legal factors	Official plan and zoning regulation	No Change	Official plan and zoning regulation
	Regional development policies	No Change	Regional development policies
	Environmental regulations	No Change	Environmental regulations
	Green building rating system	Added	Green building rating system
Political factors	Collaboration with government	No Change	Collaboration with government
	Political will	No Change	Political will
	Public opinion	Added	Public opinion

Under physical factors, C1E1 stated, "*installation of water-efficient fixtures improved the energy efficiency of the building*". Further the respondent highlighted the rainwater harvesting system and the greywater recycling system available in the building which highly influenced on having a green adaptive building.

When considering economic factors, both C2QS1 and C2QS2 mentioned that the government takes steps to provide financial benefits such as financial incentives, grants, tax credits, and rebates when implementing green adaptive reuse of buildings. Moreover, C1A1 stated that *"…this type of building is having a good market demand when considering the prevailing market value. One reason for the increased market demand shall be the enhanced sustainable features of the building*". C2E1 further stated, "*it is more important to evaluate the risk associated in such a project as it allows to identify unforeseen and unpredictable market conditions and price fluctuations*". With the risk assessment, the economic feasibility of a project shall be predicted.

Moreover, adaptability becomes an environmental factor that is required to be considered in green adaptive reuse of buildings, where it enables future changes with less impact on the environment by reducing construction and demolition waste.

Under social factors, C1QS1 confirmed that this type of building construction shall make more job opportunities for the community as it contains an additional scope of work when compared to the traditional building construction. Accessibility to the facilities is another social factor that shall enable the access of most of the community groups including people of all the age levels, and economic backgrounds. C1E1 stated that "…*green adaptive reuse of buildings should provide uninterrupted access to all the people with an interest towards the facility*".

When considering the technological factors, C2E1, stated that "…*it is mandatory to consider the construction time when integrating green adaptive reuse strategies to the building, as it demands more financial resources as well as human resources*".

The case study findings reveal that the various physical factors such as structural integrity, material durability, design complexity, workmanship, reuse age, operational convenience, building size, and green space influence green adaptive reuse buildings in Sri Lanka. Since, the prevailing climate and the foundation were not identified through the case studies, those factors were removed from physical factors.

Additionally, building value, profitability, location, operational and maintenance costs, material, and structural costs are economic factors for all the two green adaptive reuse building projects. However, site amenities are not observed in the case studies, and therefore not considered an economic factor.

The expert interviewees considered technological factors such as adaptability, innovation, building services, existing building type, and construction time as the most critical when applying green concepts to adaptive reuse buildings. Further, structural conditions, building systems, materials, and decorations were excluded factors during the case studies.

Analysing all the findings of the literature review, expert interviews, and the case studies, factors to be considered in green building adaptive re-use of buildings established and it is illustrated through Table 3.

5. CONCLUSIONS

The concept of green adaptive re-use emphasizes the value of the existing building stock as an important economic, social, and cultural resource that should not be wasted. However, developing countries have not actively engaged in green adaptive reuse of buildings. Furthermore, converting adaptive reuse buildings into green buildings remains a challenging area with limited research attention. Environmentally friendly reuse of buildings is a key approach to achieving sustainability in the built environment by reducing the environmental impact of new construction and supporting more resilient and sustainable communities.

This study identified a set of key factors influencing green adaptive reuse, which adds to the existing body of knowledge and offers a structured basis for further research. The categorised factors provide practical guidance for practitioners and policymakers in planning and implementing green adaptive reuse projects. Future research may expand on these findings by exploring how these factors apply across different contexts, building types, and project scales, thereby enhancing both theoretical understanding and practical application in the field.

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IDENTIFYING AND QUANTIFYING THE CHALLENGES OF SRI LANKAN PUBLIC-PRIVATE PARTNERSHIPS: A SENTIMENT ANALYSIS APPROACH

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ABSTRACT

Public-Private Partnerships (PPP) could be a suitable approach to cater the demand for infrastructure and the need to attract foreign investment in Sri Lanka, as it recovers from its worst economic crisis. However, the success rate of PPPs both locally and globally, is diminishing. Regardless, there is dearth of academic literature, especially empirical, done on Sri Lankan context to identify the challenges of PPPs that plague the PPP success rate. Accordingly, semi-structured interviews were held among the experts of Sri Lankan PPPs to identify the challenges of PPPs in Sri Lanka. Subsequently, considering the need to identify the most pressing challenges through a ranking system, while addressing the limitation of lack of PPP experts in Sri Lanka to gather adequate data to conduct a statistical analysis, Sentiment Analysis was done on the descriptions of each challenge, using pre-trained BERT model. The sentiment analysis provided numerical rating on the negativity of each challenge, to rank them. From the interviews, it was identified that Sri Lankan PPPs are being plagued by challenges like High Bureaucracy, Political Instability, Lack of Experts, and Lack of Co-ordination among Stakeholders, amidst others. Among them, it was identified from the sentiment analysis that Lack of Adequate Financial and Technical Capacities, Lack of Transparency and Corruption, and Lack of Legal/Regulatory Frameworks for PPPs are the most critical issues. Furthermore, this study explores the suitability of sentiment analysis and adopting BERT as a substitute for statistical analysis in studies where the responses are restricted by contexts and circumstances.

Keywords: *BERT; Opinion Mining; Public-Private Partnerships; Sentiment Analysis; Sri Lanka.*

1. INTRODUCTION

Over the past decades, the demand for infrastructure has increased exponentially to cater the public's needs. In contrast, the public funds that should be utilized to develop infrastructure remain unchanged, if not shrunk (Lembo et al., 2019). This prompts the resource-constrained governments to look for innovative solutions to redress the

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investment shortfall in these infrastructure demands. Public-Private Partnerships (PPPs) incepted as one of such solutions (Bao et al., 2023). PPPs are "a long-term contractual arrangement between the public and private sectors where mutual benefits are sought and where the private sector engages in designing, building, finance, maintain and operate infrastructure assets and related services and/or puts private finance at risk" (World Bank, 2014). On several occasions, when the efforts and resources of governments to induce infrastructure development are insufficient, PPP models have been accentuated to harness the technical superiority and effectiveness of the private sector to commission, design and build a construction project (Sehgal & Dubey, 2019). Due to these, PPPs are popularly practiced in several regions, from developed to developing countries across sectors like roads, ports, and waste management (Aerts et al., 2014; Dabarera et al., 2019).

For the Sri Lankan economy and sectors related to infrastructural development, the need for infrastructure has been ever-increasing (Jayasinha et al., 2021). Hence, PPP could be a viable solution to cater for its infrastructure demands. The end of the war in the late 2000s projected the country towards developing its economy and infrastructure. The huge inflow of foreign investments and support strengthened the country's service sector, with tourism at the forefront. The trend continued till the end of the last decade before the pandemic, and the consequent economic crisis hit the country (Hirusheekesan & Satanarachchi, 2021). While the developments have slowed down, there are signs of improvements, and the government is focused on reviving the crisis-hit construction and tourism industries. At this juncture, PPP could be used to tap into the private sector's economic and technical superiority to cater the demand for social infrastructure and attract foreign exchange to the country. Nevertheless, the success rate of PPPs is diminishing globally (Eshun et al., 2021; Vale de Paula et al., 2025), which is the case in Sri Lanka as well (Fernando et al., 2025; Weththasinghe et al., 2016).

Hence, it is essential for the academics and practitioners of PPPs in Sri Lanka to venture on finding the challenges that prevents the successful implementation of PPPs. However, unfortunately, a preliminary search in the SCOPUS index with the search string *("Challenges" OR "Barriers") AND "Public-Private Partnerships" AND "Sri Lanka"* on 1st March 2025 yielded no relatable documents while a similar broader search on Google Scholar retrieved Weththasinghe et al. (2016), a study done almost a decade ago, exploring the challenges of Sri Lankan PPPs, yet again, using a literature review. Additionally, there are also articles that discuss the challenges pertaining to specific domain of PPPs in Sri Lanka. For instance, Thennakoon et al. (2025) discusses the challenges of implementing unsolicited proposals in Sri Lanka, Kavinda and Gallage (2024) explores the challenges in selecting PPPs as a procurement option for Sri Lanka, and Kim et al. (2019) briefly discusses PPP challenges on a surface-level, amidst its broader discussion. However, this is still a dearth of articles that holistically focus on the challenges of Sri Lankan PPPs and consequently ranking them.

This calls for studies that use empirical methods to identify the challenges of PPPs in Sri Lanka. Additionally, merely identifying the challenges may not be entirely fruitful since some of them may not really be critical while the rest might demand immediate attention. Hence, it is also necessary to rank the identified challenges by using any quantitative methods, which would provide more pragmatic insights to the academics and practitioners.

Based on this, this paper aims to study the research question "What are the most challenging barriers of Public-Private Partnerships in Sri Lanka" endeavouring to provide not only qualitative insights, but quantitative insights as well, to deliver the most pressing challenges of PPPs in Sri Lanka.

2. RESEARCH METHOD

This study aims to identify the challenges of the Sri Lankan PPPs and rank them to recognize the most pressing issues of the sector. To achieve this, it was decided to initially conduct a literature review/interview to identify the challenges of Sri Lankan PPPs or PPPs in general, and then to rank them using a quantitative method. However, as mentioned in the earlier section, the number of studies done in relevance to the Sri Lankan context is minimal. Additionally, it was also realized in the preliminary levels of this study, that most of the Sri Lankan PPPs have been progressed only up to the conceptual and feasibility study level and has not been materialised towards the construction and operational phases. The pandemic and economic crisis in 2022 aggravated the situation, with no visible infrastructure PPP project being commenced from the start of this decade. This led to a serious dearth of experts in Sri Lankan infrastructure PPPs, who have involved in two or more phases of projects. The lack of extensive literature negated the possibility of literature review to identify the challenges, and even if made possible through reviewing articles from other context, the lack of possible respondents eliminated the possibility of traditional quantitative methods for ranking.

Under this backdrop, to resolve the impossibility of literature review, it was decided to conduct semi-structured interviews among the PPP experts in Sri Lanka, to qualitatively identify the challenges of Sri Lankan PPPs. Also, the anticipated data saturation would ease the impact of lack of experts in the data collection processes. Accordingly, 7 interviews were carried out as shown in Table 1.

Subsequently, the data derived from the interviews were analysed using Sentiment Analysis. Sentiment analysis, is a sub-field of Natural Language Processing (NLP) (Ramezani, 2025), which is in turn, is a domain of artificial intelligence that enables computer to understand, interpret, manipulate and generate human language (Chandra et al., 2025). Sentiment Analysis in essence, is the process of capturing the diverse sentiment information expressed natural language texts (Tao et al., 2025). It is also known as Opinion Mining, focusing on detecting, extracting, and classifying sentiments from texts.

Sentiment analysis methods could essentially be categorized into two methods as, lexicon-based or unsupervised machine learning, supervised machine learning, and with the possibility of combining the two methods (D'Andrea et al., 2015). Unsupervised machine-learning/Lexicon-based methods use sentiment lexicon, which are a set of words that contains sentiment words coded with, among other things, as positive, negative, or neutral, along with their level of strength or intensity, as the main tool for analysis. Meanwhile, in supervised machine learning, a model is first trained with some data that have already been labelled to the categories and then the model is tested by providing some sample data as input to the model for doing the analysis based on the prior training given (Samal et al., 2017). Sentiment analyses are predominantly used in identifying public sentiments on various subjects like mental health, drug reviews, e-commerce products, customer review, stock market sentiment, political views and movie reviews among others (Chandra et al., 2025; Ramezani, 2025; Tao et al., 2025).

Yet, the qualitative dataset that were collected from interviews were still inadequate to conduct a traditional supervised machine learning method, which is, training a model based on the available data. Meanwhile, the dictionaries and corpora available for lexicon-based methods simply conduct the analysis based on the words present, which are finite and do not have the ability to understand the context (D'Andrea et al., 2015). Hence, the accuracy of results stemming from lexicon-based approaches will be less since they do not have the capacity to analyse complex sentences, which will be the type of data collected from the interviews, and to understand the highly specific context of PPP.

BERT, which stands for Bidirectional Encoder Representations from Transformers, is a model for NLP developed by Google that learns bi-directional representations of text to significantly improve contextual understanding across many different tasks (Devlin et al., 2019). This has made it strong for significantly understanding contexts and analyse complex sentences. In essence, BERT is a pre-trained large language model, which can be further fine-tuned to suit different applications (Lee & Lee, 2024). Accordingly, BERT has diverse applications areas such as automatic answering of questions, machine translations, fake review detection, grammatical error detection and correction etc., among which sentiment analysis too is a popular area (Cicekyurt & Bakal, 2025; Mushtaq et al., 2025). Accordingly, it was decided to adopt BERT for the sentiment analysis in this study, due to the possibility to tap into the powerful and versatile pre-trained model, even with using small dataset. Studies like Perski et al. (2017), Xie et al. (2023) and Gatto et al. (2022) have also previously used BERT to conduct sentiment analysis on data collected from relatively small number of interviews like 10 or 12.

Accordingly, this study adopts a qualitative method, through semi-structured interviews, and a quantitative method, via sentiment analysis, to identify and rank the challenges of Sri Lankan PPPs.

3. RESULTS AND DISCUSSION

3.1 RESPONDENTS OF THE INTERVIEWS

The respondents considered for this interview are those who can be categorised as "experts" in the domain of PPPs in Sri Lanka. As discussed earlier, the number of experts in PPPs in Sri Lanka is minimal due to several reasons. Hence, professionals with experience working at any phase of a Sri Lankan infrastructure PPP project are considered experts. However, care was also taken to identify respondents with at least five years of experience in their respective professions, though it does not necessarily have to be in PPP. This was done assuming that being considered an expert, their perceptions will be more accurate and relevant to the context, with substantial experience in their respective fields.

Accordingly, owing to the lack of professionals with working experience in Sri Lankan PPPs, it was decided to consider professionals with at least five years of experience in their respective fields and have been involved in at least one phase of an infrastructure PPP.

During the interviews, data saturation occurred with the fifth respondent. However, a couple of more interviews were conducted to validate the collected data and ensure saturation. This early saturation could be attributed to the less maturity of Sri Lankan PPPs, and similar thoughts were shared among the experts regarding challenges like

transparency, accountability, political instability etc. This also indicates the gravity of such issues and the necessity to address them head-on.

The profile of the respondents has been provided in Table 1.

Table 1: Profile of the interview respondents

Respondent No.	Experience in years	Experience in PPPs
R1	10	A Quantity Surveyor involved in a PPP housing project from its inception to the procurement phase.
R2	17	A Quantity Surveyor involved in a PPP housing project during its design and construction phases.
R3	20	An Economist currently serving as a director of a government institution, involved in the assessment, awarding and procurement of PPP proposals.
R4	15	A Civil Engineer involved in the initial assessments and feasibility studies of PPP projects.
R5	35	A Chartered Quantity Surveyor and academic with over 17 years of experience in PPP and procurement
R6	16	An Accountant with experience in public finance management and serving in procurement entities, procurement committees, technical evaluation committees etc.
R7	17	A Quantity Surveyor with experience in Procurement and Contract Management

3.2 RESULTS FROM THE INTERVIEWS

When considering the barriers put forward by the interviewees, all the respondents mentioned the Lack of Transparency and Corruption associated with PPPs. R1 introduced this, as he mentioned, *"the transparency index of Sri Lanka is very less when compared to its South Asian Counterparts"*. According to the respondents, the corruption and lack of transparency initially stem from the procurement and contract awarding stages in PPP. R3 indicates several occasions where he has experienced corruption and manipulation during the procurement phase firsthand. He points out that bid value is usually overstated and sometimes awarded to a private partner with no prior similar or experience. R3 states counter-intuitively, *"To be honest, we actually need a little bit of corruption or, in other words, incentives for the people at the top for a PPP proposal to proceed further. Maybe in some European countries where the corruption level is zero, we can expect the corruption to be eliminated. However, it is very difficult in Sri Lanka to remove corruption completely. We may have to learn to deal with it and somehow proceed with the project further."* For R4, corruption comes in the form of manipulation of bid values and awarding to companies that can provide some sort of incentive to those at the decision-making level. R5 also agreed with the statement of R1, saying *"I don't want to mention it, but as we all know, there is a level of corruption involved in the PPP projects"*. While R6 agreed with the above statement, R7 cited this as one of the two significant barriers to PPP in Sri Lanka.

Additionally, only R1 and R3 were able to provide solutions to address the issue of corruption and transparency in Sri Lankan PPPs. They both agreed on an accountable

system with an independent audit for the PPP processes undertaken. R1 contemplates, *"We have to have some sort of a transparent system in our PPP processes, specifically in the procurement phase"*.

Another challenge that goes closely with corruption and lack of transparency is the high level of Political Interference and Resistance. R1 first put forward this, which was agreed by R3 as well. R3 stated that whenever a project proposal does not agree with the personal agent of ministers or politicians, it will be shoved under the shelf. He recalled a situation where a PPP proposal was assessed and approved in haste just because a person in power wanted to get the project running while he was still in office. R4 encountered an issue when opposition parties brought a bad reputation to his company during their election campaign. He said, *"There was this foreign company which also submitted a proposal along with us. Though we quoted a higher price than them, we won the bid since we have prior experience and technical capacity to undertake the project. However, the opposition parties during their propaganda blamed some corruption in the procurement processes, citing that the bid has not been offered to the lowest bidder without considering the factors of prior experience and technical capacity."*

Another challenge in Sri Lankan PPPs that could result from the above two challenges in the Diminished Investor Confidence. R2 mentioned that the economic crisis and the Sri Lankan reputation for less transparency has reduced the overall confidence of the investors, and they are predominantly reluctant to partner with the public sector. R5 agreed with this statement, adding that corruption could also be a significant contributing factor to this.

High Bureaucracy and the Complexity of Approval Processes for PPPs are also considered as a significant challenge by the experts. R1 stated, *"If we are to launch a project, we must get so many approvals for various government agencies"*. R7 added to this, *"Sometimes, even we don't know how many agencies are there to get approval from, and sometimes our proposal will get rejected or we have to repeat the entire process, just because the decision-makers decide that our proposal should be approved from a new agency, that may not even have been in the process earlier"*. Similarly, R2 stated that it is very difficult to do business with the public sector for a private company, due to the high level of bureaucracy and fragmentation involved. He stated, *"As a private company we must safeguard our reputation as a customer-friendly organization. However, if we are to partner with the government, we will have to stick to their rigid system and processes, and we end up ruining our reputation with the customers. This was mainly because of delays created by the complex processes of government."* R3, R5, and R7 also mentioned a similar situation when working with the government.

This led to another key barrier put forward by R1, which is the Lack of Co-ordination among the Stakeholders involved. R7 also mentioned that *"The complex processes in the government side have made the communication among the stakeholders difficult and it has led to lack of co-ordination among them, which could also lead to less trust"*. A similar perception was provided by R1 as well.

Another challenge prevalent regarding the government is Political Instability. The constant change of power resulted in continuous alteration of the policy directions, often resulting in the abrupt halt of PPP endeavours. While R5 vaguely mentioned this, R3 was very critical towards this barrier. R3 noted that there is no continuity or long-term plan for PPP in Sri Lanka, mainly because of this constant see-saw of power. He also lamented

that the segregated efforts and institutions created by the different parties in power have resulted in personnel with no continuous exposure to PPP or experience working over a full project lifecycle.

Another key challenge that was cited as significant is the Lack of Legal or Regulatory Framework for PPPs in Sri Lanka. This was a considerable challenge for R1, as he mentioned, *"Since there is no legal demarcation of what PPP is and what it constitutes, there are so many discrepancies among the proposed projects. Some projects are not even a PPP in actuality but are considered as PPP due to its lack of definition and legal demarcation."* He also mentioned about the intellectual property rights of private partners, specifically during the unsolicited proposals. Since the proposals will be circulated among several entities, he stressed the importance of securing the private partner's intellectual property rights. According to him, it will encourage the private partners to partner with the government without much worry. Similarly, R6 and R7 also mentioned this as a significant challenge. R6 cited the absence of legal or regulatory frameworks for PPP as a significant hindrance to appraising and progressing novel PPP arrangements without any delays.

Going on the same thought, experts also pointed out the Lack of Guidelines for PPP as one of the significant barriers to PPP in Sri Lanka. R1 revealed, *"The absence of clear framework and guidelines for PPP has resulted in professionals and public sector officials having no idea on their roles and responsibilities in a PPP project"*. He rigorously recommended forming laws and government documents containing guidelines for carrying out PPP projects in Sri Lanka. R6 vehemently blamed the outdated guidelines prevalent in the Sri Lankan public sector. He mentioned, *"the guidelines followed by the government were created in 1998 with an amendment in 2006, which is way outdated compared to the current systems in other countries. In fact, the 1998 guideline does not even have the word PPP, but we use it for PPP procurements. This is highly disadvantageous, given the need for innovative PPP mechanisms to cater for the current infrastructure needs in Sri Lanka amidst its economic crisis."* R7 mentioned this lack of guidelines as a contributing factor towards corruption since R7 viewed corruption breeds if processes are not backed by strong legal cover or guidelines.

This lack of guidelines for PPP leads to another challenge for Sri Lankan PPPs, which is the Lack of Awareness or Knowledge on PPP projects. R2 asserted that the lack of awareness of PPP, even among government officials, has made it difficult for private companies to partner with them. *"I think, since they (government officials) do not have much awareness or knowledge on PPPs, they tend to view us (private partner) as more a contractor than a partner. The idea of working together towards a common goal is not there with them."* He also mentioned that *"there are lots of last-minute changes in the procedures since the government officials themselves do not have much idea on PPP processes. This was exceedingly difficult for us since sometimes it damages our reputation with the customer."* Additionally, R3 and R6 blamed that most of the government officials do not possess adequate knowledge of PPP. For R3, *"this was highly unfavourable to the public sector, because the private sector usually comes up with innovative PPP arrangements and project types, to which the public sector is not ready to fit in, due to the lack of knowledge and awareness"*. He even blamed that some of the top-level personnel in the monitoring institutions for PPP in Sri Lanka do not have prior experience or knowledge on PPP. R6 mentioned that *"None of the government officials have proper knowledge or know-how of PPPs. Because of this, they think PPP is complex*

and takes up a lot of resources and time. Hence, they are reluctant towards going for a PPP and discourage it most of the time." R1 and R3 proposed awareness programs, books, and educational programs for concerned professionals from the private and public sectors. R1 contemplated the possibility of tertiary educational programs for the relevant professionals and PPP being included in the undergraduate curriculums of the appropriate professions.

This led to the emergence of another challenge: the Lack of PPP Experts in Sri Lanka. R3 mentioned, *"There are no strong personnel in both government and private sector to initiate a rigid PPP mechanism and proceed with it. Especially when we talk about innovative mechanisms, it is really difficult to find relevant people in Sri Lanka."* Similarly, R6 stated, *"The situation in the Sri Lankan PPP sector is worrying because it is really hard to find at least one expert who has adequate knowledge and experience in working for the entirety of a PPP lifecycle"*.

In a different domain, R1, R3, and R5 referred to the Difficulty in obtaining Adequate Long-term Financing as another critical challenge in the Sri Lankan PPP sector. According to them, the current economic crisis and Sri Lanka's history of abruptly halting projects and partnerships for political reasons have diminished investor confidence, making it difficult for the public sector to source financing. R5 mentioned that *"PPPs require long-term financing and that cannot be brought in by a single partner. Most of the time it will be difficult. So, obtaining long-term financing is a concern."* Also, R3 stated, *"In times when the government must fund a part of the project, they will fund it for a while and once they ran into any financial issues, they will say that they can't fund the project anymore. This will create an unforeseen burden on the private partner and diminish the confidence they have in the government."* Similar thoughts were shared by R1 as well.

Another key challenge discussed by the experts is the Lack of Return on Investment (ROI) for PPP projects in Sri Lanka. For R4, it would be very difficult in Sri Lanka to make the project profitable only from the tariffs collected by the services provided, to which R5 added the recent tax increases contribute even more. R4 mentioned that *"it would take at least 20-30 years to recover the investment, which is even more uncertain, given the political and financial dynamics of the country"*. He also proposed that the government provide some sort of financial relief for private partners in this context, which would encourage them to partner with the government.

The last challenge discussed by the experts is the Lack of Financial and Technical Capacities in Sri Lanka. While a part of it is already discussed from the perspective of government institutions, this challenge is based on the private sector. R4 mentioned *"Most of the contractors in Sri Lanka do not possess the adequate financial or technical capacity to carry out a major PPP development. Even in our case, we partnered with four other major construction companies in Sri Lanka to create a joint venture, with which we bid for the project."* This emphasizes Sri Lankan contractors' lack of technical or financial capacity to face the technical challenges of PPPs head-on. R5 agreed with this and added that even the local banks, as standalone entities, may find it challenging to provide such a significant long-term funding project, signifying local stakeholders' lack of financial capacity.

3.3 RESULTS FROM THE SENTIMENT ANALYSIS

Subsequently, a sentiment analysis was conducted on each challenge of PPP identified from the interviews and their descriptions provided by the experts. The aggregated and average negativity scores of each PPP challenge, resulted from the sentiment analysis on their descriptions have been tabulated in Table 2.

Table 2: Results of the sentiment analysis

PPP Challenge	Aggregated negativity score	Average negativity score
Lack of Legal/Regulatory frameworks and guidelines for PPPs	3.837	0.959
Political Interference and Resistance	2.964	0.988
Lack of transparency and corruption	3.923	0.981
Lack of adequate financial and technical capacities	3.987	0.997
Lack of co-ordination among stakeholders	0.998	0.998
High Bureaucracy	2.987	0.996
Lack of awareness and knowledge on PPPs	2.998	0.999
Lack of experts in PPPs	1.998	0.999
Suppressed ROI	2.974	0.991
Political Instability	1.934	0.967

4. DISCUSSION

Several challenges were put forward by the experts during the interview that hinder the performance of Sri Lankan PPPs. From the interviews, it was identified that challenges like lack of transparency and corruption, lack of legal/regulatory frameworks and guidelines for PPPs, and lack of adequate technical and financial capacities are more pressing issues. These were also mirrored in the results of the sentiment analysis, with lack of adequate financial and technical capacities having the highest aggregated negativity score among the challenges (3.987), closely followed by lack of transparency and corruption (3.923). These were also cited in articles such as Weththasinghe et al., (2016) and Wellsteed et al. (2019). These perceptions could also be the results of the economic crisis and ensuing fiasco of successive governments in recovering the economy, further fuelled by high level of corruption. As a consequent, it was learned that the above challenges discourage genuine and strong private partners from partnering with the government.

Tackling the above challenges would attract strong local and foreign partners, which would in turn, address other critical challenges regarding experts (1.998), suppressed ROI (2.974), awareness and knowledge (2.998) etc. Hence, by consulting with the experts, it is essential to address these critical challenges head-on, which will automatically nullify others. In addition, challenges such as bureaucracy, political interference and resistance, and political instability are mostly out of the hands of researchers or practitioners and for them to pacify, the current chaos in the macro-economic and political conditions of the country needs to be dealt with. Thus, it is more pragmatic to address the above-mentioned critical issues of PPP head-on, for the successful implementation of PPPs in Sri Lanka.

Another notable aspect from the results of sentiment analysis as observed from Table 2 is that, while the negativity scores were given for each sentence against 1, the average negativity scores of all the challenges traverse around 0.9, which suggests that while one challenge maybe relatively critical than the other, they all are equally important to be addressed as soon as possible.

Additionally, it is professed in this study that using BERT for Sentiment Analysis could be a viable method to quantify the qualitative results obtained from interviews, especially in cases where the data available are not adequate to conduct statistically sound quantitative analyses. As it was showed in Section 3.1, the number of respondents were seven, with having a total number of responses as challenges and their corresponding descriptions as 30. Such a lower number of responses will not be able to yield any statistically significant quantitative results. However, having a qualitative result, bolstered by a quantitative result, even less accurate would furnish the readers with actual impact of these challenges and how critical they are, according to experts.

Although with certain limitations as it would be discussed in the proceeding section, using a pre-trained model like BERT for sentiment analysis will eliminate several such limitations as its ability to understand complex sentences, relatively better grasp of context and ability to read sentences in both the directions, i.e. left-to-right and right-to-left. It should also be noted that a previous analysis was conducted by using lexicon-based approaches as well during the study. However, the results were not pertinent, with certain sentences with obvious negativity were given drastically lower scores. Hence, this would advocate BERT as a suitable tool for studies that struggle to quantify qualitative results, especially in cases like challenges, benefits, and applicability, to produce more refined results in addition to qualitative results. However, attention should be given to treat the results of sentiment analysis as a support and validation to the qualitative results, and not use it primarily to derive at conclusions, since they are merely the results of NLP which depends on several factors like the adopted model and richness of the data, and does not yield statistically significant results when compared to traditional statistical methods used in quantitative approaches.

5. CONCLUSION

It has been identified from this study that Sri Lankan PPPs are being plagued by several challenges such as High Bureaucracy, Political Instability, Lack of Experts, and Lack of Co-ordination among Stakeholders, amidst any others. Among them, it was identified from the sentiment analysis that Lack of Adequate Financial and Technical Capacities, Lack of Transparency and Corruption, and Lack of Legal/Regulatory Frameworks for PPPs are the most pressing issues that need to be addressed. However, the average negativity scores indicate that all the identified challenges are critical and needs to be dealt with head-on. Nevertheless, the interview results also indicate that addressing the former three challenges would automatically address several others like High Bureaucracy, Lack of PPP Experts and Suppressed ROI. Also, certain barriers demand system changes and stabilization of the country's economy which would linger for a while.

Albeit with certain limitations, this study also proposes and succeeds in using sentiment analysis as a partial substitute for statistical analysis in cases where the number of

responses are restricted by contexts and circumstances. It could be used in future studies that require quantitative analysis but unable to do so due to inadequate data.

5.1 LIMITATIONS AND FUTURE DIRECTIONS

The key limitations of the study remain in the results of the sentiment analysis, which are predominantly inherent to the method itself. The analysis was done using the pre-trained BERT model, which, though powerful, may lack in-depth knowledge on the context of PPPs and Sri Lanka. Furthermore, the data fed to the model were from the interview results done by people whose native language is not English, whereas the adopted model conducts its analysis in English. This may have compromised the accuracy of the results to an extent since the interviewees may have missed to use appropriate words to convey their sentiment. Hence, the results should only be used as a guide to bolster the interview results and not as a stand-alone result to derive at deep conclusions.

Going forward, studies based on quantitative approaches and case studies are recommended to validate the findings of this study, while empirical studies to assess the suitability of sentiment analysis to interpret data stemming from complex interview questions and developing a domain-specific model that could be adopted in studies of this sort are also encouraged.

6. ACKNOWLEDGEMENT

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7. DATA AVAILABILITY STATEMENT

The interview transcripts and codes used for the analysis will be made available upon request.

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IDENTIFYING MAINTENANCE TRAINING NEEDS IN SRI LANKA'S APPAREL INDUSTRY AND AUGMENTED REALITY AS A STRATEGIC SOLUTION

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ABSTRACT

Maintenance training in Sri Lanka's apparel industry remains largely informal and reactive, despite the sector's significant contribution to the national economy. This paper examines current maintenance training practices and needs within the industry and explores the potential of Augmented Reality (AR) as a strategic training solution. To achieve this, a qualitative research approach was adopted, using structured expert interviews with five professionals from the maintenance domain of the apparel industry. Purposive sampling ensured the inclusion of experts with substantial experience in Sri Lanka's apparel sector. Thematic analysis was conducted using NVivo software. Findings were discussed under three main topics: current training practices, training needs at different organisational levels, and the integration of AR into maintenance training. It was revealed that current practices are largely informal, reactive, and lack structure. Training needs were identified at three levels, operational, supervisory, and managerial, with skill requirements ranging from procedural knowledge to strategic decision-making. The integration of AR was found to be highly promising, with experts endorsing it as a viable solution. AR's ability to provide real-time, interactive simulations and task-specific guidance was highlighted as a major strength, improving engagement, accessibility, and adaptability. The study concludes that adopting a structured, hybrid training model incorporating AR can address skill gaps, enhance training efficiency, and better prepare maintenance personnel for evolving technological demands. These findings provide practical insights for stakeholders seeking to modernise training practices and align with global maintenance standards.

Keywords: *Apparel Industry; Augmented Reality; Maintenance Needs; Maintenance Training.*

1. INTRODUCTION

Maintenance is a critical function across industrial sectors, directly influencing operational efficiency, product quality, and cost-effectiveness. It accounts for approximately 60% to 70% of total production costs in many industries, including

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manufacturing (Mourtzis et al., 2016). Inadequate maintenance practices can lead to equipment failures, increased downtime, and safety risks (Abbasi, 2023), whereas intelligent and proactive maintenance strategies contribute to extended equipment life, reduced operational interruptions, and improved productivity (Fulcher et al., 2022). However, Li (2022), argued that the shift toward digitalized industrial systems presents challenges in upskilling maintenance personnel, particularly in adopting emerging technologies. Globally, the apparel industry is valued at over USD 1.7 trillion and employs more than 75 million people, making it a significant contributor to global manufacturing (Saxena & Khare, 2024). Sri Lanka's apparel sector alone contributes nearly 6% of GDP and accounts for over 40% of total exports, employing around 350,000 workers, with a large share engaged in production and facility operations (Vidanage et al., 2024). Despite its economic significance, maintenance training within this sector remains traditional, fragmented, and reactive, often resulting in skill gaps, inefficiencies, and delays in fault resolution (Wijesinghe, 2024). AR has emerged globally as a powerful tool for maintenance training, offering real-time, immersive guidance and reducing dependence on paper-based manuals and static procedures (Suhashi et al., 2024). Within the frameworks of Industry 4.0 and Industry 5.0, AR facilitates smarter, more human-centric maintenance practices, allowing technicians to visualize equipment, receive expert assistance remotely, and carry out tasks with higher accuracy (Runji et al., 2022). While AR applications in Sri Lanka have gained traction in education and retail, their adoption in industrial maintenance, particularly in apparel manufacturing, remains minimal and underexplored (Rajapaksha et al., 2021). Given the sector's role in Sri Lanka's national economic development and aspirations to attract foreign investment, integrating AR into maintenance training presents a timely and strategic opportunity. Therefore, this study aims to identify current maintenance training practices and needs in Sri Lanka's apparel industry and explore how AR can serve as an innovative solution to bridge skill gaps and enhance training efficiency. Accordingly, the research question is formulated as, "How can Augmented Reality be strategically utilised to address the maintenance training needs in Sri Lanka's apparel industry?"

2. LITERATURE REVIEW

2.1 AUGMENTED REALITY (AR) AND MAINTENANCE TRAINING

In the 1990s, augmented reality was defined and used to characterise specific tasks and applications (Rauschnabel et al., 2022). According to Harborth and Pape (2021), the concept of AR rapidly expanded as a scholarly community interested in the technology began engaging through conferences and workshops. With advancements in smartphone technology, it became technically feasible to apply virtual visuals onto the physical environment using mobile devices (Dargan et al., 2023). AR is increasingly utilised in technical training and maintenance as a replacement for traditional paper-based methods (PBM), enhancing operational efficiency and user-friendliness (Syed et al., 2022). In training contexts, AR enables workers to interact with both real and virtual environments simultaneously, displaying crucial information such as task progress and notifications (Yazdi, 2024). This interaction improves attention to operational conditions and speeds up information acquisition. However, Alimamy and Jung (2024), argued that the development of AR platforms remains resource-intensive and is often not fully adapted to the specific needs of users. AR remains a largely unexplored area in terms of its application for maintenance training. The integration of AR into Maintenance training

programs in apparel manufacturing has the potential to address several challenges faced by workers, such as the complexity of machinery maintenance, a lack of hands-on experience, and inefficiencies in traditional training methods (De Silva et al., 2018). While research on AR in industrial settings has demonstrated its effectiveness in enhancing worker performance, improving safety training, and reducing operational errors (Sorko & Brunnhofer, 2019), its implementation in the apparel industry remains limited in Sri Lanka. The complexity of apparel manufacturing processes, coupled with the rapid evolution of technology, highlights the need for a tailored AR training solution that can effectively address the unique needs and operational demands of the maintenance sector.

2.2 CURRENT MAINTENANCE TRAINING PRACTICES IN SRI LANKA'S APPAREL INDUSTRY

In Sri Lanka's apparel sector, maintenance operations are essential for ensuring the longevity and efficiency of production machinery(Wijesinghe & Mallawarachchi, 2019). However, training approaches within the facilities management (FM) and maintenance domains are still primarily based on traditional models such as classroom-based sessions, on-the-job training (OJT), and occasional workshops (Abdeen et al., 2019). These practices focus heavily on reactive problem-solving and are often informal, lacking standardised programs or structured evaluation methods. As a result, while they may suffice for basic skill transfer, they fall short in addressing the dynamic technical needs of modern manufacturing environments (Perera & De Silva, 2021). OJT is the most adopted strategy, wherein experienced workers mentor junior technicians by exposing them to real-time issues and practical fixes (Rathnaweera & Fernando, 2019). Though this promotes experiential learning, studies have criticised it for its inconsistency, dependency on mentor availability, and inability to cover complex or rare equipment breakdowns (Wijesinghe & Mallawarachchi, 2019b). Furthermore, paper-based manuals and verbal instructions still dominate, limiting knowledge retention and engagement among younger, tech-savvy employees (Perera & De Silva, 2021). Classroom-based training and specialised workshops are still integral components of the current training landscape in the Sri Lankan apparel maintenance sector (Jayarathne et al., 2021). These sessions often serve as introductory platforms for newly recruited technical staff or as occasional upskilling programs when new machinery is introduced (Abdeen et al., 2019). Similarly, specialised workshops tend to be conducted on an ad-hoc basis, with limited follow-up or assessment mechanisms to evaluate skill development and application in real workplace settings (Jayarathne et al., 2021). This disconnection between training content and real-world maintenance challenges contributes to skill gaps, especially in handling advanced machinery and automated systems. Moreover, the absence of well-defined and standardised training programs further challenges the effectiveness of capacity-building efforts in the maintenance sector of Sri Lanka's apparel industry. Training initiatives are often reactive, with little alignment to a broader workforce development strategy or competency framework (Wijesinghe & Mallawarachchi, 2019). This leads to inconsistencies in technical proficiency, reduced operational efficiency, and an overall vulnerability in the sector's ability to adopt emerging technologies and maintenance practices.

2.3 CURRENT TRAINING NEEDS OF THE MAINTENANCE SECTOR

The maintenance training needs within the apparel industry are diverse and vary significantly across different organisational levels. These needs are shaped by the nature of responsibilities, exposure to technology, and decision-making roles. According to Thenuwara and Sandanayake (2018), training can be effectively classified into three levels, namely, operational, supervisory, and managerial. This categorisation helps tailor training interventions to suit the specific functions and challenges at each level. At the operational level, technicians are responsible for hands-on equipment maintenance and troubleshooting. However, training is often limited to repetitive tasks, lacking depth in system-wide understanding (Abdeen et al., 2019). As a result, many workers struggle with preventive strategies or adapting to modern equipment, highlighting the need for broader, experience-based learning approaches (Wickramasinghe & Perera, 2022). Supervisory staff, such as engineers and maintenance supervisors, require a combination of technical and leadership skills. Literature emphasises the importance of training in areas like CMMS, predictive maintenance tools, and soft skills, including communication and planning (Jana & Tiwari, 2017). However, for managerial personnel, training must be aligned with organisational goals and long-term strategy. Managers should be equipped to lead digital transformation and implement initiatives like Total Productive Maintenance (TPM) and Industry 4.0 technologies (Anthonypillailionel & Oruthotaarachchi, 2025). According to Shamsuzzaman et al. (2023), strategic training helps managers shift from reactive approaches to data-driven, proactive maintenance planning.

2.4 INTEGRATING AR AS A STRATEGIC TRAINING SOLUTION

As global industries shift towards digitised and smart maintenance practices, the Sri Lankan apparel sector must modernise its training approaches to remain competitive (Wijesinghe & Mallawarachchi, 2019). One significant shortcoming in current methods is the continued reliance on paper-based procedures (PBP), which are time-consuming, inefficient, and often hinder effective knowledge transfer (Majumdar et al., 2021). In this context, Augmented Reality (AR) has emerged as a particularly promising tool for maintenance training. AR enables interactive, real-time learning by overlaying digital instructions onto physical equipment, thus enhancing comprehension and retention (Mourtzis et al., 2020). Integrating AR into facilities management (FM) training programs within the apparel sector could bridge existing skill gaps, promote a proactive maintenance culture, and align local practices with global digital trends.

3. METHODOLOGY

Research methodology outlines the strategic framework for conducting a study, encompassing the philosophical assumptions, data collection methods, and analytical techniques used to address the research objectives. As suggested by Abutabenjeh and Jaradat (2018), the methodology defines how research questions are addressed systematically from conception to interpretation. In line with this, the present study adopts a qualitative research approach, which is most appropriate for exploring the different experiences, perspectives, and contextual factors surrounding maintenance training practices in Sri Lanka's apparel industry. This approach was chosen for this study, as it allows for an in-depth understanding of the underlying factors influencing maintenance practices, training needs, and perceptions about the adoption of AR as a

strategic solution. Unlike quantitative methods that seek generalisability through numerical data, qualitative research is suited for exploring complex, context-specific phenomena that require rich, detailed narratives. This is particularly relevant in industrial environments as apparel manufacturing, where human factors, organisational culture, and technological adaptability play a critical role. To capture expert insights, the study employed structured expert interviews to ensure consistency across all participants while maintaining the depth of qualitative inquiry. Experts selected for the study include facility engineers & maintenance engineers connected to Sri Lanka's apparel sector. These individuals were chosen based on their direct experience and decision-making roles. This method is justified because it allows the researcher to explore current maintenance practices, identify specific training gaps, and assess expert opinions on the feasibility and strategic potential of AR in maintenance training. Structured interviews also reduce interviewer bias and enable the systematic comparison of responses across different stakeholder groups. Data were collected through structured interviews using a standardised questionnaire developed based on themes identified in existing literature. The questionnaire consisted of open-ended questions categorised under three themes: (1) current maintenance training practices, (2) current maintenance training needs, and (3) potential applications of AR technologies in training for the apparel industry in Sri Lanka. Purposive sampling was employed to select five experts with demonstrated expertise in maintenance practices, training methods, and augmented reality technologies. This approach aligns with the qualitative research emphasis on depth of insight rather than numerical generalisability. Each participant was chosen based on their strategic role and specialised experience in the apparel sector, ensuring a well-rounded understanding across both operational and technological dimensions. In line with qualitative standards, particularly in expert-driven studies, rich and meaningful data can be obtained from a limited number of interviews (Etikan, 2017). The small number of experts was also a consequence of availability and accessibility constraints since the roles were specialized, and the case involved a single facility. The approach applied ensures that the information obtained is highly specific and reflects the actual industry scenario, providing depth rather than breadth. The summary of the profile of the respondents is presented in Table 1 below.

Table 1: Profile of the respondents

Expert	Designation	Area of expertise	Work experience (Years)
E1	Maintenance Executive	Building Services	07
E2	Engineer	Building services and Total Productive Management (TPM)	20
E3	Facilities engineer	Building Services, Lean Management & OSH	10
E4	Automation engineer	Building Services, Machine Engineering and Automation	06
E5	Maintenance manager	Building Services and Machine Engineering	10

The qualitative data collected through interviews were analysed using thematic analysis, which is well-suited for identifying patterns and insights from textual data. For this study, the content analysis method was conducted using the NVivo software (2010) manufactured by Qualitative Solutions and Research (QSR) International (Pvt) Ltd.

4. FINDINGS AND ANALYSIS

Every respondent offered perceptions based on their experience in maintenance training within the apparel industry, and the research findings are comprehensively described under three topics hereafter.

4.1 CURRENT MAINTENANCE TRAINING PRACTICES IN SRI LANKA'S APPAREL INDUSTRY

The findings revealed that training practices for maintenance in the apparel industry are highly varied, disconnected, and largely non-standardised. The most frequently mentioned technique is on-the-job learning. All experts agreed that this method is widely applied, as it provides immediate, experiential exposure in real working conditions. It allows maintenance staff to self-learn practical skills and gain direct access to equipment and systems. However, experts noted that while effective for acquiring procedural knowledge of specific tasks, it often lacks theoretical depth and results in knowledge gaps related to broader system understanding and strategic insights. According to E3, "On-the-job learning is practical and widely used, but it does not equip technicians with a comprehensive understanding necessary for evolving maintenance challenges". Furthermore, to address these theoretical gaps, experts mentioned that classroom sessions and customised workshops are occasionally used. These interventions aim to teach foundational maintenance skills, safety procedures, and technical details related to facility management functions. However, experts highlighted that such sessions are intermittent and insufficiently integrated with practice-based learning, leading to a disconnection between theoretical knowledge and real-world application. As E2 noted, "Most training efforts are reactive and do not follow a structured curriculum aligned with business strategies". The use of ad-hoc workshops and collaboration with equipment manufacturers or service agents reinforces the reactive nature of current maintenance training practices. As many experts mentioned, although training provided by external sources is valuable for specialised knowledge, it is often dependent and uncertain, particularly when such external support is not consistently available. Another major inadequacy that was highlighted is the prevalence of poorly structured training programs. Experts noted that many organisations depend on training initiatives that lack clear learning objectives, are misaligned with operational goals, and result in weak skill development. This has been strengthened by E4 as "training initiatives are fragmented and poorly aligned with strategic goals, leading to inconsistent skill acquisition". Experts further highlighted the use of WhatsApp loop communication as an improvised training medium, demonstrating how maintenance teams have adapted to overcome communication and knowledge-sharing gaps. While such instant messaging platforms enable real-time collaboration and quicker troubleshooting, experts emphasised that they cannot replace structured learning methods. Informally communicated knowledge, they noted, is often fragmented, unverified, and lacks systematic control, which can compromise the consistency and reliability of maintenance practices. Table 2 below

summarises the experts' responses regarding the usage of current maintenance practices in the apparel industry.

Table 2: Current maintenance training practices

	Current maintenance training practices in industry	Experts				
		E1	E2	E3	E4	E5
1	On-the-job learning	✓	✓			✓
2	Occasional classroom sessions	✓				
3	Specialized workshops	✓				
4	Specific events like new equipment installation or safety updates	✓				
5	Ad-hoc workshops		✓	✓		
6	Engaging with manufacturers or agents		✓	✓		
7	Conducting poorly defined training programs			✓	✓	
8	WhatsApp loop communication			✓		

4.2 CURRENT MAINTENANCE TRAINING NEEDS IN SRI LANKA'S APPAREL INDUSTRY

Findings from expert interviews indicate that training requirements differ significantly across operational, supervisory, and management levels. At the operational level, technicians form the core of maintenance operations, performing hands-on tasks, troubleshooting equipment, and ensuring uninterrupted system functionality. However, experts mentioned that training provided to this group is often fragmented and narrowly task specific. Many technicians possess procedural knowledge but lack a comprehensive understanding of the overall maintenance process. Experts emphasised the importance of tailoring training programs to match the varying skill levels among technicians, promoting a more holistic maintenance capability. According to E2, "technicians need more than task specific training: A broader understanding is essential to improve overall maintenance effectiveness". Furthermore, they highlighted the practical challenge of organising training without disrupting ongoing operations, recommending that programs be modular, flexible, and seamlessly integrated into daily routines.

At the supervisory level, which includes supervisors, engineers, and maintenance professionals, the training needs extend beyond technical skills to encompass leadership development, strategy implementation, and the adoption of emerging technologies. Experts expressed the need for upskilling in areas such as maintenance management software, predictive technologies, and data-driven systems, which are lacking currently in Sri Lanka. Given the diverse competence levels within maintenance teams, training must be adaptable to suit different learner profiles. Here, experts E3 and E4 pointed out the preference of the supervisors for hybrid training approaches, combining traditional hands-on methods with advanced tools such as simulations and augmented reality. In addition to that, E4 emphasized that, "supervisors prefer training that blends traditional and innovative methods to prepare for future technological demands". For management-level personnel and decision-makers, training is closely tied to strategic organisational objectives. Experts stated that training programs for managers must be purposefully

designed to align with business goals, enabling them to move from reactive repair approaches to proactive maintenance strategies. Experts further opinionated that managers should be equipped not only to adopt new technologies but also to lead organisational change by overseeing the implementation of smarter, data-driven maintenance systems.

4.3 INTEGRATING AR AS A STRATEGIC TRAINING SOLUTION IN THE APPAREL INDUSTRY

Expert interviews revealed several critical limitations in the current maintenance training practices within Sri Lanka's apparel industry's Maintenance sector. While traditional methods such as on-the-job learning, classroom sessions, and workshops remain widely adopted, experts E1, E2, and E5 emphasised that these approaches have not evolved in line with the increasing complexity of maintenance systems, equipment, and digital technologies. All experts agreed that conventional training often lacks interactivity, real-time relevance, and adaptability to the dynamic operational environments now prevalent in this sector. Specifically, E3 highlighted that recent reliance on paper-based training has proven inadequate in equipping staff with the technical competencies required for today's maintenance demands. To address these shortcomings, all interviewed experts unanimously recommended adopting hybrid training models that combine traditional methods with advanced technologies. Among these, Augmented Reality (AR) emerged as a particularly promising tool for maintenance training. As E1 noted, "Technology like AR can be a game-changer in maintenance training," while E5 reinforced that by stating, "AR-based training can significantly enhance learning, especially for maintenance staff in the apparel industry." AR offers a range of strategic advantages aligned with both functional and non-functional training requirements. Experts E2 and E4 stressed the need for training systems that are intuitive, accessible, and adaptable, especially for junior or novice technicians. AR responds to this need with user-friendly interfaces, compatibility with mobile and wearable devices, and the capacity to deliver context-specific training directly at the point of task execution.

5. DISCUSSION

The study revealed a significant mismatch between existing maintenance training practices in Sri Lanka's apparel industry and the evolving demands of modern maintenance functions. Literature highlighted traditional methods such as on-the-job training (OJT), classroom-based sessions, and occasional specialised workshops. However, both the literature and research findings confirmed that these methods often lack standardisation, consistency, and long-term planning. This aligns with findings by Al-Najjar and Algabroun (2017) and Priyantha (2021), who recorded similar inadequacies in maintenance training approaches and the absence of a rich maintenance culture in apparel sector of Sri Lanka. Insights from expert interviews further uncovered additional practices currently in use in the apparel industry in Sri Lanka as training prompted by specific events like new equipment installations, demonstrations led by manufacturers or agents, and informal knowledge-sharing through WhatsApp loops. These findings suggest that current training is often reactive, fragmented, and situational rather than structured and strategic. The adaptive but unstructured learning environments reported in previous investigation in Sri Lanka confirms the use of WhatsApp loops as an improvised communication method (Weeks & Leite, 2021). In terms of training needs,

both literature and expert evidence consistently emphasised the necessity for differentiated training approaches across operational, supervisory, and managerial levels. Mourtzis et al. (2019), advocated that level division by arguing that employee's skills requirement based on the level and training programs should be specifically designed to align with the needs of each level. Further, that corroborates by (Almulla, 2023). At the operational level, workers require practical, experience-based learning to enhance system-wide understanding. Supervisory personnel need training in predictive tools, planning, and leadership, while managerial staff must be equipped to drive digital transformation and align maintenance strategies with organisational goals. As a discipline in the evolution of facilities management, these managerial requirements reflect the strategic focus (Nor et al., 2014). In comparison to the primary data in the Table 2, these claims are significantly substantiated through expert interviews. Besides, the experts confirm that classes and workshops are irregular and inadequately integrated with operational realities that resulting in a gap between theory and practice. Furthermore, experts demonstrated the absence of appropriate well-structured, standardized training programs in accordance with organizational strategic objectives which supports and elaborates the concerns already identified in the literature. The increasing complexity of machinery and the shift towards predictive, data-driven maintenance highlight the need for modern, hybrid training solutions. According to Mourtzis et al. (2020), blend learning models combining traditional and AR-enhanced approached to optimize skill acquisition and operational efficiency which is in line with the global trends. Expert perspectives strongly supported the integration of Augmented Reality (AR) as a viable strategy to meet these evolving needs at different levels. Ultimately, integrating AR into maintenance training can elevate technical competencies across all workforce levels and position Sri Lanka's apparel industry in line with global digital training practices.

6. CONCLUSION

This study offers critical insights into the current state of maintenance training practices and emerging needs within Sri Lanka's apparel industry. At present, training is largely informal and unstructured, dominated by on-the-job learning, ad-hoc workshops, and reactive knowledge-sharing mechanisms. While these methods deliver immediate practical exposure, they often fall short in fostering comprehensive theoretical understanding, leading to noticeable skill gaps in strategic and system-level maintenance thinking. Expert insights emphasise the urgent need for structured, integrated, and future-ready training frameworks that combine foundational hands-on skills with advanced technological tools. In particular, the integration of AR-based training solutions is identified as a strategic enabler, facilitating interactive, scenario-based, and readily accessible learning experiences. By adopting such innovative approaches, the apparel industry can address current competency deficits and develop a digitally skilled maintenance workforce that is aligned with global best practices and prepared for the evolving demands of modern manufacturing environments.

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IMPACT OF CONSTRUCTABILITY ISSUES IN LARGE-SCALE CONDOMINIUM PROJECTS: A CASE STUDY FOR SRI LANKA

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ABSTRACT

Sri Lanka's construction industry has experienced significant growth over the past decade, with an average growth rate of 8.5% from 2010 to 2020. Large-scale condominium projects have emerged as prominent projects in the real estate sector since they hold a dominant portion. Successful completion of these projects requires advanced construction techniques and strategic planning throughout the project, starting from pre-construction stages to project handover. The study adheres to a dual-level classification model for constructability issues in Sri Lankan condominium projects as common and project-specific issues. The evaluation of the impact of these issues on project evaluation criteria is vitally important for contractors to complete projects successfully. The study follows a sequential mixed-method approach consisting with a detailed questionnaire and were conducted among industry professionals to evaluate eight (8) constructability issues, including design complexity (DC), Mechanical, Electrical, and Plumbing work (MEP) integration issues, to check their effect on seven (7) project evaluation criteria. Through the collected consensus from the industry professionals, the constructability issues are evaluated and analysed using professional agreement rates, cross-tabulation, and using Kruskal-Wallis (KW) Test. The results generated through the KW tests, having lower $p<0.05$, show that DC, integration of MEP, and material handling are major constructability issues, while issues with $p>0.05$, including having long shear walls, work hour restrictions, are project-dependent constructability issues. This research contributes to the industry by providing actionable insights into mitigating constructability-related risks, ultimately facilitating the successful completion of large-scale condominium projects in Sri Lanka.

Keywords: *Constructability Issues; Cost Estimation; Project Attributes; Project Planning.*

1. INTRODUCTION

Construction is one of the major industries that underpin economic development across the world and is usually linked with infrastructure development, income generation, employment, and urbanization (Al-Fadhli, 2020). According to the Construction Industry

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Statistics 2025, it is among the major industries in the world, employing over 100 million people and contributing about 13% to the worldwide Gross Domestic Product (GDP). The industry's long-run impact on the economy is much bigger and also affects other industries that provide machinery, building materials, transport, and services (Langappuli, 2023). In the last decade, the construction industry has continued to grow phenomenally, with the global construction market surging from USD 9.5 trillion in 2014 to USD 12.9 trillion in 2022. Further, a growth of 35% is expected in the next eight years by 2030. (Al-Fadhli, 2020). Higher urbanization, improvement in construction technologies, and greater consideration for sustainability and resilience in the building industry have led to an upsurge in development in the construction industry (Contrada et al., 2019). The Sri Lankan construction industry is vital to the country's economic development. It had contributed 6.2% to the nation's GDP in 2020, with a Compound Annual Growth Rate (CAGR) of 15.1% (De Silva et al., 2023). The census report for 2021 by the Department of Census and Statistics, Sri Lanka, reports that the construction industry employed an estimated 1.03 million workers in 2020, or about 7.5% of total employment in Sri Lanka (De Silva et al., 2023). However, the Sri Lankan construction industry faced a severe downfall within the years of 2020 to 2023, due to the COVID-19 pandemic followed by the economic downturn. It resulted in project halts, labour shortages, and significant material price fluctuations. Large-scale projects, including condominiums, were either delayed or abandoned due to limited foreign funds and investment costs.

Prior to the economic downturn, condominium developments had the largest share in the real estate market under the construction industry, due to increased urbanization, higher demand for high-rise residential units, and foreign investments (Prathapasinghe, 2018). Between 2006 and 2017, a total of 895 certified completed properties and 15,483 condominium units were recorded in the market as of 2017 (Prathapasinghe, 2018), and it is estimated that another 200 projects under construction will add another 13,000 units. But with the effect of the downfall, according to the Urban Development Authority, only 18 new condominium projects were approved in 2022, compared to 47 in 2019. However, the sector is showing signs of recovery with an increase in approved condominium projects in urban centres like Colombo and Kandy (Central Bank of Sri Lanka, 2024). Thus, it is still important to understand the factors influencing the condominium projects within Sri Lanka. Large-scale construction projects, especially condominium developments, are pivotal in a country's development. But they are often plagued by constructability issues arising from poor integration between design and construction phases, inadequate planning, or site constraints that adversely impact project schedules, costs, and quality (Ahmed & Mahjoob, 2024). The primary aim of constructability is to enhance cost efficiency, improve the quality of the project, and serve as a bridge between the designer and the construction team (Contrada et al., 2019). Literature has consistently highlighted key constructability issues, such as excessive design complexity, inadequate integration of mechanical, electrical, and plumbing (MEP) services, site congestion, material logistics inefficiencies, and ineffective workforce and time management. Even though the significance of constructability issues has been increasingly recognized in global construction practices (Wong et al., 2006). Thus, there is a profound need to identify these constructability issues and generate proper mitigation measures to address those issues. These solutions are suggested to be long-term proactive planning rather than short-term practices for the temporal removal of the issue. Through proactive planning and a collaborative approach, completion of the project within the specified quality

standards can be ensured (Wimalaratne et al., 2021). Constructability and related issues have been widely studied globally under many research projects. These projects can be categorized as qualitative, quantitative, and mixed-approach projects. Most of these constructability issues are country-dependent, with the construction practices in which the industries are involved (Trigunarsyah, 2004). In developed economies, such as the UK focuses on design rationalization in simplifying designs to reduce on-site complications. In countries like the USA, Australia, and Singapore emphasized the development of management systems and construction practices that allow for the integration of construction expertise at earlier stages in the project as per Cheetham & Lewis (2001), Trigunarsyah (2004). However, in Sri Lanka, few empirical studies have systematically classified or quantified these issues within the context of high-density urban projects like condominiums. Thus, there is a gap that should be addressed by conducting a comprehensive study to identify the constructability issues. In several previous studies, the term constructability had been examined, but a very limited amount of work is available focusing on a dual-level classification model for the available constructability issues in Sri Lankan condominium projects. The classification is conducted under two aspects as common constructability issues and project-oriented constructability issues. The study provides a novel diagnostic framework using cross-tabulation and the Kruskal-Wallis test to analyze the impact of constructability issues across different stakeholder demographics and project features and classify them under project-specific or common constructability issues.

2. METHODOLOGY

2.1 DATA COLLECTION AND SURVEYS

This study examines constructability issues in large-scale condominium construction projects in Colombo and nearby suburbs, Sri Lanka, aiming to identify and evaluate key challenges that impact project execution. A sequential mixed-methods approach was employed, combining expert interviews and surveys as research methods and semi-structured interviews and structured questionnaires as data collection techniques. A mixed-method approach is applied to increase the generalizability and interpretability based on statistical representation of the results, connecting them with the initial expert consensus (Malina et al., 2011). Initially, 12 constructability issues and 12 evaluation criteria were identified through a literature review of Wimalaratne et al. (2021), Wong et al. (2006), Yustisia (2014), and expert interviews. A Delphi study involving 12 experienced professionals helped refine the questionnaire by filtering the most significant constructability issues based on a 75% agreement rate (Garusinghe et al., 2023). Then, the initially identified constructability issues and evaluation criteria were refined to eight and seven, respectively. The final survey is distributed to fifty-two (52) construction professionals, including project managers, engineers, architects, and quantity surveyors. They were selected from the professionals who had engaged in the construction of condominium projects to have different levels of experience, designations, project locations, and project scales. And 5-point Likert Scale is used to measure their agreement levels on the impact of each constructability issue. The Likert Scale is a widely used psychometric tool in research to measure attitudes, perceptions, or opinions by individuals (Nyutu et al., 2020). The respondents rate their “level of agreement” to the particular statement using a structured scale from “Strongly Disagree” to “Strongly Agree” (Joshi et al., 2015). This structured methodology allowed for the systematic

quantification of subjective perceptions, ensuring a comprehensive analysis of constructability issues in Sri Lankan condominium projects.

2.2 DATA ANALYSIS

The qualitative data that is collected from the respondents is given a quantitative value, where it is easy to generate a quantitative comparison of the generated results.

2.2.1 Percentage Agreement Rates

Percentage agreement rates are a statistical tool that is used to evaluate the level of respondents who have a certain level of agreement expressed to a statement. Within this study, the number of respondents who agreed or strongly agreed with the statement is considered under the agreed population for the statement, and using Equation 1, percentage agreement rates are found (Noor Aslinda et al., 2014).

$$Agreement\ rate = \frac{No.\ of\ Agreements\ (Strongly\ Agree\ count + Agree\ count)}{Total\ number\ of\ responses} \times 100\% \quad Equation\ (1)$$

This equation can be applied to find the agreement rates of 52 responses, and this method is particularly useful in identifying key factors affecting project execution by quantifying expert agreement on constructability issues.

2.2.2 Cross-Tabulations

Cross-tabulation, also known as contingency table analysis, is a statistical method used to examine the relationship between two or more categorical variables (White, 2003). Cross-tabulation in the Statistical Package for the Social Sciences (SPSS) is the method used in analysis. In the context of this study, cross-tabulation is conducted to analyse variations in perceptions of constructability issues. They are analysed based on different factors, such as designation, experience level, project duration, and project location. The cross tabulation is conducted on the basis of Equation 2 (Atkinson et al., 2021):

$$Percentage\ response = \frac{Frequency\ of\ a\ specific\ response\ in\ a\ group}{Total\ number\ of\ responses} \times 100\% \quad Equation\ (2)$$

Using the cross-tabulated percentage values, more significant constructability issues can be identified where all the respondents agreed, despite their designation, experience level, project duration, and location. Similarly, instances with different responses with the change of the considered parameters, designation, experience level, project duration, and location can also be found. Thus, a clear exposure to commonly found constructability issues and project-oriented constructability issues can be identified through cross-tabulations.

2.2.3 Kruskal-Wallis Test

To further examine the relationships between professional background, project location, experience level, and project duration with the ratings assigned to the constructability issues, the Kruskal-Wallis Test (Kruskal & Wallis, 1952). This Kruskal-Wallis (KW) Test is a non-parametric test and is selected because it is well-suited for analysing data from multiple independent groups that do not follow a normal distribution. The KW Test allows for the identification of statistically significant differences in the responses across the different demographic groups (Lelwala et al., 2024). The formula to find the H statistic in the KW test is as follows in Equation 3:

$$H = \frac{12}{N(N+1)}\sum_{i=1}^{c}\frac{R_i^2}{n_i} - 3(N+1) \qquad Equation(3)$$

where, C represents the sample number, N is the total number of samples, and R_i is the sum of ranks in the i^{th} sample. A minimum of 5 samples is required to satisfy the chi-square distribution (Kruskal & Wallis, 1952). When sample sizes are large enough ($n > 5$ for all groups), the H-statistic approximates a Chi-squared (χ^2) distribution with $C-1$ degrees of freedom. The p-value is then calculated based on the H-index using SPSS software. A small p-value (typically ≤ 0.05) indicates that the observed data is unlikely under the null hypothesis, providing strong evidence to reject it. (Bonovas & Piovani, 2023). This indicates a significant difference between the consensus of the compared sub-classes. The null hypothesis represents a statement approved by most respondents. A large p-value (greater than 0.05) suggests that the observed data is likely under the null hypothesis, indicating insufficient evidence to reject it. (Marasini et al., 2016). The results indicate that constructability issues in large-scale condominium projects can be categorized into universally recognized challenges ($p > 0.05$) and critical issues that vary across different classifications ($p < 0.05$). While some issues are consistently acknowledged across all sub-groups, others show significant differences in perception, highlighting their varying impact based on project characteristics.

2.3 QUESTIONNAIRE REFINING

An initial frequency analysis is conducted to identify the most common constructability issues having high agreement rates of more than 75% (Garusinghe et al., 2023). Table 01 provides the selected and omitted constructability issues for the questionnaire development. Constructability issues: Insufficiency of Health and Safety, Poor Monitoring and Controlling of Work Progress, Requirement for controlling of material wastage and project attributes with Design Change, Project Procurement, Project Risk, Project Stakeholder and Scope of Work Statement were omitted with respect to expert consensus and following constructability issues and project attributes were selected. Common constructability issues identified for the evaluation are as follows.

1. Complex architectural design (CD)
2. Integration issues in structural & MEP drawings (IMEP)
3. Difficulty in material handling and storing due to over-utilized land area (SM)
4. Difficulty in placing/arranging Tower cranes, Hoists, booms & stationary pumps due to over-utilized land area (OL)
5. The project consists of lengthy shear walls (LS)
6. Difficulty in material feeding due to large bulk quantities (BM)
7. Manpower (Staff + workers) at peak exceeds 500 (MPR)
8. Time restrictions on working hours (WR)

And these issues were summarized to analysed under the following project attributes:

1. Impact on project cost (IPC)
2. Impact on project duration (IPD)
3. Problems that may appear during the maintenance stage (IPM)
4. Impact on maintaining resource requirement (IRR)
5. Impact on maintaining QAQC (IQAQC)
6. Impact on maintaining productivity (IMP)
7. Impact on maintaining construction teams' motivation (ICM)

This questionnaire is further refined using the consensus, applying the Delphi study, and the final questionnaire is formed as in Table 1.

Table 1: Final Questionnaire

Constructability issue and evaluation attributes	Acronym
1. Complexity of design (Complex architectural design)	
Impact on project duration	COMP1
Impact on project cost	COMP2
Impact on maintaining QAQC	COMP3
Impact on maintaining resource requirement	COMP4
Impact on maintaining construction teams' motivation	COMP5
Impact on loss of productivity	COMP6
Possibility of problems may appear during the maintenance stage	COMP7
2. Integration issues (Integration issues in structural and MEP drawings)	
Impact on project duration	INTISS1
Impact on project cost	INTISS2
Impact on maintaining QAQC	INTISS3
Impact on maintaining resource requirement	INTISS4
Impact on maintaining construction teams' motivation	INTISS5
Impact on loss of productivity	INTISS6
Possibility of problems may appear during the maintenance stage	INTISS7
3. Overutilized land area (Difficulty in material handling and storing)	
Impact on project duration	OULA1
Impact on project cost	OULA2
Impact on maintaining resource requirement	OULA3
Impact on maintaining construction teams' motivation	OULA4
Impact on loss of productivity	OULA5
4. Lack of space for placement of construction machinery	
Impact on project duration	PCOMA1
Impact on project cost	PCOMA2
Impact on maintaining resource requirement	PCOMA3
Impact on maintaining construction teams' motivation	PCOMA4
Impact on loss of productivity	PCOMA5
5. The project consists of lengthy shear walls with lengths exceeding 10m	
Impact on project duration	PROJCH1
Impact on project cost	PROJCH2
Impact on maintaining QAQC	PROJCH3
Impact on maintaining resource requirement	PROJCH4
Impact on maintaining construction teams' motivation	PROJCH5
Impact on loss of productivity	PROJCH6

Constructability issue and evaluation attributes	Acronym
6. Difficulty in material feeding due to large bulk quantities	
Impact on project duration	DIFMAFE1
Impact on project cost	DIFMAFE2
Impact on maintaining QAQC	DIFMAFE3
Impact on maintaining resource requirement	DIFMAFE4
Impact on maintaining construction teams' motivation	DIFMAFE5
Impact on loss of productivity	DIFMAFE6
7. Manpower (Manpower (Staff + workers) at peak exceed 500)	
Impact on project duration	MANPOW1
Impact on project cost	MANPOW2
Impact on maintaining QAQC	MANPOW3
Impact on maintaining resource requirement	MANPOW4
Impact on maintaining construction teams' motivation	MANPOW5
Impact on loss of productivity	MANPOW6
Possibility of problems may appear during the maintenance stage	MANPOW7
8. Time restriction	
Impact on project duration	TIMREST1
Impact on project cost	TIMREST2
Impact on maintaining resource requirement	TIMREST3
Impact on maintaining construction teams' motivation	TIMREST4
Impact on loss of productivity	TIMREST5

3. FINDINGS

3.1 PERCENTAGE AGREEMENT RATES

The agreement rate analysis highlights complex architectural design (CD) and MEP integration (IMEP) issues as the most critical constructability challenges, particularly impacting project duration (89% PA for CD, 88% PA for IMEP) and cost overruns (90% PA for CD, 92% PA for IMEP). These issues introduce construction difficulties, coordination challenges, rework, and delays. In terms of quality assurance and quality control (QAQC), CD and IMEP recorded 71% and 78% PA, respectively, due to their role in increasing defects and compliance risks. Resource constraints were another key concern, with 93% PA for manpower requirements (MPR), 85% PA for space management (SM), and 80% PA for bulk material feeding (BM), indicating frequent disruptions in workflow and logistics. Work-hour restrictions (84% PA) and site congestion (89% PA on IPD, 87% PA on IPC) further hinder productivity (93% PA). The primary causes of productivity losses were IMEP and CD, leading to frequent rework and extended timelines. Additionally, long-term maintenance issues were strongly linked to CD (87% PA) and IMEP (82% PA), proving that constructability challenges extend beyond construction into the operational phase of buildings. Effective workforce management, supply chain optimization, and better design coordination are crucial for mitigating these challenges.

3.2 CROSS-TABULATION OF EVENTS

By cross-tabulation of the rate of agreement or disagreement, the variation of perceptions on selected constructability issues depending on different criteria like designation, experience level, project duration, and project location can be assessed.

3.2.1 For Designation

Considering COMP1, 30 out of the 52 respondents strongly agreed with the statement. The responses marked "Strongly agree" are most prevalent in the category Project Engineer/Civil Engineer, with 12 out of 26 respondents, or approximately 46%, strongly agreeing to the assessment of COMP1. Response distribution showed consistency for most components, with roles such as Project Engineer/Civil Engineer and senior management roles like Chairman/CEO/GM/DGM/AGM rating favourably. For instance, from COMP2, 20 of 52 participants agreed to this component, while another 27 strongly agreed. In the meantime, other designations, such as Project Manager/Construction Manager, are more indifferent or diversified in opinion directions. Focusing on components dealing with project challenges and manpower management obtained more mixed responses across all roles, suggesting these are areas that might require further detailing or improvement. This would mean that such components as PROJCH1 and MANPOW6, which had responses that were more neutral or diverse, indicate possible areas where roles feel less aligned or satisfied with the current approach. For instance, PROJCH1 received 14 out of 46 respondents who chose either "Neutral" or "Disagree," indicating a high percentage of mixed feelings. In general, the data shows that the components are mostly well-received, especially by higher-level management and technical staff; there are, however, some noticeable areas where neutrality indicates room for improvement. For instance, in the case of COMP4 and COMP5, about 20% to 30% responded neutrally. Thus, the wide disparities in response for senior management against technical staff is experienced considering several constructability issues such as effect of CD in IRR and IMP, effect of SL in IQAQC, IRR, ICM and IMP.

3.2.2 For Experience

Under the classification of experience, COMP1 had a very high 30 out of 52 respondents (58%) strongly agreeing, with the "05-10 years" experience category having the highest level of agreement at 73%. This shows that the more experienced the professional, the stronger the recognition of the effect of particular constructability issues. Considering COMP2, about project feasibility, most of the "More than 5 years" of experience supported this, while 54% of the "05-10 years" respondents strongly agreed with it. By contrast, in the less experienced group, less than 5 years, responses were mostly divided, such as in the area of COMP6, related to effect of CD on IMP, with 10 out of 22 and between 05 – 10 years, 12 out of 26 respondents being neutral or disagreeing from this group. This means that junior professionals do not always have the same view or level of confidence in assessing available constructability issues, whereas with years of experience, respondents' level of agreement to statements regarding risk assessment and other critical factors such as project feasibility also increase. This trend is carried forward in COMP4, considering the effect of CD on IRR where "More than 20 years" experience recorded the highest level of agreement, showing a growing confidence in such assessments as experience in the field develops. Whereas PROJCH1, checking LS on IPC, and MANPOW6, checking MPR on IMP, yielded mixed responses for the experience of less than 10 years. Response tendencies were similar for relatively less

experienced groups. In MANPOW6, 10 out of 22 participants with less than 05-year experience and 6 out of 26 participants having 05-to-10-year experience strongly disagree, disagree or stay neutral as the response. Senior professionals, particularly those with more than 20 years of experience, strongly agreed on the importance of managing project timelines and applying management techniques, as seen in TIMREST and IMEP attributes, while less experienced professionals showed disagreements or neutrality. This indicates that with increased experience, professionals become more confident and consistent in managing project timelines, feasibility, and risk management.

3.2.3 For Project Duration

Project duration data in the PDURN variable provides valuable information on how project length influences professionals' perceptions of various project characteristics. In the case of all the types of projects that last less than two years, 02 to 03 years, 03 to 04 years or more than 5 years, the dominant responses were mostly "strongly agree" or “agree” concerning how CD effects IPC (COMP2) (46 out of 52) and IRR (COMP4) (38 out of 52). This could, therefore, indicate that those dealing with the smaller projects might more readily witness first-hand how immediate architectural design would add complexity and increased project cost due to a necessarily accelerated rate of execution, consuming greater amounts of resources as a major constructability issue. As such, for projects less than 2 years, the response is more evenly distributed across categories, especially about the impact of CD on the ICM (COMP7), WR on all evaluation attributes, IPC, IPD, IQAQC, IRR, IMP, and ICM. But for projects with a lifetime of more than 05 years, the agreement rate is very high, approving the constructability issue arising due to WR. The effect of MPR on all aspects also plays a similar response pattern, highlighting the increase of the constructability issues with the longer project duration.

3.2.4 For Project Location

Based on the data provided for the urban and suburban locations, or PROLN, several patterns can be observed from the responses to several questions regarding project characteristics. Considering COMP2, or how the CD affects a project, among the urban professionals, 20 out of 39 agree or strongly agree that the CD in a project affects its IPC, IPD, and IRR. In contrast, suburban professionals show a more neutral distribution. The urban location does, therefore, exhibit a higher degree of consensus and perhaps suggests that diversity in an urban setting is more striking and should be better handled under constructability issues than in suburban settings. For COMP3, on the effect of CD on ICM, both urban and suburban, respondents are more divided. When it comes to the CD effect on IRR, 28 respondents out of 39 agree with the effect, while in suburban conditions, 5 out of 13 reject the effect on IRR. This may mean that urban projects should deal with more structured and experienced teams, probably because of a greater resource pool and better project management frameworks, while suburban areas experience challenges in this respect. When analysing INTISS attributes based on MEP integration issues, which deal with the effectiveness of specific project interventions, it can be seen that urban professionals have higher magnitudes of agreement, while suburban professionals hold more neutral or disagreement views. It follows logically that urban locations may enjoy better tools, technologies, or training programs that make interventions more effective, and suburban areas may have more obstacles in adapting such interventions.

3.3 KRUSKAL-WALLIS TEST (KW TEST)

3.3.1 KW Test for Designation

The designation of a respondent directly affects the level of experience, exposure, and understanding the person possesses towards the construction project. Thus, depending on the destination, the type of response varies. Factors that received $p < 0.05$, mainly highlights, statistically significant variations with designation. As in Figure 1, effect of CD on ICM (p – 0.03), SM on ICM (p – 0.04), OL on ICM (p – 0.00), OL on IMP (p – 0.01), BM on ICM having (p – 0.00) and WR on IMP (p – 0.04) are construction issues that are shows statistical variations with designation of the respondent. Factors having received $p > 0.05$ are statistically non-significant factors across respondent designation. With the consistency of the respondents, these factors can be justified as fundamental construction issues which are widely recorded. The effect of IMEP on all seven considered evaluation attributes, including IPC and IPD, shows p-values ranging from 0.29 to 0.91, highlighting their common availability. Out of the bulk, the effect of IMEP on IPM is considerably accepted by professionals. The impact of CD on project duration, project cost, QAQC, and resource requirement has also commonly been identified. The effect of MPR on IPC and IPD is highlighted with common PA, driving to high p-values of 0.87 and 0.90, showing their common occurrence. Working time restrictions also show comparatively high p-values of 0.05, highlighting similar responses from professionals. Thus, the analysis displayed both statistically significant and non-significant construction issues. The effect of construction issues related to material handling, work-hour limitations, and space management and their effects on team motivation, productivity, and durations seems to be unknown or neglected. These factors also should be addressed with proper construction planning.

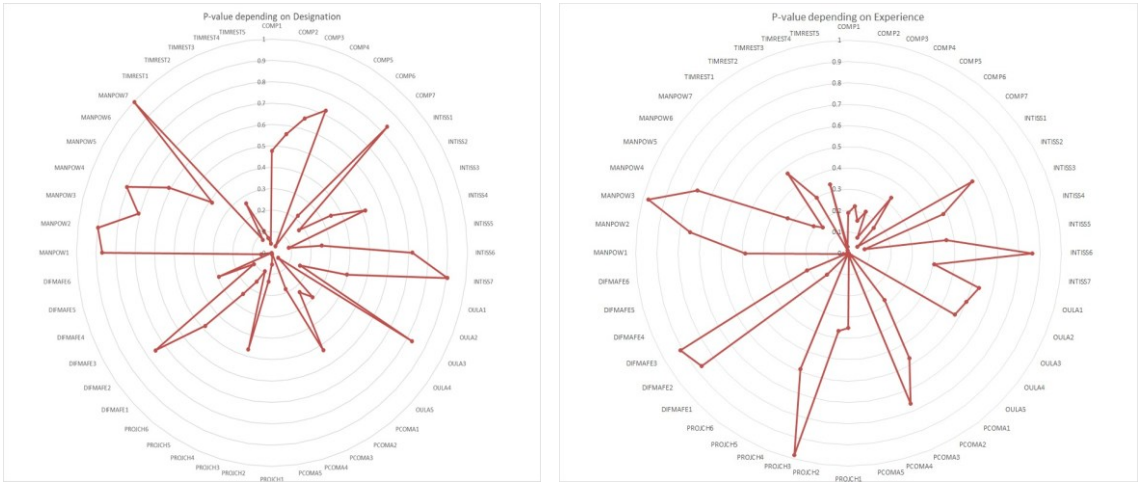


Figure 1: p-values for analysis under designation, level of experience, project duration, project cost and project location

3.3.2 KW Test for Experience

Professional experience directly influences the ability of a respondent to assess constructability issues based on their exposure and practical understanding. As in Figure 1, Material handling's effect on ICM ($p = 0.00$) and IMP ($p = 0.02$) show critical differences in how experience levels affect site logistics concerns. Similarly, OL on ICM ($p = 0.01$) and its effect on productivity ($p = 0.00$) highlight that these site constraints are more pronounced among experienced professionals with the agreement rate. The fact that

LS affects the ICM, as stated, and IMP further pinpoints structural complexities to affect perceptions across different experience levels. Meanwhile, some aspects such as effect of BM on ICM and IMP, were also with a low p value of 0.01 and 0.03, and work hour restrictions under IMP and IRR also were identified as statistically significant differences and imply that more experienced professionals seem to understand inefficiencies related to the mentioned above constraints better compared to low experienced from the agreements rates. Meanwhile, factors with $p > 0.05$ indicate a consistent perception across experience levels, implying that these issues are widely acknowledged as fundamental challenges in the industry. For example, integration issues in structural & MEP drawings (IMEP) show p-values ranging from 0.05 to 0.86, reinforcing their common occurrence. In the same vein, the impact of CD on project duration, cost, QAQC, and resource requirement maintains its consistent recognition across experience levels with higher p values from 0.08 to 0.33. This analysis identifies the significant and generally accepted construction issues and points out that, though certain factors are perceived more intensely by the experienced group of professionals compared to the rest as per the statistical variations, such as material handling, site logistics, and work scheduling. These construction issues, and generally encountered issues, require structured mitigation strategies to enhance the timely completion of the projects.

3.3.3 KW Test for Initial Project Value

The test results highlight the significant influence of financial scale on constructability in condominium projects. Complex architectural design shows variations in responses, with IPC at $p = 0.029$ and IPM at $p = 0.034$, indicating challenges in construction efficiency and resource management. Coordination issues among design disciplines are evident in larger projects, as IMEP p-values range from 0.000 to 0.007 for IPD, IPC, IQAQC, and IRR. Material handling constraints in high-value projects, particularly in over-utilized areas, are emphasized with $p = 0.039$, stressing the importance of spatial planning. Logistical challenges in urban development's require precise coordination of storage, staging, and delivery schedules. Structural demands increase with project size, affecting construction duration and cost, as shown by LS influencing IPD, IPC, IQAQC, and ICM, with p-values between 0.000 and 0.046. Work-hour restrictions, with $p = 0.019$ for IPD and $p = 0.043$ for IPC, are more prevalent in larger projects due to regulatory, environmental, and contractual factors. However, some constructability issues remain consistent across different project values, as indicated by non-significant p-values: CD on IPD ($p = 0.236$), IQAQC ($p = 0.748$), and IRR ($p = 0.184$), as well as IMEP on ICM ($p = 0.396$) and IMP ($p = 0.135$). Material handling issues (p-values 0.188-0.340 for IPD, IRR, IMP, and ICM) and MPR for IMP and ICM ($p > 0.130$) suggest that these challenges persist regardless of project scale, identifying them as inherent constructability concerns in the industry.

3.3.4 KW Test for Project Duration

The statistical analysis emphasizes the impact of project duration on constructability issues in condominium projects, highlighting how these factors change as the length of the project increases. The relationship between CD and ICM shows a significant p-value of 0.001, indicating that longer projects with complex designs are more likely to face difficulties in maintaining team motivation. Additionally, the influence of CD on IPC ($p = 0.004$) and IPD ($p = 0.028$) suggests that prolonged projects lead to increased cost and time pressures due to added complexities in design. The effect of IMEP on IMPD ($p =$

0.000) further emphasizes the growing challenges in design coordination as project duration extends, stressing the importance of careful planning and resource allocation for longer projects. The analysis also shows that project length influences BM on IRR, with a p-value of 0.003, indicating that managing the supply chain becomes increasingly difficult in longer projects. These projects require more accurate procurement and logistics planning to avoid delays and material shortages. However, factors such as the effect of SM on IPD ($p = 0.954$) and IQAQC ($p = 0.873$), as well as MPR on IQAQC ($p = 0.142$) and ICM ($p = 0.692$), demonstrate non-significant variations across project durations. This suggests that material handling and workforce management remain consistent concerns, regardless of the project duration. These persistent issues are inherent in construction, requiring ongoing management and standard solutions.

3.3.5 KW Test for Project Location

These analyses of project location impact on many of the above-mentioned constructability issues, showing significant statistical differences due to variations in professional responses. Thus, the factor of project location is a significant influence in shaping the perception of the different construction challenges. Factors with $p < 0.05$ show a statistically significant difference, while the biggest influence can be observed in CD and MPR. The impact of CD on IPC, IQAQC, and IMP consisted of statistically significant variations concerning project location at p-values of 0.03, 0.04, and 0.01, respectively, as in Figure 1, perhaps indicating the effect of the geographical context of a project. Further, the construction issue of CD to ICM also reflects location-specific issues that could affect morale, with $p = 0.03$. The analysis shows that project location also has a high degree of impact on MPR, IPD ($p = 0.00$), IPC ($p = 0.03$), and IQAQC ($p = 0.01$), which indicates that regional fluctuations in skilled labor, regulations, and the distribution of manpower are quite different. Similarly, WR also displays extreme statistical variations, though WR effect on IPD shows no significant variation at $p = 0.64$, highlighting fundamental availability of construction issue. The effect of WR on IQAQC ($p = 0.02$), IRR ($p = 0.00$), and IMP ($p = 0.00$) were significant, indicating regional boundaries setting uneven constraints on the hours of work that have a severe impact on productivity and the project timeline. Issues of integration in structural and MEP drawings, IPD ($p = 0.86$), and IPC ($p = 0.32$) did not show significant variations, suggesting that such constructability issues are similarly perceived despite the location of the project. Similarly, SM difficulties on IPD ($p = 0.76$) and OL effect on IPD ($p = 0.37$) also did not show significant variation, suggesting these issues are fundamental to construction regardless of location.

4. DISCUSSION

The findings from the agreement rate analysis, cross-tabulation, and Kruskal-Wallis tests align closely with the broader literature on constructability challenges in large-scale construction projects. Key issues such as design complexity (CD), MEP integration (IMEP), and site logistics emerged as dominant contributors to project inefficiencies, mirroring the global trends reported by Wong et al. (2006) and Capone et al. (2014). The agreement rates exceeding 85% for IMEP and CD across multiple evaluation criteria validate their critical influence, particularly on project duration, cost, and quality control. These results corroborate prior research indicating that complex designs and insufficient coordination among design disciplines often lead to rework and delays (Trigunarsyah, 2004; Cheetham & Lewis, 2001).

The strong correlations between workforce management issues, such as MPR and WR, and reduced productivity and motivation are also in line with earlier findings by Yustisia (2014) and Ahmed & Mahjoob (2024), who noted that labour inefficiencies are magnified in high-density urban projects. The cross-tabulation further highlights how professional background and experience influence perceptions, with more experienced respondents displaying a stronger consensus on the criticality of constructability issues. This trend underscores the value of institutional knowledge and aligns with Fischer and Tatum's (1997) emphasis on experiential learning in constructability planning.

Moreover, the Kruskal-Wallis test outcomes reveal statistically significant differences in perceptions based on project designation, value, duration, and location. For example, urban professionals reported more agreement with the impact of design complexity than their suburban counterparts, likely due to greater design variations and space constraints in dense cities. Meanwhile, project value emerged as a strong predictor for MEP integration and material handling challenges, confirming that scale amplifies coordination complexity, a concept widely supported in the literature (Contrada et al., 2019). Interestingly, some issues, such as IMEP and material handling, consistently showed p-values > 0.05 across all classification parameters, reinforcing their status as universally recognized constructability problems. This distinction between universal and project-specific issues is rarely explored in existing literature but provides a valuable framework for prioritizing interventions. In the Sri Lankan post-pandemic context, this differentiation is particularly relevant. The COVID-19 crisis introduced unanticipated constraints, such as workforce shortages and disrupted supply chains, which further exposed weaknesses in constructability planning (Jayakody et al., 2022). The resurgence of the industry in 2024 and 2025, while encouraging, demands a more resilient approach to managing both fundamental and situational constructability risks.

5. CONCLUSION

The study followed a mixed-method approach to conduct a dual-level comprehensive analysis to identify common constructability issues and project-oriented constructability issues. To facilitate a quantitative approach, statistical tools like the Kruskal-Wallis test and cross-tabulation analysis were utilized. The Kruskal-Wallis test and cross-tabulation analysis confirm that project duration, designation, experience, project value, and location significantly influence perceptions of constructability issues. Project duration affects team motivation, productivity, and cost, especially for complex designs (89% agreement). Designation impacts material handling (81%) and logistics (85%), while experience level influences workforce management (93%) and material feeding (76%). High-value projects face greater MEP integration (92%) and logistical issues (79%), and location affects time restrictions (96%) and manpower management (75%). Despite these variations, MEP integration, material handling, and workforce management remain universal issues with p-values > 0.05, indicating no significant difference across projects. Addressing these requires continuous improvements in planning, coordination, and resource management, while project-specific challenges need tailored mitigation strategies for improved constructability. Additionally, issues such as lengthy shear walls (50% agreement on project duration) and certain machine placement difficulties (54% agreement on productivity loss) were found to be less prominent and highly dependent on project-specific conditions. These challenges, while not widespread, require localized solutions based on project scale, design complexity, and site constraints rather than

industry-wide reforms. The fundamental issues are persistent across the industry, requiring constant attention and standard strategies to resolve them. The study encountered several limitations, as the study is only restricted to condominium projects in the urban or suburban areas of the country, not focus on a rural context. Further, the questionnaire relied on expert consensus, thus, there can be bias based on respondents' organization roles or personal experience levels. But tailored strategies may be required to deal with the project-specific challenges, while fundamental issues will need to be managed through continuous improvements in planning, coordination, and resource allocation. Future research can be established by analysing across varying building types, investigating the effectiveness of specific mitigation measures and integrating novel techniques to solve constructability issues.

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IMPACT OF MATERIAL WASTE MANAGEMENT ON CONSTRUCTION COST OF THE PROJECTS IN SRI LANKAN CONSTRUCTION INDUSTRY

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ABSTRACT

Material waste management plays an important role in the cost of a construction project. In Sri Lanka, inefficient material waste management significantly inflates project costs. Therefore, it is required to identify cost-significant inefficiencies in material waste management in Sri Lankan construction projects. Hence, this research carried out to identify cost-significant inefficiencies in material waste management in Sri Lankan construction projects. This research carried out a literature review which helped in findings the status of material waste management practices in construction projects. Mixed methods were adopted by combining qualitative and quantitative research approaches. The primary data for this study is collected through semi-structured interviews and questionnaire survey from the industrial experts purposely selected based on this research problem. The data collected were analyzed using manual content analysis and the Relative Importance Index method. As per this study, limited recycling facilities, design changes and variations and inefficient material handling are found out to be some of the major inefficiencies exist in the material waste management practices among building projects in Sri Lanka. This study further highlights inefficient design and planning process, insufficient regulations, inaccurate measurements and limited storage space as the major reasons for those inefficiencies. The best applicable strategies to overcome these inefficiencies were derived. Hence, this study highlights the major cost-significant inefficiencies in the material waste management practices specifically among the building projects in Sri Lanka, with the reasons for these inefficiencies and address on how to overcome these inefficiencies.

Keywords: *Building projects; Sri Lanka; Inefficiencies; Material waste; management; Strategies.*

1. INTRODUCTION

1.1 BACKGROUND

Construction waste generation is a significant issue in Sri Lanka, affecting the environment and the efficiency of the construction industry. Waste management involves managing resources such as site planning, transportation, storage, material handling, re-use, recycling, and disposal. The Western Province accounts for 60% of the total solid

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waste generation, amounting to 7000 metric tons per day. The construction industry in Sri Lanka faces challenges in disposing of waste properly, increasing project costs and causing long-term debt problems.

Building companies can save money by buying in bulk and using recycling stations to reuse materials. However, poor waste management methods, lack of strict laws, inadequate recycling centres, and tools further exacerbate the problem. The industry is highly fragmented, with material waste management companies, construction companies, and freelancers not working together to find effective ways to cut waste. Inefficient construction material waste management significantly contributes to increased project costs and environmental impacts worldwide (Osmani, Glass & Price, 2008; Yuan, Shen & Wang, 2011). In Sri Lanka, construction waste causes a serious challenge, yet research explicitly linking material waste handling to construction cost overruns remains limited. Existing studies tend to focus on waste generation rates and disposal methods rather than quantifying cost implications. The fragmented nature of Sri Lanka's construction industry further complicates effective waste management, as poor coordination among contractors, waste managers, and freelancers inhibits the adoption of efficient waste reduction practices. Globally, proactive waste management planning and stakeholder collaboration have proven essential to minimizing waste and controlling costs, but these strategies are underexplored in the Sri Lankan context. Additionally, weak enforcement of waste management regulations and inadequate recycling infrastructure exacerbate inefficiencies and increase project expenses.

This lack of comprehensive research and regulatory oversight underscores the need to investigate the cost impact of material waste management inefficiencies in Sri Lanka and develop customized solutions to improve sustainability and reduce construction costs. Despite differing social, economic, and environmental conditions, research is lacking on how waste management impacts construction costs. This highlights the need for effective waste management practices.

2. LITERATURE REVIEW

2.1 DEFINITIONS OF MATERIAL WASTE MANAGEMENT

Construction waste management involves material waste management, elimination, recycling, and reuse of materials (Hussain, 2016). The three most important steps in waste management are during the project phase, planning, and the completion phase. The construction industry employs various approaches; each specifically designed for its unique needs. Studies show that waste-conscious systems are crucial for handling waste effectively (Begum et al., 2007). In Malaysia, workers are not aware of waste management, while construction sites in the UAE lack proper attention. As per the studies done by Mohan et al. (2024), India's economy could benefit from less litter, and the 3R system (reduce, reuse, recycle) should be implemented. Indians should create less material waste when building and removing items, and schools should use previously used items. Pisuttu et al. (2024) advocate for the reuse of trash to reduce its environmental impact. Programs should be run to educate people about waste management and its contribution to the economy and environment.

2.2 STATUS OF MATERIAL WASTE MANAGEMENT

The construction industry is increasingly concerned about environmental protection and resource efficiency. Old methods of waste production, such as wood, concrete, and metal, end up in landfills over 75% of the time (Akanbi et al., 2018). The waste management process involves project teams, contractors, and suppliers, and circular economy ideas play a crucial role in cutting waste. Design choices and proper storage and handling are essential for meeting global sustainability goals and reducing waste production and disposal costs. Recycling and reusing old bricks, such as the REBRICK process, can help reduce litter and landfill waste. End-of-life trash can be disposed of through recycling, reusing, or landfilling (Akanbi et al., 2018). The goal is to recover as many resources as possible and minimize the impact on the world. Reusing building materials can save money, as shown by a BIM-based whole-life performance prediction (Akanbi et al., 2018). New ways to buy items for a circular economy, such as barcodes and tracking systems, can also help manage waste and save money. Circular economy ideas, new technologies, and good policies have been shown to reduce building costs and promote environmentally friendly practices (Karavezyris, 2007; Chen et al., 2021). Proper waste management requires using new tools, following rules, and thinking creatively about reuse. These tips can help construction companies save money and make the world a better place when used together.

2.3 IMPACT MATERIAL WASTE ON CONSTRUCTION COSTS

Builders play a crucial role in economic growth, but they also generate significant material waste, which increases building costs. This literature review highlights the importance of material waste management and the circular economy in reducing construction costs. Further Akanbi et al. (2018) emphasized the need for reusing construction materials, while Bao et al. (2019) mentioned procurement innovations for a circular economy. Begum et al. (2006) study the benefits and drawbacks of waste reduction in Malaysia. Bao et al. (2019) have suggested barcode systems can help reduce construction waste and save money. Bilal et al. (2020) have discussed the challenges in implementing the circular economy in the construction sector and propose solutions. Esa et al. (2017) have incorporated ideas on reducing waste disposal costs. Mahpour (2018) highlights the main issues preventing waste management from using circular economy methods. Chen et al. (2021) have highlighted that construction waste can be turned into useful materials, reducing costs. Simulations and good planning can help reduce costs. Changes in rules, waste management, circular economy, new technologies, and construction industry policies are key factors affecting building prices.

2.4 STRATEGIES FOR EFFECTIVE MATERIAL WASTE MANAGEMENT

To be sustainable, the accumulation of material waste must be eliminated. This is particularly true now as people are more concerned about resource depletion and environmental harm. This analysis examines research from a variety of disciplines, including engineering, finance, and environmental technology, to determine the most effective waste management strategy. Through many studies, they have discussed the significance of handling garbage in a way that promotes a circular economy. A financial system that operates circularly must reuse building materials (Akanbi et al., 2018). BIM stands for construction Information Modelling. It makes it easier for people to monitor how well a structure will function over time. Bao et al. (2019) have demonstrated the

significance of Suzhou's retail options for expanding China's economy in all directions. The cost of reducing building waste must be considered. Begum et al. (2006) examined the advantages and disadvantages of landfilling in Malaysia to determine whether it makes sense economically. This demonstrates how crucial it is to identify affordable and effective techniques. For the same reason, Mahpour (2018) has emphasized the challenges that arise when implementing circular economy concepts to manage waste from building and demolition while finding solutions to overcome challenges.

2.5 CHALLENGES AND OPPORTUNITIES OF THE CONSTRUCTION INDUSTRY IN MATERIAL WASTE MANAGEMENT

Around the world, the act of disposing of and dumping material waste affects businesses, individuals, and the environment (Akanbi et al., 2018). Some economies are beneficial because they aim to make goods more useful and spend less. This literature review examines the challenges and possibilities in handling construction and demolition trash by utilizing several research studies. Waste elimination becomes challenging in a revolving economy, as items undergo repeated construction. According to Bao et al., (2019), the construction industry must have several ways to buy materials to have the transition to a circular economy. They discovered that issues are unique everywhere and need various approaches to resolution in Suzhou, China.

In 2017, Nasir et al. conducted another study that examined the distinctions between direct and circular supply chains in the construction industry. It appears that using circular approaches reduces waste and improves resource utilization. Concepts from the circular economy can be helpful, but addressing the construction and demolition of trash with them is challenging for several reasons. These issues include inadequate infrastructure, a lack of knowledge, and a lack of government monitoring, according to Mahpour (2018). Some states, like Malaysia, also have clear regulatory problems. In their benefit-cost analysis, Begum et al. (2006), for instance, concluded that waste reduction techniques were both economically feasible and challenging to manage. According to Akanbi et al. (2018), a BIM-based whole-life performance estimate can be used to save construction resources. This demonstrates how digital tools can accomplish more with less. This trend is further reinforced by the utilization of system dynamics models to analyze the management of various kinds of waste (Hao et al.,2010). They have used this information to determine ways to enhance on-site waste management. Factors like income also have an impact on trash management, particularly in developing nations. In his investigation, Manowong (2012) has emphasized the significance of involving stakeholders and assisting them in developing their abilities. They have emphasized the necessity of interdisciplinary approaches that consider wealth disparities. It has been noted that managing waste from construction and demolition in a circular economy is challenging and can be approached in a variety of ways.

3. RESEARCH METHODLOGY

This chapter elaborates on the methodological framework adopted to achieve the research objectives. To achieve the research objectives, the mixed method approach was followed. Thus, it was decided that a mixed-method approach could give a more comprehensive understanding of the research, which qualitative and quantitative methods could offer separately.

This research emphasized the construction material waste management solutions in building projects in Sri Lanka. To identify the effect of inefficiencies on the construction cost of projects, semi-structured interviews were conducted among professionals. Table 01 shows the profile of the respondents of semi-structured interviews. Utilizing content analysis, the information gathered from the interviews was analysed. A simple content analysis method was used to conduct the analysis.

Table 1: Profile of Interviews

Respondents	Designation	Years of experience
R1	Material Engineer	6
R2	Chartered Civil Engineer, Program Director	37
R3	Chartered Quantity Surveyor	22
R4	Free Lance Consultant - Design Engineer	35
R5	Civil Engineer in Central province Engineering office	18
R6	Civil Engineer	12

Following the interviews, a questionnaire survey was conducted to collect quantitative data on the inefficiencies of existing material waste management strategies and practices in Sri Lankan building construction projects. The survey aimed to identify the most significant inefficiencies, their underlying causes, and possible strategies for improvement. A purposive sampling approach was used to select industry professionals such as project managers, site engineers, quantity surveyors, and architects, as these roles have direct involvement in material handling, procurement, and waste reduction activities

The questionnaire consisted of three sections: identification of inefficiencies, reasons contributing to these inefficiencies, and strategies to address them. A five-point Likert scale was used to measure the perceived level of impact or importance of each factor. The survey was distributed via both electronic platforms and printed copies to ensure accessibility, with clear instructions provided to respondents and follow-up reminders to encourage completion.

In this study, the Relative Importance Index (RII) was adopted as a principal analytical technique to prioritise the identified inefficiencies in material waste management within the Sri Lankan construction industry. The method facilitated the conversion of expert evaluations into quantifiable measures, enabling the systematic comparison of factors based on their relative significance. Through this approach, inefficiencies were ranked according to their impact on construction project costs, thereby providing a rigorous, evidence-based framework for formulating targeted interventions to enhance waste management practices.

$$RII = \frac{\sum W}{AxN} = \frac{1n1 + 2n2 + 3n3 + 4n4 + 5n5}{5 * N} \qquad Equation\ (1)$$

- W – weighting given to each factor by the respondents
- nx = Number of respondents rate on each choice
- N = Number of respondents (40 for this study)
- A = Highest weight (5)

The Relative Importance Index, 0 ≤RII ≤1

4. DATA ANALYSIS

4.1 QUALITATIVE DATA ANALYSIS

4.1.1 Inefficiencies and Reasons for those Inefficiencies in Material Waste Management Practices in Sri Lanka

The respondents indicated that material waste contributed between 5% and 30% to the total cost of construction. Additionally, most materials include steel, pipes, electrical wires, cement, sand, and tiles. Thus, Sri Lanka's material waste management practices include the following significant inefficiencies.

Thus, the following are Sri Lanka's main inefficiencies in material waste management practices.

Through semi-structured interviews, inefficiencies in material waste management were investigated. Poor regulations and enforcement, limited recycling facilities, unstable market for recycled products, inaccurate material estimation / ordering more materials than required to avoid shortages, inefficient material handling, damage to materials, inefficient transport methods, uneconomical design, design changes and variations, poor quality control, poor workmanship, not enough salvaging and reviewing, limited technology adoption, poor cutting and fabrication practices, limited standardization of materials, limited research and knowledge, not good security measure and ineffective communication are identified inefficiencies of from the semi structured interviews.

Furthermore, this study also found the major reasons for inefficiencies. There were Not enough regulations, inaccurate measurement, limited storage space, inefficient design and planning processes, weather and environmental effects, poor communication among project stakeholders, lack of awareness of material handling and proper material waste management, insufficient training practices, no proper guidance, cultural factors, delays in delivering, use of outdated tools, unforeseen site conditions, focus on speed over accuracy and overlooking minor defects that lead to later rework were identified through interviews.

4.2 DEMOGRAPHIC FACTORS ANALYSIS

Out of 55 professions, 40 respondents completed the questionnaire survey to determine the impact of inefficiencies on project construction costs in Sri Lanka. Accordingly, the response rate is 72.72%.

In this study the majority of the respondents 32.50% were Project Managers with a frequency of 13 Professionals and minority of the respondents of the 7.50%, were Site Engineers and Engineers with a frequency of 3 Professionals.10%(4) of the respondents were Senior Quantity Surveyors, 22.50% (9) of the respondents were Senior Engineers, 10% (4) of the respondents were Quantity Surveyors and 10% (4) of the others respondents participated in the questionnaire.

40% (16) of the respondents in this survey belong into the category of construction contracting, 37.50% (15) belong into the category of construction consulting, 17.50% (7) belong into the category of developer or client organization, and 5% (2) belong into the other organization categories. This indicates that the Contracting category had the most responses. This indicates that the Contracting category had the most responses.

The experience of the survey respondents was categorized into different periods of experience. 10% of respondents have four or more years of experience in the construction industry. 7.50% (3) of the 55 respondents have 6–10 years of work experience, which is the least amount in any category. Of the 55 responders, 9 (22.50%) have 11–15 years of construction sector job experience. Ten of the 25.00% of respondents have 16–20 years of experience in the building sector. It has also been determined that, out of the 55 respondents, 35.00% (14) have greater knowledge and skill in the construction business, having worked for more than 20 years. Experts with over 20 years of experience in the building business make up a larger percentage of those who completed the questionnaire.

4.3 QUANTITATIVE DATA ANALYSIS

4.3.1 Impact of the Inefficiencies in the Material Waste Management on Construction Cost of the Projects in Sri Lanka (Buildings)

Results of this study provide an indication of the Relative Importance Index (RII) and rank of identified inefficiencies of the material waste management in the construction industry of Sri Lanka. Here, each inefficiency was ranked considering the impact on the project cost.

- The **Mean** value ($\bar{X}$) of the RII values is,

  $\bar{X}$ = **Σ RII / No. of Inefficiencies** $\bar{X}$ = 13.085/18

  $\bar{X}$ = 0.727

Table 2: Ranking of inefficiencies of highest impact

Inefficiencies	RII (X)	(X-$\bar{X}$)	Rank
Limited recycling facilities	0.830	0.103	1
Design changes and variations	0.800	0.073	2
Inefficient material handling	0.785	0.058	3
Poor workmanship	0.780	0.053	4
Poor quality control	0.765	0.038	5
Unstable market for recycled products	0.750	0.023	6
Limited technology adoption	0.735	0.008	7
Inaccurate material estimation /ordering more materials than required to avoid shortages	0.730	0.003	8
Poor regulations and enforcement	0.730	0.003	8

Based on the Relative Importance Index (RII), the inefficiencies affecting material waste management and construction costs in Sri Lankan building projects were ranked as follows:

Limited recycling facilities were rated as Very High in their negative impact, making them the most critical inefficiency. Design changes and variations followed with a high ranking, indicating a significant effect on costs. Inefficient material handling was also considered High, ranking third in impact. Poor workmanship received a Neutral ranking, reflecting a moderate influence on project expenses.

The unstable market for recycled products was rated as Neutral, though still important, with potential cost implications that could be reduced by improving local availability and use of recycled materials. Limited adoption of technology was ranked Low, showing less but still relevant impact on construction costs. Lastly, inaccurate material estimation (leading to over-ordering) and poor regulation and enforcement were rated Very Low, indicating a minor effect on construction costs according to respondents. RII values clearly show that there is high impact on construction costs of those inefficiencies.

Each inefficiency identified contributes to increased construction costs in specific ways. Limited recycling facilities and an unstable market for recycled materials force contractors to rely on new materials, which raises both procurement and disposal expenses. Design changes, inaccurate estimations, and inefficient material handling result in rework, material wastage, and project delays, all of which increase labour and material costs. Poor workmanship and inadequate quality control also lead to frequent defects and the need for corrective work. Furthermore, limited adoption of technology and weak regulatory enforcement hinder effective planning, monitoring, and coordination. These factors collectively increase overall project costs and reduce operational efficiency.

4.3.2 Reasons Applicable for the Inefficiencies in the Material Waste Management on Construction Cost of the Projects in Sri Lanka (Buildings)

Results of this study provide an indication of the Relative Importance Index (RII) and rank of identified reasons applicable to the inefficiencies in the material waste management in the construction industry of Sri Lanka.

- The **Mean** value ($\bar{X}$) of the RII values of these reasons is

  $\bar{X}$ = **Σ RII / No. of Reasons** $\bar{X}$ = 11.320 / 15

  $\bar{X}$ = 0.755

Table 3: Ranking of reasons applicable for the inefficiencies

Inefficiencies	RII (X)	(X-$\bar{X}$)	Rank
Inefficient design and planning processes	0.825	0.070	1
Lack of awareness of material handling and proper material waste management	0.820	0.065	2
Not enough regulations	0.815	0.060	3
Inaccurate measurement	0.805	0.050	4
Insufficient training practices	0.785	0.030	5
No proper guidance	0.765	0.010	6
Limited storage space	0.760	0.005	7

Inefficient design and planning processes were ranked as first major reason of applicable for the inefficiencies in the material waste management on construction cost of the projects in Sri Lanka (Building). Design errors and changes have severe impact on the project cost. Lack of awareness of material handling and proper material waste management was ranked as the second reason for the inefficiencies. By using Relative Importance Index, not enough regulations were found for the third reason applicable for the inefficiencies. Inaccurate measurement was identified as the fourth reason applicable to the inefficiencies of material waste management in the construction industry of Sri

Lanka. If any item is missed during construction phase, even if it can be constructed by supplementary work, it will cost higher than the first cost due to market fluctuations. Insufficient training practices was ranked fifth by respondents. The overall rank shows that no proper guidance was ranked as the sixth reason. Limited storage space was ranked as the seventh reason.

4.3.3 Strategies to Overcome the Inefficiencies in the Material Waste in the Construction Industry of Sri Lanka (Buildings)

The identified main strategies for overcoming the inefficiencies in material waste were identified based on the ranks made according to the results of the RII.

- The **Mean** value ($\bar{X}$) of the RII values of these inefficiencies is

  $\bar{X}$ = **Σ RII** / **No. of Inefficiencies** = 8.050 / 10

  $\bar{X}$ = 0.805

Table 4: strategies for overcoming the inefficiencies in material waste

Inefficiencies	RII (X)	(X-$\bar{X}$)	Rank
Invest in proper material storage facilities and recycling facilities	0.850	0.045	1
Use of strict and rigorous waste management policies and practices at site level and creating some motivational and incentive schemes for workers and staff working towards these goals	0.850	0.045	1
Carry out the material waste management plans for every project into the initial planning and design phase	0.840	0.035	3
Develop comprehensive awareness programs and training programs about material waste management	0.830	0.025	4
Implement quality control measures to reduce material defects and waste	0.820	0.015	5

The analysis reveals that the top strategies for overcoming inefficiencies in material waste management in the construction industry of Sri Lanka include investing in proper storage and recycling facilities, using strict waste management policies and practices at the site level, and creating motivational and incentive schemes for workers and staff. The government should implement a construction material waste reduction plan policy, outlining permissible amounts and management techniques, along with incentives and penalties for construction companies.

The third strategy is to implement material waste management plans for every project during the initial planning and design phase, ensuring efficient designs and strict rules on construction sites. The fourth strategy is to develop comprehensive awareness programs and training programs about material waste management, promoting education and research for construction workers and staff.

The fifth strategy is to implement quality control measures using the Relative Importance Index (RII = 0.820) to reduce material defects and waste. Quality management software can be used to control quality throughout the project.

Other strategies include using suitable material and waste management software systems, adopting proper stock balance procedures, enabling flexible delivery schedules, improving mathematics knowledge, and using new technologies like Building Information Modelling (BIM) for waste management.

We should use and try to adopt more efficient new technologies, such as AI-based tools and modules like BIM and Revit. These advanced technologies can greatly enhance our project management, improve accuracy, and streamline various processes, ultimately leading to better outcomes and reducing inefficiencies. Establishing a proper ERP system for the construction industry would help overcome this issue. It will facilitate linking each department to ensure minimal wastage and optimal use of materials. Additionally, using a mobile app to update relevant details linked to the ERP system can further improve the process. Implementing the Lean Six Sigma methodology would also help run the project smoothly and minimize waste by addressing every bottleneck in the process.

5. CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This section provides a concise overview of the entire study, highlighting key findings and how the research objectives were addressed. Effective material waste management is crucial for reducing construction costs and minimizing environmental impact. Traditional construction methods often result in excessive waste, but the integration of circular economy principles, precise planning, and technologies like Building Information Modelling can significantly reduce these inefficiencies. Reusing materials, improving on-site handling, and engaging all stakeholders contribute to better outcomes. With innovative strategies, regulatory compliance, and a focus on sustainability, the construction industry can achieve both environmental responsibility and cost efficiency.

The Sri Lankan construction industry faces significant inefficiencies in material waste management, affecting project performance. These include limited recycling infrastructure, frequent design variations, and poor on-site material handling. Systemic issues like inadequate design processes, lack of regulatory enforcement, and inaccurate estimation methods further contribute to these inefficiencies. The sector needs a paradigm shift embracing digital transformation, institutional accountability, and continuous improvement. Key recommendations include investing in site-level infrastructure, institutionalizing strict waste management policies, and leveraging advanced digital tools. This holistic transformation can lead to greater cost-efficiency, resource optimization, and environmental sustainability.

5.2 RECOMMENDATIONS

The following recommendations are given on the impact of material waste management on construction costs of projects in the Sri Lankan construction sector based on the findings and results of this study. Recommendations for the Sri Lankan Government

The government should implement a construction material waste minimization plan, highlight acceptable amounts and management methods, and offer incentives and penalties for inefficiencies. On-site appointments of a material waste officer can help control waste inefficiencies. Regulations should be passed to manage construction waste materials, and adherence should be closely monitored. A recycling market should be

established through policies that support this. Mandatory workshops on waste management inefficiencies and their impact on construction costs should be mandatory for all parties involved. Regular material specifications in contract documents should be changed to reduce the need for regular materials in government buildings.

5.2.1 Recommendations for the Sri Lankan Construction Industry

Construction sites should invest in weatherproof storage facilities and hazardous material storage to prevent pollution and waste. Engage with local communities to develop recycling programs and partner with recycling companies. Adopt advanced technologies like AI-based tools and waste management software to improve project management and reduce inefficiencies. Establish an Enterprise Resource Planning (ERP) system to link departments and minimize wastage. Implement Lean Six Sigma methodology to address bottlenecks and minimize waste.

Workers and staff should work together, and awareness campaigns, education, and research on waste management are essential. Employees should receive ongoing training on material handling and installation. Designers should carry out efficient designs, and contractors should enforce strict rules to minimize waste. Motivational and incentive schemes can motivate workers and staff towards waste management goals. Close supervision and material availability monitoring are crucial for achieving these goals.

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IMPACT OF THE SRI LANKAN GOVERNMENT ECONOMIC REFORM PROGRAMMES ON THE CONSTRUCTION INDUSTRY SINCE YEAR 2022

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ABSTRACT

The recent economic crisis in Sri Lanka has had a devastating impact on each economic sector, and the construction sector is no exception. Hence, the Sri Lankan government has entered into an agreement with the International Monetary Fund (IMF) to perform an economic reform programme to uplift the country from its insolvent position. However, there is a lack of studies on the impact of economic reforms on the construction industry. Hence, this research aims to identify the impacts of the current economic reform programme of the Sri Lankan government on the construction sector. A comprehensive literature review was conducted to understand the economic crisis, the economic reform programme and its impact on Sri Lanka. Further, under the qualitative research approach, 20 semi-structured interviews were conducted with the experts in the construction sector selected through purposive sampling. The collected data was analysed through code-based content analysis using N-Vivo software and manual content analysis. According to the findings, import restrictions, increased material prices and fuel shortages were highlighted as the major challenges faced by the industry, which led to project terminations, staff turnover, increased construction costs, and bankruptcies. Further, IMF programme objectives such as restoring macro economy, ensuring debt sustainability, establishing export-driven economy and emphasising anti-corruption are appreciated by the experts while highlighting the need for more objectives to be included in future revisions. . Findings of this study can be utilised by the government to improve its reform programme in future to safeguard the construction industry.

Keywords: *Construction Industry; Economic Crisis; Economic Reform Programme; IMF Programme; Sri Lankan Construction Industry.*

1. INTRODUCTION

The construction industry is one of the major industries affecting economic growth, especially in developing countries (Jayamal et al., 2023). Therefore, changes and issues related to the economy of a country including economic crisis directly affect the performance of the construction sector and vice versa (Gnanothayan & Kauškale, 2022).

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An economic crisis is a negative situation faced by any nation as a result of a downturn in their economy due to several factors.

In the year 2022, Sri Lanka recorded the deepest contraction in the economy in history due to the economic crisis (Central Bank of Sri Lanka, 2023). This has resulted from a series of events such as the Easter Sunday bomb attacks in 2019, the COVID-19 pandemic, the Russia-Ukraine war, economic mismanagement, high dependence on foreign debts, reduction in foreign reserves, currency decline and inflation (Pathirana, 2021; George et al., 2022). As with many other industries, the construction sector is extremely sensitive to economic downturns due to its interdependent relationship with the economy (Musarat et al., 2021). Therefore, structural reform is essential, which focuses on long-term development of the country, the construction industry and especially the economy to address the economic crisis.

Economic reform refers to the changes to the government policies when the current economic policies are not satisfactory or the alternate policies which provide preferable productivity to the current productivity of the economy (Khemani, 2017). In the Sri Lankan context, the country has requested extended funds from the IMF to improve its economic performance in the year 2022. The IMF has approved a three billion extended fund facility for 48 months duration to uplift the economy of the country (IMF, 2023). However, the economy is still unstable, with risky debt management (IMF, 2024a). Due to the symbiotic relationship between the construction sector and economy, the economic reform programme will create a significant impact on the construction sector. On the other hand, there is a lack of investigation into the impact of the Sri Lankan government's economic reform programme on the construction sector. Therefore, it is essential to investigate the impact of the economic reform programme on the construction sector in order to minimise the further effects and strengthen the industry. Hence, this paper presents the research findings on the impact of the economic crisis as well as the economic reform programme on the Sri Lankan construction sector. This paper starts with an introduction, followed by a literature review. Section 3 outlines the research methodology, while Section 4 presents the research findings and discussion. Finally, the paper concludes with a summary of findings and recommendations.

2. LITERATURE REVIEW

This section reviews the literature on the economic crisis, its impact on the construction industry in global and Sri Lankan contexts, economic reform programmes, and its impact on the Sri Lankan and global construction sector.

2.1 ECONOMIC CRISIS AND ITS IMPACT ON THE CONSTRUCTION SECTOR

An economic crisis is a situation in which a country's economy is significantly affected by a financial crisis. Moreover, the Gross Domestic Product (GDP) decline, liquidity dry-up, and inflation or deflation are some of the main indicators of an economic crisis (India Today, 2022). After the Great Recession in 2008, the global economy was significantly affected in 2020 due to the COVID-19 pandemic. According to IMF (2022a), global economic growth has decelerated to 2.7% in 2023 from 6% in 2021. However, the factors contributing to the crisis extend beyond COVID-19. China's economy was affected due to continuous lockdowns, which consequently affected the global economy due to its influence on the global supply chain (Saliu & Memaj, 2023). Moreover, the war between Russia and Ukraine in 2022 has also had a significant impact on the economy worldwide

in numerous sectors (Saliu & Memaj, 2023). The economic crisis has significantly affected the construction sector, especially firms with low financial capabilities, including the additional costs to ensure site hygiene, construction delays, high rates of unemployment, labour shortages, large projects being halted or terminated, overdue payments for completed works which affect cashflow, and material shortages (De Silva et al., 2023).

On 12 April 2022, Sri Lanka announced a pre-emptive sovereign default on all its foreign debt of about $50 billion. The sovereign default precipitated the worst economic crisis in the country's post-independence history (Moramudali, 2024). Specific decisions and policies implemented by the Sri Lankan government in the past and global and local conditions including the Easter Sunday Bomb attack in April 2019, the COVID 19 pandemic, and the Russia-Ukraine war have significantly contributed to the economic crisis in Sri Lanka (Pathirana, 2021).

The Sri Lankan economic crisis has directly impacted the performance of the construction industry, which resulted in 75% of construction projects being halted due to the increased building material prices and fuel shortage (De Silva et al., 2023). According to Jayamal et al. (2023), slowdown or complete shutdown in government-funded projects, only execution of foreign-funded projects, and disruptions to the proper functioning of construction sites due to health concerns were some of the challenges faced by contractors. Further, the local investors, clients, and contractors had insufficient financial reserves to invest or continue their projects and difficulty in obtaining any bank loans worsened the crisis and affected the payment to the third parties and other stakeholders including suppliers, labour wages and repayment of loans (Jayamal et al., 2023). According to Razeek (2022), in 2022, the total overdue payments due to the economic crisis is Rs. 100 million. Moreover, the construction industry is forced to rely on locally manufactured materials and finished goods due to the import restrictions (Pathirana, 2020). In addition, several difficulties were faced by the industry including material shortage, construction delays, staff turnover, non-recovery of payments from clients, disruption in machinery operations due to fuel shortage, high rate of unemployment, high rate of bankruptcy, and additional cost for idling machines due to fuel shortage (Pathirana, 2021; Jayamal et al., 2023).

2.2 ECONOMIC REFORM PROGRAMME AND ITS IMPACTS ON THE CONSTRUCTION SECTOR

Economic reform programmes are policies introduced by the government of any nation which change the way the economy is organised (Khemani, 2017). The Nigerian government initiated a reform programme in 2023 and was able to reduce the inflation from 32% to 24% in 2024 with the monetary tightening. The Pakistan government entered into an agreement with the IMF on 25th September 2024 for a 37-month Extended Arrangement for 7 billion US dollars (IMF, 2024b). Further, Argentina entered into an agreement with the IMF in March 2022 for a 30-month Extended Fund Facility (EFF) amounting to 44 billion USD (IMF, 2022b). According to Hill International (2024), the Pakistan construction industry is expected to boom in the following years, along with the vertical developments initiated all over the country.

The Sri Lankan government initiated the preliminary discussion with the IMF within a week after the announcement of default on foreign debt. The agreements and the timeline of activities with the IMF are shown in Figure 1.

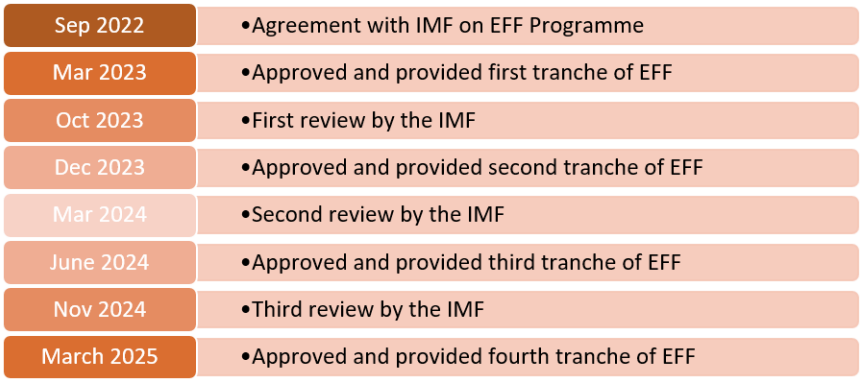


Figure 1: IMF Programme Outline for Sri Lanka
Adopted from (IMF, 2024f, 2024h; CBSL, 2025; Ada Derana, 2025)

The Sri Lankan government entered into an agreement with IMF for a four-year IMF Programme with EFF of 2.9 billion USD in March 2023 (Nicholas & Nicholas, 2023). The main objective of EFF programme for Sri Lanka is to restore macroeconomic stability, debt sustainability, protect the poor and vulnerable from the impact of economic crisis, emphasise anti-corruption, governance reforms and ensure financial sector stability (IMF, 2023a). Moreover, the government has introduced the new Central Bank Act to replace the previous Monetary Law Act (Nicholas & Nicholas, 2023). The Government introduced the Economic Transformation Bill, which includes numerous economic targets to be achieved in the next 15 years (The Parliament Democratic Socialist Republic of Sri Lanka, 2024).

Further, the government enacted the Public Financial Management Act No. 44 of 2024 by repealing the Fiscal Management Act No.3 of 2003 in August 2024. The act repealed the Fiscal Management Act due to a breach of the Fiscal Management Act (Finance.lk, 2024). The newly implemented Act includes numerous objectives to ensure transparency and accountability in public financial management in future. Moreover, Public Debt Management Act No. 33 of 2024 was also implemented in June 2024 which includes main objectives, including payment of debts on time and obtaining loans with low risk (Public Debt Management Act, 2024).

Moreover, the IMF emphasised the need to provide the Central Bank of Sri Lanka (CBSL) more freedom to make decisions without political influence (IMF, 2024c). Further, in December 2024, the Sri Lankan government restructured its 12.55 billion USD international bond debt with new but untested instruments, linked to economic growth and governance. Moreover, by finalising this bond exchange, Sri Lanka became the fourth country to conclude its bond this year following Ghana, Ukraine, and Zambia (Ada Derana, 2024a). Moreover, the Sri Lankan government has announced to uplift the import restrictions on vehicles for personal use from the 1st of February 2025 (Ada Derana, 2024b). Further, the government has announced a few tax reforms in December 2024 to be implemented from April 2025 (Taxadvisor.lk, 2024).

The government has implemented a few other policies as well including (Standing Deposit Facility Rate (SDFR) and Standing Lending Facility Rate (SLFR) being reduced to 8.5% and 9.5% respectively, the treasury bill limit being increased to Rs. 6,000 billion from Rs. 5,000 billion, Inland Revenue Act No.04 of 2023 was enacted, VAT for goods and services supplied and imported goods increased up to 18% from 15%, VAT exemption for petrol, diesel and LP Gas was removed, and VAT registration threshold

reduced to 60 million per annum from 80 million per annum (CBSL, 2022, 2024). Moreover, Nicholas and Nicholas (2023) emphasised that the CBSL has now focused on the interest rates to control the cash flow in the market. Earlier, the CBSL assumed that the main duty of the Central Bank is to control the cash flow in the system. However, the CBSL and IMF have accepted that they should not control the cash flow in the system directly, instead, they should influence the economy through the interest rates during a crisis. Since the economic reforms have been implemented since 2022, there has been limited research on the subject. Furthermore, as the construction industry plays a significant role in the economy, a comprehensive study is necessary to examine the impact of the aforementioned economic reform programmes on the sector. Hence, this study aims to identify the impacts of the current economic reform programme by the Sri Lankan government on the construction sector.

3. RESEARCH METHODOLOGY

Three methodological steps were employed under the qualitative research approach to accomplish the aim of the research. First, a comprehensive literature review was conducted to explore the economic crisis and economic reform programmes initiated by Sri Lanka and other countries during their economic downturn, and the effects of those reforms on the construction sector. The sources used for the literature review were research papers, journal articles, books, official reports, conference proceedings, and newspaper articles. Second, a desk study examined the Sri Lankan government's economic reform program since 2023 using various sources, including government documents, reports, newspaper articles, sources from reliable government websites, and publications. Finally, semi-structured interviews with construction experts were carried out to identify the effects of those reforms on the construction sector. Respondents were selected through snowball sampling to ensure diverse and most appropriate responses. Twenty semi-structured interviews were conducted with both consultants and contractors, including professionals from various institutions, to assess the impact of the economic crisis and economic reform programme on the construction industry. The respondent's profile is given in Table 1.

Table 1: Profile of the respondents

Code	Organisation type	Designation	Experience
R1	Consultant Organisation	Quantity Surveying Department Head	27
R2	QS Consultancy Firm	Director	32
R3	QS Consultancy Firm	Director	32
R4	Contractor Organisation	Manager Projects Monitoring and Controlling	10
R5	Contractor Organisation	Chief Executive Officer	20
R6	Consultant Organisation	Chief Executive Officer	20
R7	Consultant Organisation	Director	55
R8	Consultant Organisation	Director	40
R9	Contractor Organisation	Deputy General Manager	20
R10	Consultant Organisation	Quantity Surveying Department Head	26
R11	Consultant Organisation	Director	18

Code	Organisation type	Designation	Experience
R12	Consultant Organisation	Managing Director	22
R13	Consultant Organisation	Director	25
R14	Consultant Organisation	Chief Quantity Surveyor	30
R15	Consultant Organisation	Director	35
R16	Contractor Organisation	Chief Engineer	30
R17	Consultant Organisation	Director	23
R18	Consultant Organisation	Chief Executive Officer	18
R19	Contractor Organisation	General Manager Contracts and Estimates	17
R20	Contractor Organisation	Project Manager	18

As shown in the table, semi-structured interviews were conducted with 20 experts currently practising in the construction industry, covering Directors, CEOs, Quantity Surveyors, Engineers, and Project Managers. Interviewees were selected based on their expertise, experience and sound knowledge of the construction industry and the IMF reform programme and its impact on the industry. Their experience ranged from 10 to 50 years, both in Sri Lanka and abroad. The collected data was analysed using manual content analysis and NVivo software was used to analyse the data using code-based content analysis.

4. RESEARCH FINDINGS AND DISCUSSION

The key research findings obtained through expert interviews are presented in this section. The impact of the economic crisis and the economic reform programme on the construction sector is analysed in this section.

4.1 CHALLENGES FACED BY THE CONSTRUCTION INDUSTRY DURING THE ECONOMIC CRISIS

During the interviews, the experts were requested to explain the challenges they had faced during the economic crisis. Further, the respondents were requested to identify the

Name	Files	References
Challenges Faced by the Construction Industry	20	281
A sudden increase in building material prices	20	20
Construction projects were halted or terminated by the Employer	19	19
COVID-19 affected infrastructure projects	16	16
Difficult to continue the works due to regular power cuts	19	19
Fuel shortage to continue the projects	20	20
High rate of bankruptcy	14	14
Import restrictions on construction materials and forced to rely on local materials	19	19
Inability of contractors and clients to obtain loans to finance the projects	19	19
Insufficient financial reserves to invest or continue the projects	20	20
Labour wages and staff salaries have increased beyond the normal level	9	9
Less projects and demand to the contractors due to decline in other sectors	20	20
Nonrecovery of payments from clients	19	19
Other	7	11
Decreased Consumer Confidence	1	1
Delay in Regulatory Approvals and Permits	2	2
Difficult to continue the business	1	1
Exchange rate volatality	1	1
Expensive software licenses due to increased exchange rate	1	1
Increased Insurance Costs	1	1
Increased Legal Disputes and Contractual Issues	1	1
Lack of innovation and performance	1	1
Less government support espcially subsidies	1	1
Unsustainable competition due to lower margin bid pricing	1	1
Shortage of cash flow affected the payments to other stakeholders	17	17
Staff turnover due to skilled labourers' migration and brain drain	20	20
The additional cost incurred due to machines and equipment idling	19	19

Figure 2: Challenges faced by Sri Lankan construction industry during the economic crisis

challenges which have not been listed in the interview guideline. Figure 2 summarises the challenges faced by the stakeholders.

All the respondents agreed that there is a severe increase in material prices. R1 said, "*cost of imported construction materials such as steel, cement, and MEP components increased drastically*". R4 added to that, stating "*the employers could not afford the escalation because it was two times the initial cost. Therefore, mainly the locally funded projects, terminated or suspended"*. According to R1, the fuel crisis mainly impacted rural area projects, especially road projects. "*In building projects, a few types of machinery employed, and we needed the fuel to run the generators, which is more manageable*", according to R5.

Further, R1, R4, R5, and R8 mentioned that they had several disputes stemming from insufficient financial arrangements, due to unexpected increases in costs. Further, R8 highlighted that the cost has increased by another 60% due to inflation. Moreover, R4 highlighted that "*financial reserves were not enough for the locally funded projects, whereas the foreign-funded projects continued, due to currency depreciation and the fund was in foreign currency"*. Moreover, R20 emphasised that "*financial institutions were reluctant to provide loans as Central Bank is not encouraging to provide the loan as the banking system may get collapsed",* which is the main reason for insufficient financial reserves. Strengthening this statement, R5 said, "*construction industry was identified as a high-risk industry to provide loans during the crisis by the financial institutions*". While highlighting the payments to other stakeholders, except R2, R9 and R19, all the respondents mentioned that they have experienced a severe issue paying their suppliers and labourers. Further, R8 mentioned that "*due to the crisis, not a single supplier gave credit basis material to contractors".* R2, R9, and R19 mentioned that they were able to manage the payments to some extent due to the mix of projects they had, where they received the payments for foreign funded projects on time.

R16 highlighted that *"there is a 60% reduction in projects due to regular power cuts*" whereas, R20 mentioned that *"processes were halted or slowed down because night shift was not a practical solution due to increased labour charges for overtime*". On the contrary, R2 mentioned that "*we obtained fuel from the government on quota basis. However, our regular works were disrupted. But we managed based on power cut schedule and increased the working hours and did night shifts*". Further, respondents highlighted that the project progress was affected dramatically due to import restrictions especially elevators according to R8 and R20. Moreover, respondents R2, R5, R7, R12, R14, and R17 highlighted that most of the SMEs were not bankrupted due to economic crisis, but they have diversified into other businesses.

Apart from the challenges identified through the literature review, the respondents have identified a few other challenges. R1 added "*delay in regulatory approvals and permits, decreased foreign investment in construction projects, increased legal disputes and contractual issues, increased insurance costs, and decreased consumer confidence*" to the list. Further, R5 highlighted "*companies are tendering at very low margins which will be an unsustainable level of competitiveness*", R6 mentioned that "*the cost of software licenses was very high due to the increase in exchange rates*", R10 discussed the low performance and low productivity, R12 mentioned that "*difficulty in continuing the business in the existing level and forced to shrink the business*", R16 stated that "*no government support received and lack of motivation*", R19 included "*exchange rate*

volatility and delay in procurement and payment procedures" and R20 discussed the challenges in restarting the projects after a halt.

4.2 IMPACT OF ECONOMIC REFORM PROGRAMME PROPOSED BY THE SRI LANKAN GOVERNMENT ON THE CONSTRUCTION INDUSTRY

The objectives of the IMF programme, Public Financial Management Act and Public Debt Management Act were listed in the interview questionnaire to identify the impact of each objective on the construction sector. Table 2 summarises the key findings.

Table 2: Impact of objectives of IMF programme on the construction industry

Objectives	Impact			No Impact
	Positive	Negative	Both	
Restore macroeconomic stability	18	1	1	0
Ensure debt sustainability	18	0	2	0
Protect the poor and vulnerable community from the impact of economic crisis	3	0	2	15
Emphasize on anti-corruption	19	0	1	0
Governance reforms and ensure financial sector stability	18	0	1	1
Increase real GDP growth rate at 5% until 2027 and 8% for the next 15 years	19	0	1	0
Unemployment is aimed to be reduced to 5% in 2025	9	0	6	5
Establish an export-driven economy in 2040	19	0	1	0
Reduce the government annual financing needs to GDP ratio below 13% in 2032	1	16	3	0
Reduce the government annual debt service in foreign currency to GDP ratio below 4.5%	2	12	6	0
Reduce the public debt to GDP ratio below 95% in 2032	0	13	6	1
The current account deficit should not exceed 1% of GDP annually	8	5	7	0
Objectives of Public Financial Management Act	19	0	1	0
Objectives of Public Debt Management Act	18	0	2	0

According to the majority of the respondents, restoring the macro economy will benefit the construction sector directly, and R1 mentioned that "*macro-economic stability tends to restore investor confidence, which is critical for the construction industry*". However, R3 argued that *"the government never looked at the SME sector. 97.4% is SMEs in Sri Lanka. Therefore, monopolies survived, oligopoly survived, not the SMEs*". Except for R1, R3 and R5, all the respondents believed that debt sustainability would boost the construction sector by attracting foreign investors, whereas R5 argued that "*debt sustainability leads to reduced Capex spending, which has a direct negative impact on the construction sector*". Except for R1, R7, R16, R18, and R19, the other respondents mentioned that the protection of poor people will not create any impact on the

construction sector, whereas R1 argues that "*protection of poor people could lead to funding for low-cost housing projects, providing opportunities for construction firms*".

Moreover, the majority of the respondents highlighted that objectives including establishing export-driven economy, increasing real GDP growth to 8%, anti-corruption, and objectives of Financial Management Act will impact positively the construction sector. Further, R1 and R20 stated that "*To meet debt obligations, the government may cut funding for public sector projects, limiting opportunities for construction companies*". Moreover, when considering the objective of maintaining the current account deficit below 1%, R1 stated that "*efforts to reduce the deficit may lead to import restrictions*", whereas R4 agreed with the statement by mentioning "*there might be import restrictions, but yet again in the long run, it will be positive*". Moreover, R1 highlighted that the reduction in annual debt servicing in foreign currency to GDP ratio will negatively impact the industry by stating that "*to achieve this target, the government may cut back on infrastructure spending*" and R2 agreed with the statement by stating "*leads to* a *reduction in construction project investment as construction projects are mostly funded through debts*". Further, when reducing unemployment, depends on the initiatives taken, the impacts will differ. If those merely create job opportunities to reduce unemployment, it may lead to negative impacts as well. However, if unemployment is reduced, according to R18, "*if one is employed, then they have more disposable income, and that will lead to more construction projects*". However, the majority of the respondents believed that these objectives did not directly address the issues in the construction industry.

Further, Table 3 summarises the key findings regarding implemented policies.

Table 3: Impact of the policies implemented on the construction industry

Policy Measures	Impact			No Impact
	Positive	Negative	Both	
SDFR and SLFR is reduced to 8.5% and 9.5% in March 2024	19	0	1	0
STaRR project credit scheme loan limit is increased up to Rs. 400,000	0	0	1	19
The Saubhagya loan scheme and Domestic Agriculture Development loan scheme were concluded in 2023	0	1	1	18
Introduced the Manusavi loan scheme for Sri Lankan migrant workers	2	7	1	10
Decided not to introduce new loan schemes	0	9	1	10
Direct issuance of SLDB was suspended	0	6	1	13
The treasury bill limit is increased to Rs. 6,000 billion	1	2	4	13
Allowed the importation of a list of goods which were temporarily suspended	19	0	1	0
All individuals above 18 years should register to the IRD	1	6	1	12
VAT increased upto 18% from 15%	0	19	1	0

Policy Measures	Impact			No Impact
	Positive	Negative	Both	
VAT exemption for petrol, diesel, and LP Gas was removed from January 2024	0	19	1	0
The VAT registration threshold was reduced to 60 Mn from 80 Mn per annum	0	17	2	1
Restructured 12.55 billion USD international bond debt	17	0	3	0
Uplift the import restrictions on vehicles	1	2	2	15
Revised the personal income tax	11	1	1	7
Withholding tax is increased from 5% to 10%	0	15	3	2
18% VAT is applicable for digital services	0	7	1	12
Taxes on betting, gaming, tobacco and liquor industries will increase from 40% to 45%	1	1	1	17
VAT exemption for domestic dairy products	0	0	1	19
Stamp duty on leases will increase from 1% to 2%	0	18	1	1

Among the policies implemented, most of the respondents stated that policies included increasing the loan limit for the STaRR project, VAT exemption for domestic dairy products, taxes on betting, gaming, and tobacco industries, uplifting the import restrictions of personal vehicles and conclusion of Saubhagya loan scheme and Agricultural loan scheme will not create any major impacts on the construction sector. However, the VAT increase from 15% to 18%, removal of VAT exemption for petrol, diesel and LP Gas and decrease in VAT registration threshold will directly negatively impact the construction sector. R2 highlighted that by mentioning, "*if somebody is building a factory or any building, the cost has increased by 3%*". Further, R15 explained this impact mentioning "*if a company is VAT registered those companies will not have an impact as they collect the VAT component and pay whereas, if the company is not registered, it is a disadvantage for them. And when it comes to the client's point of view, they have to pay more money for a project*". In addition, R4 highlighted that "*the VAT for condominium was zero, and when it is increased up to 18% at once, the condominium projects were totally dropped"*.

Moreover, when analysing the impact of a debt restructuring of 12 billion USD, the majority of the respondents accepted it as a favourable step toward the construction sector. R10 stated "*confusion of insolvency can be, taken out, so that may, encourage the investments*", whereas R6 argued that "*despite the attraction of investors, we have to continue paying these debts for so many years in the future. That means there is less, to invest in the country*". The importation of materials that were restricted during the economic crisis is considered a favourable step by the majority of the respondents, whereas R1 argued that "*Increased imports could lead to foreign currency outflows, reducing the dollar reserves*". Moreover, the increase in stamp duty is also highly criticised by the respondents, stating that *"it increased operational costs, reduced profitability, especially for smaller contractors*" according to R1. Moreover, regarding the revision of personal income tax, some respondents believed that it would not create any major impact on the construction sector, whereas others argued that it would positively impact the industry. R1 stated that it "*provides more disposable income for the*

public, potentially improving spending on construction-related goods and services". Further, R6 highlighted that "*higher disposable income will reduce the pressure on companies having to increase salaries*". However, R3 argued that "*still the tax percentages are very high. Therefore, the disposable income is very low, which will decrease the investment in the construction sector. Still, nonpayers are not identified, and taxes are not collected"*.

Therefore, all the experts highlighted that the implemented policies are not sufficient to address the issues in the construction sector and close attention is required towards the construction sector.

5. CONCLUSIONS AND RECOMMENDATIONS

The economic crisis is a significant condition which dramatically affects the major sectors of a national economy including the construction sector due to their interdependency. The Sri Lankan economic crisis and declaration of insolvency have created a large impact on the construction sector. To recover from the economic crisis, a proper economic reform programme should be implemented. However, as a major contributing industry, the issues in the construction sector should be addressed, and policy measures should be taken to improve the industry. Hence, to analyse the impact of the economic crisis on the construction sector and the impacts of the economic reform programme on the construction sector, 20 semi-structured interviews were conducted under the qualitative approach. Since the research is focused on the impact of the economic reforms on construction sector, the sample included only the experts from construction sector who has vast knowledge regarding IMF reform programme. Further, the study was limited to the economic crisis since 2020, IMF reforms in 2022 and their impact on construction industry. The majority of the respondents highlighted import restrictions, power cuts, insufficient financial reserves, increased material prices and construction costs, fuel shortages and staff turnover as the main challenges faced by the industry during the economic crisis. The respondents emphasised that some of the challenges are still faced by the industry even after three years. Further, the findings revealed that, some objectives of the IMF programme including restoring macro-economic stability, ensuring debt sustainability, establishing export driven economy, and ensuring anti-corruption are considered preferrable objectives of the IMF programme. However, a few other objectives including reduction in current account deficit, reduction in annual financing needs and annual debts to GDP ratio are considered positive objectives from the country's economic perspective although those are negative on the construction sector investments. While analysing the policies implemented, VAT increase is highly criticised by the respondents and considered as the money collection process to pay the debts rather than investing in public projects. Therefore, other than the expected positive impacts received from the objectives of the IMF reform programme, the implemented policies have not created an evident impact on the construction sector. The majority of the policies have neither created any impact nor negative impacts whereas very few created positive impacts. Therefore, the industry expects and requires more policies to be implemented in the future. Hence, it is recommended the government authorities and the industry experts to revisit the IMF reforms and customise the policies to address the ongoing issues of construction industry due to economic crisis. This research findings will be beneficial for the government to improve the policies in future to encourage the construction industry to grow which will directly improve the national economy through GDP contribution. As

the next step, this research will investigate the policies to be implemented in future to enhance the construction sector.

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IMPROVING INSULATION IN SRI LANKAN HIGH-RISE BUILDINGS: DEFECTS, CAUSES, AND SELECTION CRITERIA

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ABSTRACT

Insulation plays a crucial role in achieving energy efficiency, thermal comfort, and sustainability in high-rise buildings. However, when there are problems with the insulation such as water leakage, crack formation, and thermal bridging the building performance is affected. The paper analyses the most prevalent defects in insulation together with their causes and principal factors considered in selecting to enhance insulation performance within high-rise buildings. A qualitative research approach has been adopted by carrying out case studies on 15 high-rise buildings located within Sri Lanka and through 40 respondents survey including semi-structured interviews with five professionals from the industry. The study reveals that water damage and pest infestations are common defects at 86.7%and 80%, respectively. The foremost factor is linked to inadequate climate considerations, coupled with insufficient standards of workmanship as well as material selection. Besides these issues, maintenance has been inadequate; neither have regulations governing insulation been adequate. Experts' views indicate that the three most important factors in selecting suitable insulating systems are building profile, technology, and material properties, which can be avoided by effective design strategies, quality of materials selected, and regular maintenance. This will contribute to the field since there is a need for some structured selection criteria using BWM to improve insulation longevity; costs of maintenance would also be reduced, while performance as a whole could be enhanced. Further research is recommended on new technologies concerning insulating systems along with regulatory criteria aimed at maximizing efficiency for insulations utilized in high-rise constructions.

Keywords: *Causes; Defects; Factors; High-Rise Buildings; Insulation.*

1. INTRODUCTION

In the high-rise building sector, maximizing energy efficiency depends on the reduction of heating and cooling, which helps to minimize operational costs (Martin et al., 2012), as well as emissions and other associated environmental impacts (Bond et al., 2013). High-rise buildings have been rapidly increasing worldwide due to insufficient land availability in populated areas and their primary role as essential buildings in modern cities and capitals (Shakir et al., 2021). Identifying and rectifying structural defects is

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essential to extend building lifetime and improve their overall performance (Ahzahar et al., 2011). Kumar et al. (2020) explained that the building envelope insulation is crucial for an energy-efficient and comfortable indoor environment because the envelope accounts for 50–60% of total heat gain or loss in a building. Building insulation plays a vital role in maintaining indoor thermal conditions by reducing heat transfer between the building and the external surroundings (Al-Sallal, 2003). Overall, recognizing defects early can enable buildings to take preventive actions to improve insulation, ultimately leading to enhanced energy efficiency, lower energy costs, and more comfortable living space (Osorio, 2023).

Straube and Finch (2009) argued that moisture is one of the primary causes of insulation defects often resulting in mold growth, corrosion, and deterioration of building materials. It results in costly structural repairs, downtime for operations, interior finishes, and items being damaged or lost, among many other repercussions (Nguyen et al., 2018). While past studies have been focused on energy efficiency and insulation materials, there has been limited exploration of insulation defects, their causes, and selection criteria to prevent failures (Xing et al., 2021; Liu et al., 2017), researchers have not focused on how to select proper insulation considering their significant factors. In the Sri Lankan context, customers are dissatisfied due to the aspects of less stability and durability of the structure (Karunasena & Ranatunga, 2009). Therefore, the study investigates common insulation defects in high-rise buildings, exploring their causes and impacts, assessing the impact on maintenance requirements in high-rise buildings and developing an assessment methodology to rank the insulation selection criteria.

2. LITERATURE REVIEW

2.1 THE ROLE OF INSULATION IN HIGH-RISE BUILDING

Insulation plays an essential role in maintaining indoor thermal comfort and reducing energy consumption in high-rise buildings (Al-Sallal,2003). However, energy demand strongly depends on the effectiveness of the applied strategies which include the proper design of the building envelope and the choice of proper components within a building to minimize heat loss or gain (Al-Homoud, 2005). Further author stated that insulation is considered a simple yet highly effective energy-saving technique that can be applied across various sectors, including residential, commercial, and office buildings, to improve high-rise buildings' thermal efficiency, maintain structural stability, and guarantee occupant comfort, insulation has played a fundamental aspect of modern construction technique. According to Kumar et al. (2020). To ensure optimal thermal performance it is essential to consider various elements of a well-designed insulation system, including appropriate materials, installation methods, and regular maintenance strategies to its sustained effectiveness over time. Furthermore, utilizing thermal insulation brings other benefits, including fire protection, personal comfort, condensation control, and sound control (Aditya et al., 2017).

2.2 IMPORTANCE OF INSULATION

The structural system of each building is exposed to the influence of individual external effects (Pasek & Kesl, 2015). To mitigate these effects, low heat absorption pavement includes heat shielding, water retentive, thermal resistance, and permeable types that have been developed to reduce temperatures and lessen heat impact on nearby structures (Chen

et al., 2018). Acoustic insulation is the capability of insulation material to dissipate sound energy due to resonance or thermal and friction loss (Schiavoni et al., 2016). In fact, to improve this importance, insulation materials should meet various requirements, including the lowest thermal conductivity, mechanical resistance, adaptability of the construction site, emission of fumes during a fire, robustness, resistance to freezing or thawing, water resistance, cost (Villasmil et al., 2019) and environmental impact (Liu et al., 2017). The optimum insulations are assessed through the life-cycle cost analysis (LCCA), a useful economic assessment tool to achieve sustainable objectives that lead to better long-term performance of the building with lower operating costs (Tam et al., 2017; Islam et al., 2014). Buildings with good insulation reduce discomfort from extreme temperatures and provide a comfortable living and working environment (Çomaklı, & Yuksel, 2004).

2.3 COMMON DEFECTS IN INSULATION SYSTEM

Straube and Finch (2009) argued that moisture is one of the primary causes of premature building enclosure deterioration. As indicated by Straube and Schumacher (2007), inconsistent indoor temperatures are one common sign that may suggest thermal bridging areas where heat transfer is insufficient insulation layers. Overall, recognizing these signs early can enable buildings to take preventive actions to improve insulation, ultimately leading to enhanced energy efficiency, lower energy costs, and more comfortable living space (Osorio, 2023). Table 1 below presents the common defects that occur in an insulation system.

Table 1:Common defects in an insulation system

Source	Indicator									
	Aging	**Mold Growth**	**Bad Odour**	**Pest infestation**	**Cracks**	**Water Damaging**	**Loss of Flexibility**	**Moisture damage**	**Changes in Temperature**	**Peeling Paints**
(Berardi & Nosrati, 2018)	✓	✓			✓	✓		✓		✓
(Al-Homoud, 2005)	✓	✓			✓	✓				
(Berge & Johansson, 2012)	✓					✓		✓	✓	
(Straube & Schumacher, 2007)		✓			✓	✓		✓	✓	
(Johnson, 2024)		✓		✓		✓		✓		
(Kumar et al., 2020)			✓					✓		
(Schiavoni et al., 2016)				✓		✓				
(Abu-Jdayil et al., 2019)							✓	✓	✓	
(Dong et al., 2023)								✓	✓	

Source	Indicator									
	Aging	Mold Growth	Bad Odour	Pest infestation	Cracks	Water Damaging	Loss of Flexibility	Moisture damage	Changes in Temperature	Peeling Paints
(Rezaeı, 2020)									✓	
(Karamanos et al., 2008)								✓	✓	

Accordingly, scholars have identified moisture, aging, and changing temperature as the main indicators of insulation issues. Water damage as infiltration is dependent on the tightness of the building construction, exterior shielding, temperature differences, wind velocity, and building height (Al-Homoud, 2005).

2.4 CAUSES FOR INSULATION ISSUES IN HIGH-RISE BUILDINGS

High-rise building integrity is further complicated by the possibility of structural damage and health risks such as mold growth resulting from neglecting thermal bridging and moisture control (Azim & Torii, 2024). This exposure defects the interior of the building and must be fully-prevented due to its adverse effect on human health (Stanaszek-Tomal, 2017). To avoid those issues, it is essential to use quality materials, hire qualified workers, implement a proper management system, and ensure adequate supervision throughout the construction process (Borku, 2020).

According to the findings of the literature review, it can be mentioned that poor material quality, moisture accumulation and poor installation practices are the most common causes of poor insulation.

Table 2: Causes for defects

No	Causes	Source
01	Poor material quality	[1], [2], [3], [4], [5], [6],
02	Inadequate climate & Environmental Exposure	[1], [9],
03	Workmanship and design errors	[6], [10], [5]
04	Moisture Accumulation	[2], [7], [10],
05	Biological Growth	[6], [7]
06	Lack of Standards for Biological Protection	[6]
07	Inadequate supervision	[8]
08	Thermal bridges	[6], [9]
09	The rate of permeability and water absorption	[7]
10	Biological Infiltration	[11]
11	Acidic Metabolic Byproducts	[11]
12	Poor installation practices	[6], [9], [10]
13	High Diffusion Resistance of Insulation	[6]

No	Causes	Source
14	Lack of maintenance	[11]
15	Improper Paint Selection	[11]

(Azim & Torii, 2024) [1], (ASHRAE, 2021) [2], (Schiavoni et al., 2016) [3], (Abu-Jdayil et al., 2019) [4], (Ruivo et al., 2016) [5], (Stanaszek-Tomal, 2017) [6], (Karamanos et al., 2008) [7], (Borku, 2020) [8], (U.S. Department of Energy, 2020) [9], (Tenwolde & Rose, 1996) [10], (Savva et al., 2018) [11]

2.5 FACTORS NEED TO BE CONSIDERED WHEN SELECTING BUILDING INSULATION

Table 03 below provides a summary of the research's findings with reference to the deciding criteria in the selection of insulation.

Table 3: Factors to be considered when selecting insulation.

No	Causes		Source
01	Purpose of application	Materials	[1], [2], [3], [4], [7], [11]
02	Easy application		
03	Material design & availability		
04	Durability		
05	Thermal conductivity		
06	Thickness & Density		
07	Resistant to UV		
08	Porosity and permeability		
09	Sustainability of Materials		
10	Mechanical effect	Technology	[10], [6], [7], [8], [12]
11	Special skills and equipment		
12	Testing requirements		
13	Building orientation and Location	Building Profile	[4], [6], [11], [15],
14	Structural elements of the building		
15	Operating Condition		
16	Occupancy		
17	Cost of materials	Cost	[3], [4], [5], [10], [8], [10], [18]
18	Transport cost		
19	Laying cost		
20	Labor cost		
21	Operating cost		
22	Temperature Fluctuation	Climate and Environmental condition	[4], [9], [14], [19]
23	Environment sustainability		
24	Chemical & Biological reaction		
25	Local Codes and Standards	Legal requirements	[14], [13], [16]
26	International Codes and Standards		

No	Causes		Source
27	Experience	Suitability of contractor	[17], [18]
28	Reputation		
29	Maintenance		
30	Cost, Time & Quality		
31	Availability of human resource		

(U.S. Department of Energy, 2020) [1], (North American Insulation Manufacturers Association, 1996) [2], (Aditya et al., 2017) [3], (Mahlia & Iqbal, 2010) [4], (Kumar et al., 2020) [5], , (Berardi & Nosrati, 2018) [6], (Villasmil et al., 2019) [7], (Abu-Jdayil et al., 2019) [8], (Azim & Torii, 2024) [9] ,(Tam et al., 2017) [10], Schiavoni et al., 2016) [11], (Wei et al., 2015) [12], (Windapo & Cattell, 2010) [13], (Dong et al., 2023) [14], (Albatayneh et al., 2018) [15], (Zagorodnyuk et al., 2017) [16], (Plebankiewicz, 2009) [17], (Sodangi, 2011) [18], (Pasek & Kesl, 2015) [19]

The building insulation contributes to a positive net energy balance through a larger amount of energy saved through the insulation application than the energy required to manufacture the insulation material itself (North American Insulation Manufacturers Association, 1996). Insulation of buildings is done by using a variety of building insulation materials accompanied by its thermal conductivity (Aditya et al., 2017). In addition to that Mahlia and Iqbal (2010) stated there are relevant factors to be considered during material selection, such as cost, durability, climate factor, availability, heat transfer mode, the ease level of installation, and building orientation. In the realm of sustainable construction, recent research has also emphasized the use of advanced technologies to optimize energy efficiency and reduce carbon emissions (Azim & Torii, 2024). Further author stated that future research should explore emerging insulation technologies and their impact on energy efficiency. Therefore, exploring new insulation technologies could advance energy efficiency in building practices. Mechanical strength is a crucial factor when selecting insulating materials (Abu-Jdayil et al., 2019).

Optimal building orientation is a very low-cost solution in architecture that can significantly reduce energy consumption in the building sector (Albatayneh et al., 2018). For energy conservation, selecting efficient structural elements is essential when renovating buildings (Brauers et al., 2012). The author indicated that the method for insulation of the building envelope is selected depending on the structure, building materials, and the purpose of the partition, as well as other objectives. Occupancy behaviours account for about 30% of the variance in overall heating consumption and 50% in cooling consumption (Dong et al., 2023). One of the most important factors to consider when selecting building insulation material is cost (Mahlia & Iqbal, 2010). The building insulation investment is linked to the reduction of thermal energy consumption necessary to heat a building; the costs are related to the purchase, transport, and laying. Labor costs for insulation depend on materials and finishes (Aldykiewicz et al., 2022).

The review of existing literature also pointed out that the environmental performance of building insulation materials depends on their climatic conditions (Kumar et al., 2020). The structural system of each building is exposed to the influence of individual external effects like temperature fluctuations. The structural system damage risk of representative building caused by cyclical temperature changes depends on the character of insulation on the building envelop and the probability of damage of construction insulated from the internal side caused by temperature changes increases with the increase of the stiffness

of the construction (Pasek & Kesl, 2015). The legal obligations concerned with thermal insulation have become stricter, and the changes are made regularly (Abu-Jdayil et al., 2019). According to Abu-Jdayil et al. (2019),, the international standards related to the specifications of traditional thermal insulators will be referred to in the subsequent sections when valid. Applying the principles of the law to the creation of insulation solutions, build a system from its constituent elements (Zagorodnyuk et al., 2017). Contractor prequalification is a complex process that usually involves multiple decision-makers with different levels of experience (Alhumaidi, 2014). Choosing a qualified contractor increases the chances of successful completion of a project by achieving the client's goals of keeping the schedules of the cost, time and quality (Sodangi, 2011).

2.6 APPLICATION OF BEST WORST METHOD APPROACH (BWM)

The best criterion is compared to the other criteria, and all the other criteria are compared to the worst criterion, in the comparison oriented MCDM method known as BWM (Abadi et al., 2017). The BWM can be used to compare decision-making factors on insulation because it approaches a pairwise comparison-based method that offers a structured way to make the comparisons (Ahmadi et al., 2017). The benefit of this approach is that it lessens the degree of ambiguity or inconsistency in the outcomes, fewer violations, reduced pairwise comparisons, and its total deviation, flexibility, and simplicity make this method perform better than other MCDM methods (Rezaei, 2015).

3. RESEARCH METHODOLOGY

The methodology outlines the approach to carry out the intended study objectives. Initially, a literature review on the insulation in high-rise buildings and factors influencing the selection of proper insulation was carried out. Secondly, the case studies were carried out focusing on the insulation of high-rise buildings having a minimum of 20 stories. A total of fifteen high-rise buildings located in Western Province Sri Lanka were chosen, representing four different building types to capture a diverse range of insights. The selection included two office buildings, four hotel buildings, four commercial buildings, and five residential buildings. These buildings were intentionally chosen through purposive sampling to align with the study's objective. During the case study, semi-structured interviews were conducted with industry experts in building insulation. Purposive sampling is used to select interviewees who have expertise in and interest in the research subject being investigated (Etikan et al., 2016). Table 04 includes details about the experts who were selected.

Table 4:Details of respondents

Respondent	Profession	Designation	Experience
E1	Engineering	Civil Engineer	25 Years
E2	Engineering	Chief Maintenance Engineer	18 Years
E3	Engineering	Chief Engineering Manager	20 Years
E4	Manager	Maintenance Rectification Engineer	22 Years
E5	MEP Engineering	Assistant Director Engineer	17 Years

According to interviews and case studies most influencing sub-factors were identified under different categories. Five expert interviews were carried out with professionals who had direct involvement with the selected buildings. They were from four of the 15

buildings two from the same building and three from different ones. The interviews focused on gaining general insights into insulation challenges, importance, and selection criteria. In total, 40 respondents (including five experts) who are engineers and facility managers in the field were surveyed for the preference data collection of main factors to be considered in the selection of building insulation. Under the case study, different types of defects and their causes were explored through observation, documentation, and photographs. Manual content was used to analyze the collected data. In particular, the priority level of the elements influencing the decision to building insulation was ranked using the Best Worst Method (BWM).

4. RESULTS AND DISCUSSION

Information gathered through the expert interviews and case studies were analyzed using manual content analysis. Based on the expert opinions on the main selection factors, priority levels were developed. While some buildings were maintained in such a way that they optimally performed, those buildings presented significant defects such as moisture damage, water damage, cracking, and pest infestation. In many cases, insulation defects were due to ineffective or failure to prioritize maintenance practices leading to a lack of attention to insulation. Expert interviews revealed that maintenance is essential for insulation performance but many high-rise buildings often do not prioritize maintenance activities properly. All experts highlighted that "Insulation failures could be reduced through routine inspections and preventive maintenance".; However, E3 argued that "*there should be a proper insulation selection factor consideration for reducing defects from the initial stage*", a view supported by E4 and E5.

4.1 INSULATION DEFECTS AND CAUSES



Figure 1: Insulation defects

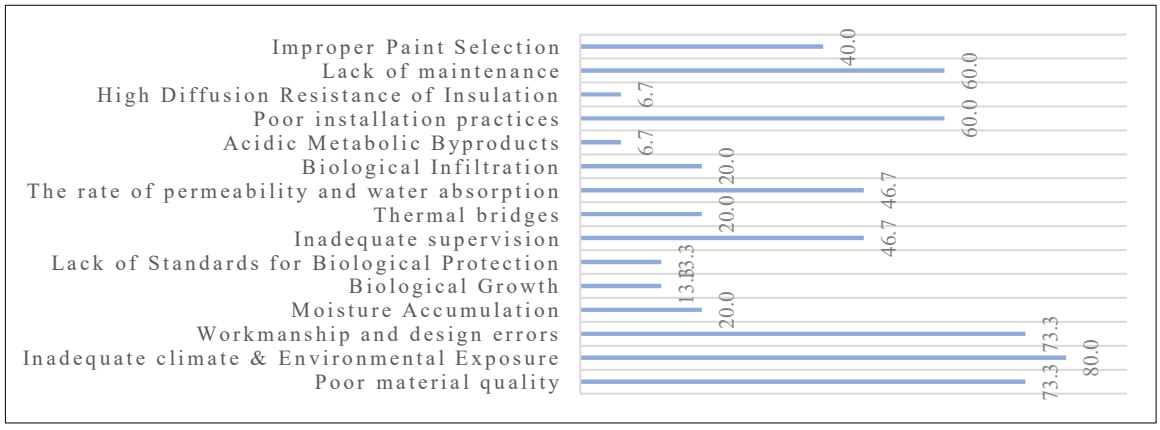


Figure 2: Causes of insulation defects; frequency percentage

Figure 01 shows that all buildings experienced a variety of insulation defects. By analysing the data collectively, the percentages shown in Figure 02 were calculated based on the total number of identified causes across all defect observations.

Table 5: Frequency of common defects in buildings

Frequency of common defects		
Defects	**Observations**	
	Percentage	**Number of Buildings Having**
Water damaging	86.7%	13
Pest infestation	80%	12
Cracks	80%	12
Moisture damage	73.3%	11
Peeling paints	66.7%	10
Aging	60%	9
Staining	53.3%	8
Changes in temperature	33.3%	5
Mold Growth	13.3%	2
Loss of flexibility	13.3%	2
Bad Odor	6.7%	1

Table 05, on the other hand, lists which specific defects occurred in each building, thereby supporting the data interpretation and ensuring transparency in the analysis. Water damage (86.7%) and infestation from pests (80%) stand as the main defects observed in these buildings. Additionally, insulation systems are showing structural or material weakness based on the high frequency of observed cracks (80%). Observational data reveals structural issues in insulation systems that reduce their performance capacity for insulation and building functionality.

According to experts' interviews, data demonstrates that weather conditions are the significant cause of insulation defects since all respondents identified it as a primary cause. Experts indicate that poor material quality is the next critical concern, with 4 out of five of responses, highlighting "*the importance of skilled installation practices and technical knowledge"*. Further E03 demonstrated "*wrong material selection along with degradation of building insulation systems hence underscoring the need for durable and suitable materials*". E04 stated that "*inadequate design along with insufficient maintenance stands as major contributors to insulation problems"*. This experts' statements prove top three causes shown in Figure 02 based on case studies.

The causes shown in Figure 02 have direct relationships with previously observed defects in Table 05 the combination of inadequate climate consideration (80%) and poor workmanship (73.3%) results in cracking and temperature changes because the design fails to environmental factors. Better design processes combined with suitable material selection and regular maintenance practices will help significantly reduce defects and improve building performance. The research findings confirm previous studies that link moisture accumulation, poor material quality, and improper installation problems to insulation failure (Straube & Finch, 2009; Nguyen et al., 2018). According to Osorio (2023), thermal bridging due to poor installation is a critical factor affecting insulation performance.

4.2 MAINTENANCE PRACTICES

The case studies revealed that while all buildings acknowledged the importance of insulation maintenance, it was often not prioritized. Most maintenance activities were reactive rather than preventive, typically addressed only when defects became severe or repairs were unavoidable. Instead of following a scheduled maintenance plan, practices were carried out on an ad-hoc basis, resulting in delayed responses to insulation issues.

Figure 3 illustrates the frequency of maintenance practices observed in the selected buildings. It shows that 93.3% conducted general inspections, and 73.3% involved skilled experts in evaluations. However, only 66.7% monitored temperature differentials, and just 26.7% checked for odour changes, reflecting the lower occurrence of odour-related defects. Overall, the findings emphasize the need for consistent and scheduled maintenance to prevent major insulation failures and to enhance building performance and occupant comfort.

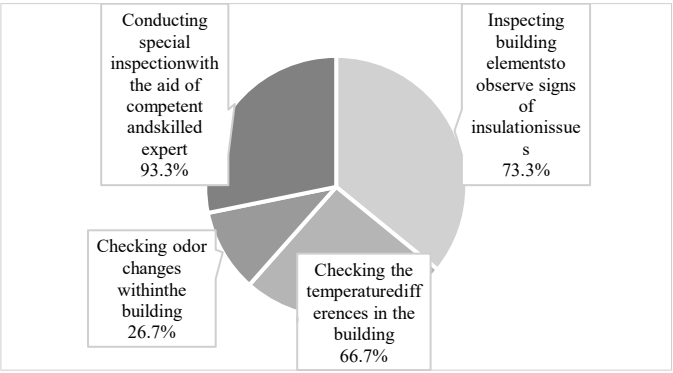


Figure 3: Maintenance practices percentage

4.3 INSULATION SELECTION CRITERIA

As the building is being constructed from scratch or renovated, selecting the right insulation system from the early design stage is the best approach to ensure long-term efficiency and performance. Clients select the cheapest available options, such as the cheapest materials, low-budget contractors, prioritising cost over other important factors. However, as agreed by all respondents, building profile, technology, and materials are the most considerable factors when selecting an insulation system. To mitigate the above defects, experts illustrated that insulation selection should prioritize building profile factors, such as structural design, and building orientation to match building specifications. Building insulation practice requires updating its installation technology and testing requirements in combination with fastening approaches to reduce thermal bridge defects. Choosing materials with the combination of moisture resistance, durability, and thermal efficiency to prevent early degradation and improve long-term performance.

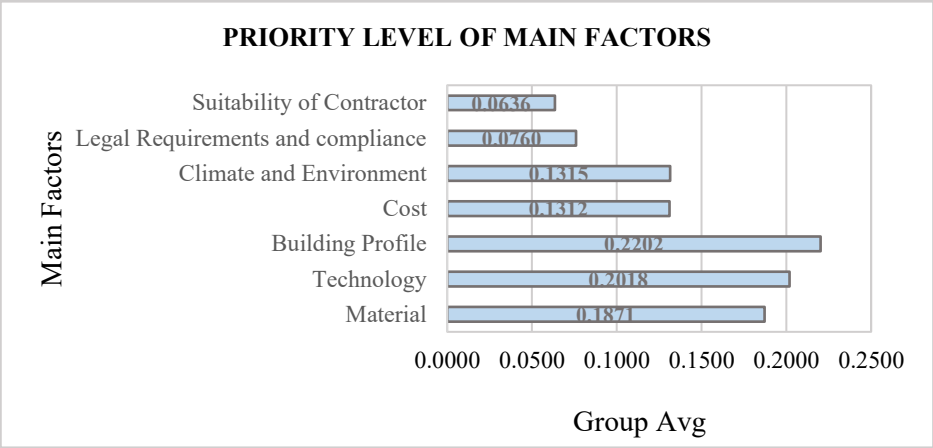


Figure 4: Priority level of insulation selection

According to the survey requirement, respondents were selected to provide their rankings by taking into account the primary insulation selection criteria. Consequently, the bar graph (Refer to Figure 04) represents the view of a preference survey regarding the criteria that should be considered sequentially while choosing insulation. Simply expressed, the graph illustrates that the experts and respondents applied the BWM to indicate the subfactors' relative importance within each set of factors, based on how they perceived it, and the corresponding weights and averages were generated in accordance with their perceptions. The global weights were determined using group average and the corresponding weights were generated in accordance with respondents' perceptions for each main factor. The BWM was applied by identifying the best and worst criteria, followed by pairwise comparisons using a scale of 1 to 9. Respondents entered their preferences into an Excel-based model, which automatically calculated the optimal weights through linear optimization. Final weights were averaged to determine the priority ranking of selection factors. The most important category for affecting the choice of insulation, according to Figure 04, was one associated with the building profile, whereas the category with the least influence was one related to the suitability of the contractor. While selecting the optimal insulation decisions, the final results provided a clear understanding of the most important decision factors. The findings of this study provide valuable insights into the insulation decision-making process in high-rise buildings in Sri Lanka, with particular emphasis on the prioritization of selection criteria using the Best-Worst Method (BWM).

4.4 DISCUSSION

These findings are aligned with previous studies, such as by Asadi et al. (2012), who emphasized the importance of energy performance in sustainable building design, and by Al-Homoud (2005), who highlighted the long-term benefits of thermal insulation on building performance. Moreover, the identification of key determinants and causes of insulation defects contributes to addressing performance gaps observed in local construction practices. The methodological approach used in this study, combining expert judgment with BWM, also proved effective in quantifying subjective decision criteria, offering a structured path for future decision-making in the construction sector (Rezaei, 2015). Additionally, the BWM's ability to reduce inconsistency in expert evaluations made it particularly suitable for this study, where decision factors span technical, environmental, and economic dimensions.

This study also highlights limitations and future research opportunities. One major limitation is the reliance on expert opinion, which, although valuable, may introduce subjectivity and may not capture the full range of stakeholder perspectives, such as developers or end-users. Furthermore, the study was geographically confined to Sri Lanka, limiting the generalizability of the findings to broader contexts. Future studies should explore comparative analyses across different regions or building typologies to validate the applicability of the identified criteria. Incorporating diverse views would also enrich the findings and better reflect real-world decision-making scenarios. Integrating life cycle cost analysis (LCCA) and environmental impact assessment could also enhance the robustness of the insulation selection process (Ding, 2008). Moreover, the study's findings could serve as a practical guideline for facilities managers, engineers, and policy makers in implementing more informed insulation strategies tailored to local building needs. Overall, the study provides a strong foundation for further research aimed at enhancing sustainable building performance and supports informed decision-making in high-rise construction.

5. CONCLUSION

This study is mainly concentrated on the impact of insulation defects on high-rise buildings' performance and energy efficiency. As the main technique, the researchers followed the three-phase process that included a study of 15 buildings, 40 respondents who answered the survey, and interviews with five industry experts. The study confirmed the fact that moisture damage, pest infestation, and cracking are the most frequent insulation problems. This information was provided by experts who stated that these problems primarily stem from poor material choice, unsuitable installation techniques, and not considering environmental factors. In order to determine the ranks, the initial phase of the BWM implementation incorporated both the most critical and the least significant factors. The research recognized that building profile, technology, and material properties are the most critical factors in selecting effective insulation systems. It has been reported that negligence in meeting these aspects would lead to higher maintenance costs and premature insulation failures. To further enhance the situation, the regulation of the industry and increasing awareness in the industry can help minimize insulation failures and enhance long-term building efficiency. The findings can serve as a benchmark for improving insulation standards and reducing operational inefficiencies that can guide industry practitioners in selecting and maintaining insulation systems more effectively, ultimately contributing to improved building performance, energy efficiency, and occupant comfort. In addition, this study offers recommendations for both industry and academia, such as integrating insulation into facilities management plans, considering climate-based selection criteria, and applying smart monitoring systems. While the study provides valuable insights, it is limited by its geographic scope, being focused solely on high-rise buildings in Sri Lanka's Western Province. This study suggests future research on IoT-based smart monitoring for insulation, integrating insulation into facilities management, considering building profiles in retrofits, climate impacts on insulation choices, and insulation maintainability. Further limitations included access restrictions to data from some organizations, some expert interviews being held online, and respondents' unfamiliarity with ranking certain insulation factors.

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INTEGRATING BIM INTO BUSINESS MODELS OF CONSULTANCY FIRMS: BARRIERS AND ENABLERS

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ABSTRACT

Building Information Modelling (BIM) has revolutionised the construction industry by enhancing collaboration, visualisation, and decision-making throughout project lifecycles. For consultancy firms, especially in Sri Lanka, integrating BIM into their business models (BMs) presents both significant opportunities and complex challenges. This study explores the barriers and enablers associated with incorporating BIM into the BMs of Sri Lankan consultancy organisations. A mixed-methods approach was adopted, combining expert interviews and a questionnaire survey among industry practitioners. Key barriers identified include high initial investment costs, difficulties in maintaining Level of Development standards, and a shortage of BIM-skilled professionals. Conversely, major enablers include greater international opportunities, time savings, and enhanced competitiveness. According to the findings, the financial, technological, and organisational challenges hinder BIM integration; strategic focus on enablers such as proper training, digital transformation, and client awareness can facilitate effective adoption. This study provides valuable insights for consultancy firms aiming to align with global digital transformation trends and highlights the need for further research into BIM-related business model attributes for consultancy firms.

Keywords: *Building Information Modelling (BIM); Business Models; Consultancy Organizations; Sri Lanka.*

1. INTRODUCTION

The construction industry is an important sector in a country's economy, encompassing various stakeholders who collectively drive project success (Badi & Diamantidou, 2017). Consultants play a pivotal role among these stakeholders by offering professional expertise throughout the project lifecycle. Consultancy firms operate as business entities by providing specialised professional services (Zainon et al., 2018) and advising clients on construction projects and investments while ensuring that the project meets design, budget, and regulatory criteria (Azhar, 2011). Specifically, quantity surveying consulting firms provide precise cost estimates and execute cost management strategies, thereby minimising budget overruns and enhancing financial efficiency (Ahmad et al., 2019).

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Therefore, being business entities, consultancy firms must adopt strong and sustainable business models (BMs) to remain competitive and maximise value (Euchner, 2016).

Business models (BMs) provide strategic direction for organisations by articulating the value proposition offered to customers, identifying the target market, and outlining revenue generation mechanisms (Das et al., 2023). According to Martins et al. (2015), BMs are instrumental in generating profitable income while assessing current and future costs to ensure long-term financial sustainability. The BM of a consulting firm must consist of several essential elements that support its success and sustainability (Euchner, 2016). Consultancy firms must integrate these essential elements to their business that enable effective management of fixed costs, such as salaries, office rent, and operational expenses, and market responsiveness to achieve sustained profitability and growth (Bullinger et al., 2016).

To fully capitalise on the potential of their BMs, consulting firms must also remain agile and responsive to technological advancements (Euchner, 2016). Among these, Building Information Modelling (BIM) stands out as a transformative innovation in the construction industry. BIM has transformed the construction industry by enhancing collaboration and decision-making throughout a project's lifecycle. It provides comprehensive insights into the planning, design, and execution of construction projects (Olawumi & Chan, 2018; Perera et al., 2022). BIM creates a digital platform that enhances collaboration and coordination among project stakeholders throughout the project lifecycle, including architects, engineers, quantity surveyors, and contractors (Walasek & Barszcz, 2017). Integrating emerging technologies like BIM within consultancy firms' BM offers strategic opportunities to diversify their services and remain competitive and innovative in this dynamic business environment, and generate new revenue streams (Abbasnejad et al., 2021).

However, successful integration of BIM into BM of consultancy firms requires not only adopting BIM Technology but also realigning business elements facilitating BIM integration. BIM-based Quantity Surveying tools enable consultants to provide more accurate and reliable cost management solutions, increasing market competitiveness (Won et al., 2013). BM can leverage technological advancements into strategic advantages. Therefore, consulting firms must adopt a BM that aligns with BIM implementation. However, implementing BIM requires a significant investment in hardware, software, education, and training, making it an expensive endeavour for many businesses (Suranga et al., 2018). Similarly, integrating BIM into BMs may present several barriers that need to be addressed, alongside enablers that should be strengthened.

However, this area remains underexplored in the Sri Lankan context. While global studies have examined the relationship between BIM and BMs (Mazen, 2013; Fagbenro et al., 2022), local research has primarily focused on the growth and establishment of consulting firms without integrating BIM within their BMs. This gap highlights the need to understand how BIM can be strategically integrated into BMs by initially addressing barriers and strengthening enablers. Accordingly, this research aims to advance the understanding by identifying the barriers and enablers to integrating BIM into the BMs of Sri Lankan consultancy organisations within the construction industry.

2. LITERATURE REVIEW

2.1 BIM IN THE CONSTRUCTION INDUSTRY

Building Information Modelling (BIM) is a digital system that manages construction projects from start to finish (Suranga et al., 2018). It allows stakeholders to visualise, simulate, and assess designs in a virtual space, leading to better decisions and improved coordination (Kocakaya et al., 2019). More than just software, BIM integrates people, processes, and technology to streamline project management across all phases (Zainon et al., 2018). BIM boosts construction efficiency, accuracy, and collaboration (Sadek et al., 2020). It supports real-time teamwork on a shared platform, reducing design flaws and rework. With features like scheduling (4D), cost tracking (5D), and sustainability (6D), BIM improves coordination, minimises delays, and controls costs (Abdel-Hamid & Abdelhaleem, 2023). It also enhances quality control, cuts waste and supports code compliance.

In Sri Lanka, BIM use is still emerging, lagging behind developed countries (Fathima et al., 2024). While large firms and global projects have begun adopting BIM, many local companies continue to rely on traditional methods such as 2D CAD drawings, manual quantity take-offs, and paper-based scheduling and documentation (Perera et al., 2022). Key barriers include low awareness, high costs, and limited technical skills (Olawumi & Chan, 2018).

2.2 SIGNIFICANCE OF BIM FOR CONSULTANCY ORGANISATIONS

Consultants ensure that projects meet client expectations, adhere to regulations, and are completed on time and within budget. Consultancy firms in Sri Lanka face challenges, such as limited technology adoption, regulatory hurdles, and a shortage of skilled labour, which hinder their growth, competitiveness and efficiency (Manoharan et al., 2022).

Consultancy firms in the construction sector can attain competitive advantages, enhanced procedures, and superior project outcomes by incorporating BIM into their workflows (Fagbenro et al., 2022). Quantity Surveying (QS) firms can utilise 5D BIM to improve the precision of cost estimations, hence minimising the risk of budget overruns (Zainon et al., 2018). BIM enables consultants to provide more extensive services to clients, such as real-time cost updates and clash detection among various building systems (Abd & Khamees, 2017). Through BIM adoption, consultancy companies can extend their services with sustainability assessments, lifecycle cost evaluations, and improved project management features (Onososen et al., 2022). The market demands consultants who use advanced technology for project management, and the adoption of BIM technology helps firms claim this valuable market space (Rogers et al., 2015) BIM also helps consultancy firms fulfil client demands for accurate, timely information, leading to better client satisfaction and meeting the industry's precise timing requirements. According to Wang et al. (2020), the use of BIM enables consultants to collaborate with other stakeholders, resulting in faster project delivery while maintaining budget control and ensuring high quality. Therefore, BIM has become a vital tool in the construction industry, significantly impacting the operations and functions of construction consultancy firms.

2.3 BUSINESS MODELS OF CONSULTANCY ORGANISATIONS

Construction consultancy firms showcase their value creation strategies through BMs that outline their operational processes, methods of delivering client value, and profit-generating activities (Rogers et al., 2015). In dynamic business environments, it is essential for companies to quickly identify emerging technologies and develop effective strategies to capitalise on their potential (Fagbenro et al., 2022). Since BMs often drive organisational change, it is crucial to design adaptive BMs that respond to technological advancements and regulatory shifts (Martins et al., 2015). Recent trends are to merge BMs with value-based perspectives like early engagement and lifecycle approaches, further enabling strategic partnerships, technology integration, and strategy formulation. (Das et al., 2023).

A well-designed BM can foster strategic collaboration by integrating technology and corporate strategies to tackle critical challenges, like customer dissatisfaction, market fragmentation, and technology resistance (Martins et al., 2015). Clear pathways for technology adoption enable businesses to enhance resilience and sustain competitiveness in rapidly changing markets (Stone & Parnell, 2023). Integrating BIM into BMs of construction consultancies helps gain competitive advantages, streamlines processes, and improves project outcomes with value additions (Fagbenro et al., 2022). Evolving construction industry demands that Sri Lankan consultancy firms adapt to technologies like BIM to remain competitive and add value to clients. Thus, integrating BIM into a consultancy firm's BM is essential.

2.4 BIM ADOPTION IN CONSULTANCY ORGANISATIONS

Despite BIM's numerous advantages, consulting firms often face significant challenges regarding its implementation (Suranga et al., 2018). Effective adoption of BIM by consultancy firms is frequently hindered by several barriers such as significant initial costs, reluctance toward abandoning traditional processes, and a lack of recognised industry standard protocols (Sun et al., 2015). Collectively, these barriers can hinder the integration of BIM into consulting firms' BM, limiting the ability to gain the full range of BIM advantages. Several studies, as summarised in Table 1, highlight the key obstacles hindering BIM adoption within consultancy organisations.

Table 1: Barriers to BIM adoption for consultancy organisations

Code	Barriers to BIM adoption in consultancy organisations	Authors
B01	High expenses for training staff on new BIM software and integrated practices.	C, J, K, L, N, E, F
B02	Significant initial investment needed for BIM-related software and hardware	A, C, D, K, I
B03	Elevated costs for implementing new processes and BIM technology	C, L, N, I
B04	Insufficient support from top management for adopting BIM practices	C, H, L, N, I
B05	Resistance among professionals to transition to BIM modelling	C, J, E
B06	Limited support for BIM adoption within the company	L, N, C, D, H, J
B07	Lack of standardised procedures, protocols, and guidelines	L, N, C, D, J

Code	Barriers to BIM adoption in consultancy organisations	Authors
B08	Shortage of skilled professionals and in-house expertise to support BIM practices	L, N, C, D, J
B09	Widespread resistance to adopting new processes associated with BIM	L, K, C, H
B10	Inadequate BIM object libraries and modelling standards	L, N, G, F
B11	Limited project opportunities to apply and test BIM capabilities	K, N, C, H
B12	Lack of interoperable platforms for seamless BIM integration	L, N, C
B13	Insufficient comparative research between traditional and BIM-based projects	K, C
B14	Incompatibility issues of BIM with other software platforms, affecting usability	K, B, M
B15	Low satisfaction with the return on investment (ROI) from BIM implementations	I, J, M
B16	Legal uncertainties related to ownership, intellectual property, and insurance	K, L, M
B17	Minimal demand or interest in BIM from clients, reducing motivation for adoption.	J, K, B, M, J
B18	Operational-level reluctance to incorporate BIM in daily workflows	K, M
B19	Reluctance among team members to openly share data in collaborative BIM settings	B, M
B20	Confidence in existing methods	L, N, C, M, G
B21	Compatibility issues during software integration and document sharing	L, N, C, D
B22	Limited market support and weak trends favouring BIM adoption	L, N, C, D
B23	Low industry awareness of BIM's advantages and potential	K, N, H
B24	Lack of comparative cost-benefit analysis to highlight BIM's financial advantages	B, C, H, K, N

A - (Ahmad et al., 2019), B - (Arayici et al., 2011), C - (Gardezi et al., 2014), D - (Gerges et al., 2017), E - (Ghaffarianhoseini et al., 2022), F - (Hamma-adama et al., 2020), G - (Hatem et al., 2018), H - (Khosrowshahi & Arayici, 2012), I - (Nguyen & Nguyen, 2021), J - (Oesterreich & Teuteberg, 2019), K - (Rogers et al., 2015), L - (Sun et al., 2015), M - (Walasek & Barszcz, 2017), N - (Won et al., 2013)

As depicted in Table 1, the main barriers focus particularly on financial constraints and organisational and technological difficulties. Table 1 reveals that high implementation costs, internal resistance to change, limited technical expertise, and inadequate digital infrastructure are the main barriers preventing BIM adoption in consultancy firms.

On the other hand, consultancy firms possess several enablers that can help overcome these barriers and facilitate the effective adoption of BIM. Various authors have identified key enabling factors that support BIM integration within consultancy organisations, which are outlined in Table 2.

Table 2: Enablers of BIM adoption in consultancy organisations

Code	Enablers of BIM adoption in consultancy organisations	Authors
E01	Growing awareness of BIM in global practices	C, D, K, L
E02	Strong leadership and top management support	H, K
E03	Investment in training and development	D, J
E04	Clear BIM standards and protocols	C, H
E05	Support for gaining a competitive advantage in the market	G, H, K
E06	Trend of using BIM for the management of construction project information	E, F, H, K
E07	Providing an overall sustainable construction environment	E, F, H, K
E08	Improving the coordination of construction documents	E, F, H, K
E09	Enhanced visualisation	A, B, E, K
E10	Real-time collaboration among all project professionals and stakeholders	A, B
E11	Systematic training programs for staff integrating R&D strategies	A
E12	Redesigning the organisational structure to suit an effective BIM implementation	A, H, I, L
E13	Building effective client-consultant relationships	A, L
E14	Introducing a digital transformation strategy with realistic objectives	A, E, F, G
E15	Investing in suitable software solutions for a BIM-enabled working environment	G, H, K
E16	Improving coordination processes with external suppliers	C, H
E17	Integration with existing systems	B, I
E18	Client awareness and demand	C, J
E29	Comprehensive cost-benefit analysis	C, H, L

A - (Abbasnejad et al., 2021), B - (Arayici et al., 2011), C - (Azhar, 2011), D - (Babatunde et al., 2020), E - (Badi & Diamantidou, 2017), F - (Elmualim & Gilder, 2014), G - (Gardezi et al., 2014), H - (Gerges et al., 2017), I - (Khosrowshahi & Arayici, 2012), J - (Olawumi & Chan, 2018), K - (Khosrowshahi & Arayici, 2012), L - (Won et al., 2013)

These enablers highlight the strategies, resources, and organisational conditions that can drive successful BIM adoption, such as client awareness, technological integration, and the establishment of standardised protocols. The identified barriers and enablers of BIM adoption in consultancy firms provide a basis for empirically investigating the barriers and enablers associated with BIM integration into Sri Lankan construction consultancy firms' BMs.

3. METHODOLOGY

A mixed-methods approach was employed to gather both in-depth qualitative insights and quantitative data on the integration of BIM into the BMs of consultancy firms. Qualitative data were used to identify the key barriers and enablers specific to the Sri Lankan context, while industry-wide trends and priorities were revealed using quantitative data. Semi-structured interviews were conducted, allowing the researcher to explore predefined information related to the topic from the literature and gain contextual insights. Accordingly, barriers and enablers identified in the literature were presented to

the experts to assess their relevance to the Sri Lankan context, and additional barriers and enablers were also considered. Interviews were conducted with ten industry experts who were purposefully selected based on the criteria outlined in Table 3.

Table 3: Profiles of interviewees of experts

Expert	Designation	Experience > 15 Years	Experience in top management of a Consultancy Firm > 10 years	Experience with BIM
E1	Director	✓	✓	✓
E2	Senior Quantity Surveyor	✓	✓	✓
E3	Director	✓	✓	✓
E4	Director	✓	✓	✓
E5	Director	✓	✓	✓
E6	Director	✓	✓	✓
E7	Director	✓	✓	✓
E8	Director	✓	✓	✓
E9	Director	✓	✓	✓
E10	Director	✓	✓	✓

Barriers identified in the literature and through interviews were used to develop questionnaires for collecting quantitative data. A questionnaire survey was conducted targeting a sample of 45 industry practitioners, selected using a purposive sampling method, who are members of top and middle management in consultancy organisations across Sri Lanka. The collected data were analysed using a content analysis method and statistical methods, such as RII, used to analyse quantitative data from a questionnaire survey.

4. FINDINGS AND ANALYSIS

Expert interviews explore the barriers and enablers associated with integrating BIM into the BMS of consultancy firms within the Sri Lankan construction industry. They provide valuable insights into the key factors influencing BIM adoption and paving the way for the next phase, where the significance of these factors was assessed within the Sri Lankan context. In addition to the barriers and enablers identified in the existing literature, the interviews revealed additional factors that further shaped the integration process, as shown in Table 4.

Table 4: Additional barriers found through expert interviews

Barriers	Percentage of experts	Enablers	Percentage of experts
Maintaining the Level of Development (LOD) details (E2, E4, E5, E6 and E10)	50%	Improved accuracy in estimation and financial forecasting with enhanced credibility (E1, E4, E5, E6, E9 and E10)	60%
Dependence on specific software platforms (E3 and E4)	20%	Time saving due to the enhancement of coordination and reducing rework (E5, E8, E9)	30%
Low trust in the Accuracy of the model (E2)	10%	Long-term cost savings & higher profitability due to efficiency improvements (E7, E8, E10).	30%
Requirement of continuous development and learning (All the Experts)	100%	Adaptability to remote work & cloud collaboration (E1. E4 and E7)	30%
Difficulty in recruiting and retaining BIM-skilled and trained staff (All the experts)	100%	More international opportunities (All the experts)	100%
		Lower risk due to the absence of human errors and minimised rework (E2, E3, E5, E9)	40%
		Support for gaining Competitive advantage (All the experts)	100%

The questionnaire survey, based on barriers and enablers identified through literature and interviews, was conducted to identify key factors in the Sri Lankan context. Of the 45 distributed, 32 responses were received, yielding a 71.11% response rate. Barriers and enablers with an RII above 0.8 were selected to highlight the most critical factors, focusing the analysis on those with the most significant potential impact.

4.1 BARRIERS TO INTEGRATING BIM INTO BUSINESS MODELS

Using RII analysis and ranking, the most significant barriers to integrating BIM into consultancy firms' business models were identified. Barriers with an RII above 0.8 were considered most critical, as shown in Table 5.

Table 4:Significance of barriers to BIM adoption to BMs of Consultancy firms

Barrier	RII Value	Rank
High initial investment for software and hardware	0.961	1
Maintaining LOD details	0.922	2
High expenses for training staff	0.861	3

Barrier	RII Value	Rank
Difficulty in recruiting and retaining BIM-skilled & trained staff	0.850	4
Lack of interoperable platforms	0.822	5
Low satisfaction with ROI	0.822	5
Requirement of continuous development and training	0.811	7
Low industry awareness of BIM's benefits	0.811	7
Low trust in model accuracy	0.805	9
Dependence on specific software	0.800	10

The highest-ranked barrier to BIM adoption is the high initial cost of hardware and software (RII = 0.961), also confirmed by all interviewed experts. Maintaining Level of Development (LOD) details ranks second (RII = 0.922), with experts E2, E4, E5, E6, and E10, noting challenges in keeping models detailed and accurate throughout project phases.

The third and fourth barriers are the high staff training cost and difficulty recruiting and retaining BIM-skilled staff. Experts emphasised this concern; E2 noted, "*We have to allocate some of the user licenses of BIM software just for training staff for about 3 months, which is a high cost for us*". E6 added that trained staff often leave before firms see returns. As a result, many firms feel that the financial ROI from BIM is slow or unclear, and it ranked fifth in the survey, with an RII of 0.822. Inadequate interoperable platforms also rank fifth, reflecting ongoing issues in integrating different BIM tools, as noted by experts E3 and E4.

All the experts emphasised the need for continuous development and training regarding BIM software and its users, due to the rapid pace of software updates and upgrades. In the survey, it ranked seventh. Low industry awareness of the benefits of BIM also took seventh place (RII 0.811). E9 noted that low industry awareness limits the client base of consultancy firms for BIM integration, which affects their BMs. "*Some Sri Lankan practitioners still trust manual methods over BIM outputs due to their extensive experience*" [E2]. Dependency on specific software ranks tenth (RII = 0.800), with E3 and E4 mentioning that being locked into one solution reduces flexibility and raises long-term costs.

Addressing these high-priority barriers is important in facilitating BIM adoption into BMs of construction consultancy firms in Sri Lanka.

4.2 ENABLERS OF INTEGRATING BIM INTO BUSINESS MODELS

Table 6 indicates the enablers for integrating BIM into business models of consultancy firms that carry points above 0.8.

Table 6: Significance level of enablers of BIM adoption

Enabler	RII Value	Rank
More international opportunities	0.956	1
Time saving	0.956	1
Support for gaining a competitive advantage	0.944	3
Proper training programmes for staff	0.944	3

Enabler	RII Value	Rank
Improved accuracy	0.928	5
Enhanced project visualisation	0.928	5
Clear BIM standards and protocols	0.917	7
Real-time collaboration among project stakeholders	0.894	8
Introduction of a digital transformation strategy	0.839	9
Adaptability to remote work & cloud collaboration	0.833	10
Improving the coordination of construction documents	0.833	10
Long-term Cost Savings & Higher Profitability	0.817	11
Growing awareness of BIM in global practices	0.811	12
Having effective client-consultancy relationships	0.811	12
Lower risk of human errors and rework	0.800	14

The top two enablers, with an RII of 0.956, were more international opportunities and time savings. Experts noted increased remote job possibilities related to BIM for Sri Lankan consultants from regions like the Middle East, the UK, and Australia. As E8 stated, "*BIM enables better coordination and reduces rework, saving time compared to manual methods.*"

Support for gaining a competitive advantage and proper staff training (RII 0.944) were the next top-ranked enablers. Experts emphasised that BIM adoption is key to securing international job opportunities with competitive advantages. Proper staff training is possible since "Sri Lanka has better committed resource persons to conduct proper training programmes of BIM" [E2, E7]. BIM's ability to enhance accuracy and project visualisation ranked fifth (RII 0.928). "BIM allows us better to understand the project scope, layout, and sequencing, so that we can make more informed decisions." [E3, E6].

Clear BIM standards and protocols, real-time collaboration, digital transformation strategy, remote/cloud work adaptability, and better document coordination ranked 7–10 (RII > 0.8). Experts noted BIM's globally recognised standards ensure quality and compatibility. "*Currently, most businesses, including us, think of digital transformation, so it will positively affect BIM adaptation.*" [E1]. In addition, "*Consultants demand more advanced documentation management strategies, for which BIM will help.*" [E8]. Long-term cost savings, global BIM awareness, better client-consultancy relationships, and reduced errors/rework ranked 11–14. E7, E8, and E10 highlighted BIM's role in minimizing waste and delays and improving financial outcomes. Experts also noted that BIM can be further strengthened due to established client-consultancy relationships.

Overall, the analysis shows that enablers focused on ROI and workforce capability can accelerate effective BIM integration into consultancy business models.

4.3 DISCUSSION

The study's findings support and extend the existing literature on BIM and BMs. Literature highlighted the BM innovation of consultancy firms with BIM as a key impact, as BIM drives firms to rethink workflows, project delivery, and management approaches. With BIM integration, firms deliver faster, higher-quality, and more cost-effective projects, improving competitive positioning.

This study highlights the key enablers that can support Sri Lankan consultancy firms in effectively integrating BIM into their BMs while addressing and overcoming major barriers. Key enablers include improved accuracy and enhanced credibility (E1, E3, E6), consistent with Zainon et al. (2018). Improved visualisation (RII 0.928) supports better client communication and real-time collaboration (RII 0.894), which builds trust among stakeholders and aligns with Abbasnejad et al. (2021) and Arayici et al. (2011). Critical success factors include training (RII 0.944), leadership support (RII 0.800), and clear standards (RII 0.917), which enable consultancies to maximise BIM's benefits, which were identified as barriers by Gardezi et al. (2014), Won et al. (2013) and Sun et al. (2015) in the literature.

Major barriers include high initial costs and training expenses (RII 0.861), consistent with Oesterreich and Teuteberg (2019) and Rogers et al. (2015). Technical issues, such as maintaining LOD (RII 0.922) and interoperability (RII 0.822), identified in this study align with the findings of Rogers et al. (2015) and Walasek and Barszcz (2017), which highlight operational-level reluctance and disruption of workflows. Organisational resistance (RII 0.778) and limited management support (RII 0.783) reflect organisational, cultural, and governance barriers, as mentioned by Gardezi et al. (2014) and Nguyen and Nguyen (2021), which are highly influenced to the adaptive nature of BMs.

5. CONCLUSIONS

This study aimed to explore the enablers and barriers to integrating BIM into the BMs of consultancy firms in Sri Lanka, highlighting the importance of BIM integration towards competitive advantages, operational efficiency, and enhanced value creation of BMs. When strategically aligned with BMs, BIM adoption significantly drives innovation and project success.

Key enablers include access to international job opportunities, skilled trainers, and alignment with global digital transformation trends, which provide direction to consultancy firms to reform their operations, enhance service offerings, and gain a competitive advantage. However, high upfront costs, resistance to change, and difficulty in recruiting and retaining BIM-skilled and trained staff are the main challenges. By strategically adopting enablers and proactively mitigating barriers, Sri Lankan consultancy firms can gain long-term value and operational efficiency by BIM integration to BMs as a strategic tool and competitive advantage.

Theoretical contributions include a deeper understanding of how BIM integration influences consultancy firms' BMs in a developing country context, concerning enablers and barriers. This study guide on the management of consultancy firms on the key factors that support and hinder BIM integration into their BMs, offering actionable insights.

The study focused on BIM adoption within the Sri Lankan construction industry, specifically targeting the business of quantity surveying consultancy firms. Future research should examine BIM-related business model elements to understand value creation and optimise operations. This will help firms align with digital transformation goals, ensuring sustained competitiveness in the evolving construction sector.

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INTEGRATION OF LEAN KAIZEN MODEL TO ENHANCE MATERIAL EFFICIENCY IN CONSTRUCTION PROJECTS: A LITERATURE REVIEW

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ABSTRACT

The construction industry, being a major consumer of materials, has increasingly prioritised optimising resource usage, thereby highlighting the importance of Material Efficiency (ME). Meanwhile, lean construction has emerged, promoting value maximisation and waste minimisation, with the Kaizen technique gaining attention for enhancing processes and reducing waste. This study aims to investigate the applicability of the Kaizen model to enhance the ME in construction projects. A comprehensive literature review was conducted, with the content analysis approach employed to analyse the data. The findings indicate that Kaizen can effectively address ME challenges in the construction sector by overcoming associated barriers. Key challenges to ME include a lack of training and awareness, high costs, excessive regulations, and inadequate technological integration, which can be mitigated through Kaizen techniques such as Poka-Yoke, Gemba walks, Jidoka, and 5S. Furthermore, integrating Kaizen with ME is hindered by cultural barriers, insufficient training and involvement, and limited resource availability. To address these challenges, the study recommends implementing industry-wide training and awareness initiatives, strengthening collaboration among project stakeholders, and introducing government incentives and regulatory support for projects prioritising ME and Kaizen practices. This research contributes to theoretical knowledge by bridging the gap in integrating Kaizen to enhance ME in construction and provides practical insights for facilitating its effective adoption through the mitigation of identified barriers.

Keywords: *Kaizen; Lean Construction; Material Efficiency.*

1. INTRODUCTION

The construction industry significantly influences a country's economic development (Ajayi & Oyedele, 2015). It is a major consumer of natural resources and a waste generator, utilising nearly 40% of global energy and contributing to 36% of CO2 emissions (United Nations Environment Programme, 2024). With the growing demand for raw materials driven by population growth, prioritising Material Efficiency (ME) in

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the construction industry is essential to achieving sustainable development (Safa et al, 2014). ME in construction involves optimising resource use to minimise waste, reduce costs, and environmental impact (Almakayeel et al, 2023). In addition, it focuses on improving the lifecycle performance and recyclability of materials (Kabirifar et al., 2020). As resource scarcity and environmental concerns have risen, the importance of ME has grown significantly (Peng et al., 2023). Higher ME levels result in less waste, lower expenses, and improved sustainability (Almusaed et al., 2024). Meanwhile, Babalola et al. (2019) revealed that lean construction techniques have also been linked to quality improvements, productivity gains, and waste reduction.

Lean construction models enhance efficiency and productivity by eliminating non-value-added activities, standardising procedures, and promoting continuous improvement (Ikuma et al., 2011). Karlsson and Tagesson (2021) highlighted the adaptation of lean manufacturing principles to construction, focusing on continuous improvement, waste reduction, and value enhancement. Tools such as the Last Planner System (LPS), Kaizen, Kanban, Integrated Project Delivery (IPD), and 3D BIM are employed to optimise production systems and boost ME (Babalola et al., 2019). The Kaizen model, originating from lean manufacturing, supports ME improvement through small, incremental changes and waste elimination at every project stage (Omotayo et al., 2018). In addition, Okpala et al. (2024) revealed that the Kaizen fosters cooperation among all parties and long-term sustainability of ME gains, supported by systems like total quality management, just-in-time (JIT), total productive maintenance, and small group work. ME is thus continuously assessed and enhanced throughout the project lifecycle with Kaizen's principles (Androniceanu et al., 2023).

The current construction industry faces significant challenges in material wastage and inefficiency (Kabirifar et al., 2020). Meanwhile, Kaizen techniques help to improve productivity and efficiency by identifying and eliminating waste (Cherrafi et al., 2019). Sundararajan and Terkar (2022) discuss how applying Lean-Kaizen principles in the manufacturing sector enhances overall productivity by increasing system efficiency and improving worker satisfaction. In the context of the construction sector, effective material management plays a crucial role in enhancing overall productivity and promoting sustainability (Rodríguez et al., 2022). Accordingly, the application of Kaizen principles has the potential to contribute to the overall productivity of construction projects by mitigating various challenges (Babalola et al., 2019). Therefore, the integration of ME with the Kaizen model could promote resource efficiency in construction projects (Androniceanu et al., 2023). Consequently, there is an industry need for effective integration of the Kaizen model of lean construction to enhance ME in construction. Numerous scholars have explored the implementation of lean concepts within the construction industry (Albalkhy & Sweis, 2020; Babalola et al., 2019), the application of the Kaizen model in lean construction (Omotayo et al., 2018; Syaputra & Aisyah, 2022), and ME in construction projects (Peng et al., 2023). Previous studies have also addressed Kaizen-based solutions for improving energy efficiency (Androniceanu et al., 2023) and enhancing production efficiency in the manufacturing sector (Sundararajan & Terkar, 2022). Furthermore, research has examined the implementation of the Kaizen model to improve performance in housing projects (Ikuma et al., 2011).

However, despite this extensive body of research, no studies have specifically investigated the use of the Kaizen model to enhance ME in construction projects. Moreover, there is a lack of in-depth analysis assessing how Kaizen techniques could

address ME challenges and the barriers to implementing Kaizen with ME in construction. Therefore, this study aims to fill this gap by investigating the applicability of the Kaizen model to enhance ME in construction projects, drawing upon existing literature. Its objectives are to investigate the key challenges of current ME practices in the construction industry, to assess how the techniques of Kaizen can be used to overcome ME challenges in construction projects, and to investigate the barriers of integrating Kaizen with ME in construction.

2. RESEARCH METHODOLOGY

A robust literature review process strengthens knowledge advancement by integrating insights from various empirical studies and developing a structured theoretical foundation (Kraus et al., 2022). Standalone literature reviews enable researchers to critically assess existing scholarship, uncover gaps, and propose directions for future research (Snyder, 2019). In particular, a narrative literature review method offers a detailed synthesis of previously published findings, presented in a descriptive format (Juntunen & Lehenkari, 2021). Accordingly, this study adopts a narrative literature review approach to investigate the applicability of the Kaizen model to enhance ME in construction projects. The literature search was conducted across three academic databases: (i) Google Scholar, (ii) Web of Science, and (iii) Scopus. The search strategy focused on key terms such as "Kaizen", "lean construction", "challenges" and "material efficiency". In selecting the sources, priority was given to journal articles and conference papers published within the past fifteen years to ensure contemporary relevance. Figure 1 illustrates the overall research process adopted in this study.

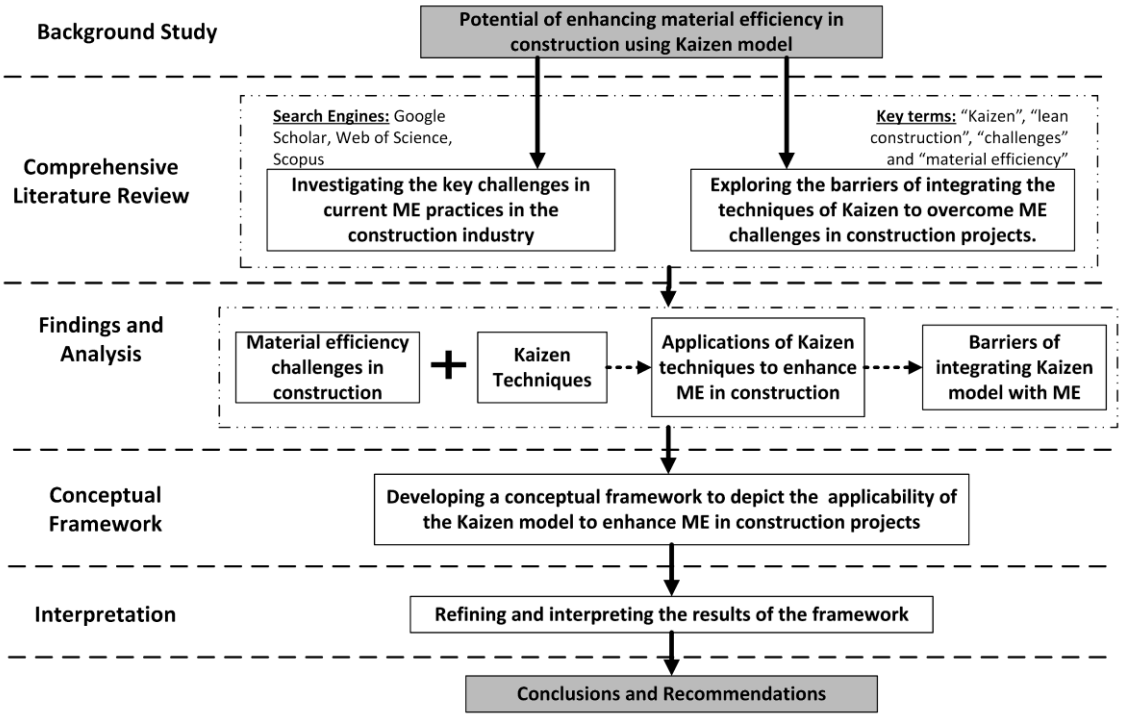


Figure 1: Research process

As presented in Figure 1, the research process commenced with a background study to establish a foundational understanding of the importance of improving ME in the

construction sector and the potential role of Kaizen techniques. Following this, a comprehensive literature review was undertaken to critically examine the existing knowledge on ME challenges in construction, Kaizen techniques, and integration barriers. The data collected were analysed using manual content analysis, a method particularly suited for categorising qualitative data and ensuring contextual sensitivity (Bengtsson, 2016). Manual coding allowed the findings to be systematically classified under major themes and sub-themes, enhancing the clarity and depth of the analysis. This approach is widely recognised for its ability to derive meaningful patterns from narrative data where statistical analysis is not feasible (Stemler, 2015). Thus, content analysis supported the structured exploration of how Kaizen can contribute to overcoming ME challenges in construction projects.

3. FINDINGS

This section explores the key challenges faced by the construction industry in improving ME, along with Kaizen techniques, and their applications to enhance ME in construction. Further, it identifies the barriers to integrating ME with the Kaizen model.

3.1 MATERIAL EFFICIENCY IN THE CONSTRUCTION INDUSTRY

The concept of ME optimises material utilisation in manufacturing processes, minimising waste and environmental impact while addressing material extraction and replenishment to promote sustainability (Ajayi & Oyedele, 2015). Broadly, ME can be defined as the ability to use materials in a way that maximises their functional utility while minimising the input of raw materials, energy, and waste generation (Kabirifar et al., 2020).

3.1.1 Challenges of ME in Construction

The construction industry faces numerous challenges and barriers in improving ME, which are critical for enhancing sustainability and reducing environmental impacts (De Sa & Korinek, 2021). Table 1 summarises notable challenges to implementing ME in the construction industry, identified by various past studies.

Table 1: Challenges of ME in construction

Challenge Category	Main Challenges	Authors (in code)														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Operational and Management	Poor material handling and storage	•						•			•			•		
	Lack of skilled labour leading to waste and rework					•									•	
	Inadequate site management practices													•		•
Design and Planning	Poor planning, scheduling and coordination		•		•								•			
	Design inefficiencies											•				•

Challenge Category	Main Challenges	Authors (in code)														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Technological	Lack of effective material procurement planning													•	•	
	Lack of technological integration			•		•						•				
	Lack of access to advanced technologies						•		•						•	
	Obsolete construction technologies											•			•	
Regulatory	Insufficient regulations			•			•	•								
	Lack of government incentives												•		•	
Supply chain related	Lack of availability of sustainable materials								•		•					•
	Poor relationships with suppliers				•					•				•		
	Scarcity of materials		•												•	
Knowledge and Cultural	Insufficient training and awareness on ME practices				•					•						
	Resistance to change												•			•
Financial Constraints	High initial cost in implementing ME solutions	•						•					•			
	Lack of financial support and incentives											•			•	

A:(Abdullah et al, 2024), B:(Ajayi & Oyedele, 2015), C:(Almakayeel, 2023), D:(Bhatia et al, 2020), E:(Brändström et al, 2024), F:(De Sa & Korinek, 2021), G:(Drenth, 2023), H:(Ongechi & Mandala, 2021), I:(De Pinto, 2023), J:(Safa et al, 2014), K:(Mehr & Omran, 2013), L:(Allwood et al., 2013), M:(Sogaxa & Simpeh, 2022), N:(Rodríguez et al., 2022), O:(Pauliuk et al., 2021)

According to Table 1, while planning and management challenges, such as design inefficiencies and poor material handling, are evident, deeper systemic issues like inadequate training and insufficient regulations also critically undermine ME efforts (Almakayeel, 2023). In addition, technological and financial challenges also hinder effective material management in construction projects. Overall, these challenges reflect not only operational shortcomings but also a broader need for cultural and institutional change to embed ME practices within the construction sector.

3.2 KAIZEN AND ITS TECHNIQUES

Lean, originating from the Toyota Production System, is a systematic approach to continuous improvement by eliminating waste and enhancing value (Albalkhy & Sweis, 2020). Lean Construction, first proposed by Koskela, enhances value by eliminating waste and fostering trust and open communication within organisations (Ikuma et al., 2011). The concept of Kaizen, described in lean, was rooted in Japanese philosophy and emphasises continuous improvement through small, incremental changes (Singh & Singh, 2013). It is focused on continuous quality improvement that involves all stakeholders in identifying problems and collaboratively implementing solutions (Jamadar et al., 2021). This concept centres on eliminating non-value-added activities through small, incremental changes to enhance productivity, quality, and efficiency (Cherrafi et al., 2019).

Kaizen techniques focus on continuous, incremental improvements in manufacturing processes, emphasising accountability, value-added analysis, and setting achievable cost-reduction targets within work cells (Sundararajan & Terkar, 2022). These techniques are considered attractive performance improvement methods in practice, as their application costs are low (Okpala et al., 2024). In this study, ten specific Kaizen techniques were identified based on their frequency of mention in the existing literature and their relevance to improving material efficiency in construction. Table 2 presents a summary of the main Kaizen techniques along with their respective sources.

Table 2: Techniques of Kaizen

Techniques of Kaizen	Authors (in code)									
	A	B	C	D	E	F	G	H	I	J
Value stream mapping (VSM)	●	●			●		●	●	●	●
Just In Time (JIT)	●	●			●	●	●		●	
Gemba	●	●		●	●				●	
Plan Do Check Act (PDCA)	●		●				●		●	●
5S					●		●	●	●	●
Muda	●	●			●	●	●			
Poka-yoke	●	●			●		●			
5 Whys		●					●			
Jidoka		●					●			
Andon		●					●			

A:(Cherrafi et al., 2019), B:(Galzignato, 2018), C:(Al-Hyari et al., 2019), D:(Kumar et al., 2015), E:(Androniceanu et al., 2023), F:(Jamadar et al., 2021), G:(Okpala et al., 2024), H:(Önay & Seçkiner, 2024), I:(Podlesny, 2024), J:(Syaputra & Siti Aisyah, 2022)

In the context of construction, Kaizen techniques focus on structured events designed to optimise processes, enhance productivity, standardise workflows, and reduce lead times (Ikuma et al., 2011). As per Table 2, the most highlighted techniques include Gemba, JIT and VSM as they are consistently recognised for their effectiveness in lean construction practices. PDCA and 5S are also considered crucial techniques for identifying and solving problems, ensuring continuous improvement.

3.3 ENHANCING THE MATERIAL EFFICIENCY IN CONSTRUCTION PROJECTS BY INTEGRATING THE KAIZEN TECHNIQUES

Integrating the Kaizen model with ME in construction projects is important as it supports sustainable practices and waste reduction (Önay & Seçkiner, 2024). Sustainable construction prioritises reducing environmental impacts and conserving resources, which relates to ME (Almakayeel et al, 2023). Hence, the synergy between Kaizen and ME can significantly contribute to advancing efficiency in construction practices (Podlesny, 2024). Table 3 summarises the applications of Kaizen techniques in overcoming ME challenges in construction projects.

Table 3: Integrating Kaizen techniques to enhance ME in construction

Main Challenges	Kaizen Techniques	Applications of Kaizen techniques in enhancing ME
Poor material handling and storage	Poka-yoke	Organise tools and materials to reduce time wasted and avoid damage.
Lack of skilled labour leading to waste and rework	5 Whys	Use visual guides or safety triggers to avoid wrong material usage.
Inadequate site management practices	Gemba	Use iterative planning to constantly refine scheduling and procurement strategies.
Poor planning, scheduling and coordination	Jidoka	Identify root causes of procurement delays or design rework.
Design inefficiencies	PDCA	Include real-time observations in site supervision.
Lack of effective material procurement planning	5S	Conduct pilot tests and gradually integrate new technologies in cycles.
Lack of technological integration	Muda	Use real-time digital dashboards to alert teams of tech failures or resource overuse.
Lack of access to advanced technologies	Andon	Create feedback loops between construction professionals and policymakers through pilot projects.
Obsolete construction technologies	VSM	Eliminate waste from over-ordering or long transport routes.
Insufficient regulations	JIT	Track material delivery issues in real time with visual boards.
Lack of government incentives		Create structured, visual environments that improve learning habits.
Lack of availability of sustainable materials		Implement small-scale training and improvement trials to reduce resistance.
Poor relationships with suppliers		Identify and cut unnecessary costs through waste elimination.
Scarcity of materials		
Insufficient training and awareness on ME practices		
Resistance to change		
High initial cost in implementing ME solutions		

Main Challenges	Kaizen Techniques	Applications of Kaizen techniques in enhancing ME
Lack of financial support and incentives		
Authors: (Omotayo et al., 2018), (Cherrafi et al., 2019), (Ikuma et al., 2011), (Jamadar et al., 2021), (Androniceanu et al., 2023), (Arya & Jain, 2014), (Syaputra & Aisyah, 2022), (Önay & Seçkiner, 2024), (Barbosa et al., 2023), (Kumar et al., 2015), (Podlesny, 2024), (Al-Hyari et al., 2019)		

As summarised in Table 3, various Kaizen techniques can be applied to address ME challenges in construction. For instance, the 5S technique directly contributes to enhancing ME by improving the organisation of material storage and handling areas. By systematically sorting and arranging materials, maintaining cleanliness, and standardising storage practices, 5S reduces the time wasted in searching for materials, minimises the risk of material damage, and prevents unnecessary reordering due to misplaced stock (Önay & Seçkiner, 2024). Jamadar et al. (2021) reported that implementing 5S in construction sites not only improved workspace organisation but also led to measurable reductions in material wastage, thereby enhancing overall ME. This demonstrates how the practical application of Kaizen techniques can achieve significant improvements in construction resource management.

Accordingly, lean construction methods, when implemented correctly, hold great potential for reducing waste and resource consumption, thus enhancing the sustainability of building projects (Ikuma et al., 2011). The integration of Kaizen approaches further augments the construction process, particularly by improving lead times and workflow efficiency (Barbosa et al., 2023). This highlights the critical role of lean and continuous improvement models in driving more efficient and productive construction practices. To encourage continuous improvement in construction, professionals must gain a comprehensive understanding of Kaizen concepts (Omotayo et al., 2018). The integration of Kaizen techniques offers significant opportunities to improve ME and sustainability in construction projects. Nevertheless, the construction industry faces several obstacles in adopting the Kaizen model (Albalkhy & Sweis, 2020).

3.3.1 Barriers to the Integration of the Kaizen Model with Material Efficiency

Integrating ME with Kaizen methodologies faces several barriers that hinder effective implementation (Caldera et al., 2019). Understanding these obstacles is crucial for successfully implementing Kaizen in the construction industry. Table 4 summarises some main barriers identified in previous research.

Table 4: Barriers to the integration of Kaizen with ME

ME and Kaizen Integration Barriers	Authors								
	A	B	C	D	E	F	G	H	I
Cultural Barriers		●	●	●	●	●			●
Lack of Training and Involvement	●		●	●	●			●	●

ME and Kaizen Integration Barriers	Authors								
	A	B	C	D	E	F	G	H	I
Limited resources	●	●	●	●	●		●		
Leadership Commitment						●		●	●
Poor Administration							●	●	●
Financial Constraints					●				●
Limited Understanding of Kaizen Principles	●	●							
Regulatory Challenges						●			
Need for Continuous Evaluation						●			
Uncontrolled Inventory									●

A:(Arya & Jain, 2014), B:(Caldera et al., 2019), C:(Cherrafi et al., 2019), D:(Gaikwad & Sunnapwar, 2019), E:(Kabzhassarova et al., 2021), F:(Karlsson & Tagesson, 2021), G:(Kurdve & Bellgran, 2020), H:(Singh & Singh, 2023), I:(Syaputra & Siti Aisyah, 2022)

It is evident from Table 4 that integrating ME with Kaizen is a challenging endeavour. The most common barriers identified include cultural barriers, lack of training and involvement and insufficient resources. Previous studies have highlighted these challenges as the most prominent compared to less significant barriers such as financial constraints, regulatory challenges, and the need for continuous evaluation. For instance, the cultural barriers, including resistance to change and traditional mindsets, largely hinder the implementation of Kaizen techniques in ME practices (Kabzhassarova et al., 2021). To fully attain the benefits of Kaizen, stakeholder participation and effective management are vital (Pauliuk et al., 2021). Al-Hyari et al. (2019) emphasise that a cooperative approach involving all stakeholders is necessary for the successful implementation of Kaizen in construction projects.

4. CONCEPTUAL FRAMEWORK

A conceptual framework serves as a structured guide for exploring the research problem, often developed through a critical review of relevant literature (Juntunen & Lehenkari, 2021). It outlines key factors and relationships in the research scope and can be presented either narratively or visually using flowcharts, mind maps or diagrams (Gaikwad & Sunnapwar, 2019). In line with this, Figure 2 presents the conceptual framework developed to examine the applicability of the Kaizen model in improving ME in construction projects.

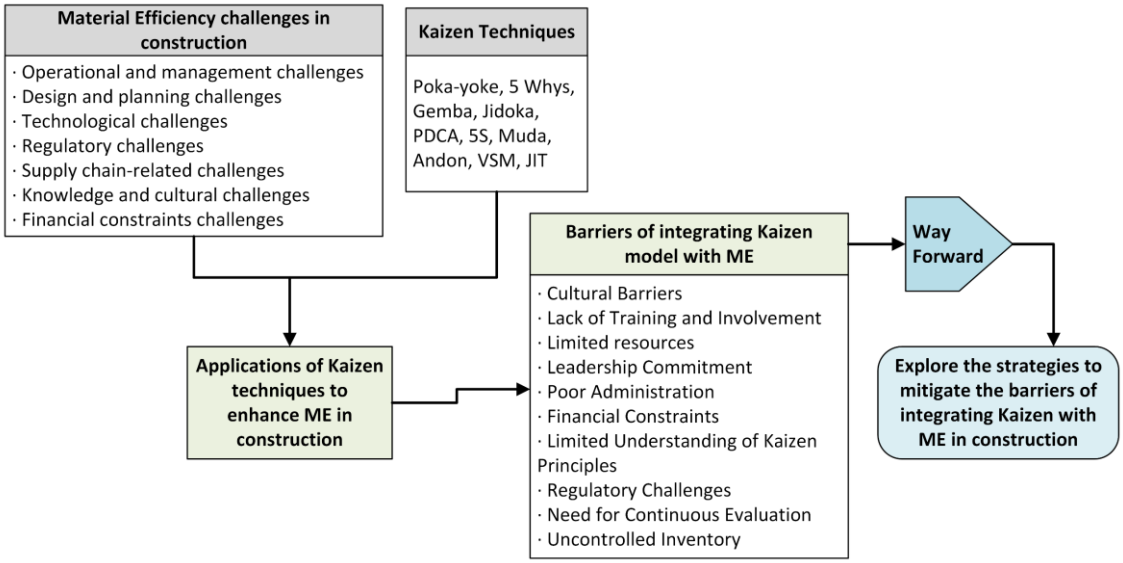


Figure 2: Conceptual framework

As illustrated in Figure 2, challenges related to ME in construction projects can be addressed through the implementation of the Kaizen concept, which emphasises continuous improvement via incremental changes. Figure 2 initially depicts the key ME challenges in construction alongside the Kaizen techniques applicable to address them. By integrating these two aspects, it demonstrates the applications of Kaizen techniques to mitigate ME-related issues. Following this integration, Figure 2 outlines the barriers to implementing Kaizen within ME practices. Finally, it presents the potential future directions as to explore the strategies to overcome the barriers associated with this integration. The application of Kaizen techniques helps to reduce errors in material handling, thereby contributing to waste minimisation and resource conservation (Cherrafi et al., 2019). Furthermore, the adoption of the Kaizen model supports the achievement of sustainability goals within the construction industry (Omotayo et al., 2018). However, integrating Kaizen into ME practices require careful consideration, as several barriers, including cultural barriers and limited understanding of Kaizen among stakeholders, may impede this process (Caldera et al., 2019; Kabzhassarova et al., 2021). Consequently, future research should focus on identifying and developing effective strategies to overcome these barriers and facilitate the successful application of Kaizen techniques to enhance ME in the construction sector.

5. CONCLUSION AND RECOMMENDATIONS

This study aims to investigate the applicability of the Kaizen model to enhance ME in construction projects based on existing literature. The findings suggest that the integration of the Kaizen techniques and ME holds significant potential for the construction industry, particularly in terms of reducing material waste and promoting sustainability. Moreover, it is highlighted that the importance of continuous improvement in construction processes, where the implementation of Kaizen can drive efficiencies and enhance the overall performance of construction projects. However, barriers such as cultural barriers, limited training and understanding, and poor administration need to be addressed to fully realise the benefits of this integration. Accordingly, it is recommended that industry-wide training and awareness programs be implemented, promote stronger collaboration

between all project stakeholders, from planners to suppliers, and offer government incentives and regulatory support for projects that prioritise ME and Kaizen techniques. This study contributes to theory by extending existing knowledge on lean construction by specifically investigating the applicability of the Kaizen model to enhance ME in construction projects, an area that has received limited focused attention in prior research. In terms of industrial contribution, this study highlights the importance of adopting Kaizen techniques to improve ME, identifies the key barriers hindering their integration in construction practices, and proposes actionable recommendations for industry stakeholders to enhance resource efficiency, sustainability, and overall project performance. Considering the limitations of this study, primarily its reliance on a literature review, there is potential bias in article selection and exclusion of non-English publications, which may not fully capture the relevant findings. Consequently, the generalisability of the results is limited. Nevertheless, despite these limitations, this study can serve as a benchmark for future in-depth research in this area.

Further studies are directed to explore the strategies to overcome the barriers to integrating Kaizen and ME in construction, encouraging its practical application. Methodologies such as case studies and surveys can be adopted to examine the real-world applications of Kaizen in ME practices and to capture stakeholder perceptions of this adoption. Additionally, comparative studies between developing and developed countries are recommended to understand how contextual factors influence the integration of Kaizen and ME in construction, thus guiding targeted implementation strategies globally.

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INTEGRATION OF THE CONCEPT OF SOCIAL PROCUREMENT INTO CONSTRUCTION PROCUREMENT IN SRI LANKA

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ABSTRACT

Construction procurement significantly influences project outcomes in Sri Lanka, yet current practices continue to prioritise cost and efficiency over long-term social impact. This imbalance has created a gap in addressing social needs through public projects, highlighting the relevance of Social Procurement as an approach that embeds social value into procurement decisions. Social procurement offers the potential to promote equity, inclusion, and community development through construction activities. Despite its growing application globally, social procurement is yet to be implemented in Sri Lanka. Thus, this study aims to investigate how to integrate social procurement into the existing procurement methods in Sri Lanka. It specifically examines the four recognised types of social procurement, and the challenges associated with each. Using a qualitative choice, data was gathered through 15 semi-structured interviews and analysed through content analysis. The findings reveal that all four types can be implemented in Sri Lanka, though their integration is influenced by type-specific and shared challenges. Common barriers identified across all types include limited knowledge and training, difficulties in engaging marginalised communities, and restricted access to funding. The study also establishes clear links between social procurement types and Sri Lanka's dominant procurement models. Importantly, the findings suggest that implementation should begin with Type 1 and Type 2, which offer the most immediate feasibility. Overall, the study concludes that while social procurement presents significant potential, its success depends on a phased, locally adapted strategy supported by strong policy direction and institutional commitment.

Keywords: *Construction; Procurement; Social Procurement; Socio-economic; Sri Lanka.*

1. INTRODUCTION

Over the years, industries, including construction, have undergone significant transformation, and so has the concept of procurement (Kim & Kim, 2024). As the construction industry continues to advance, procurement methods have progressively shifted from traditional approaches to more sophisticated systems such as management-oriented, integrated, and collaborative procurement strategies (Nguyen & Le, 2022). In

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this context, construction procurement refers to the process of acquiring knowledge, manpower, equipment, or administrative essentials to accomplish a project's objectives (Patel et al., 2025). Furthermore, the establishment of connections among different stakeholders, the determination of the persons in charge, and the determination of the roles and responsibilities of each individual regarding risks also come under this process (Zhao et al., 2022). Generally, procurement practices prioritise the bid with the lowest cost over other aspects (Windapo et al., 2020). However, in recent decades, these practices have experienced a marked shift, reflecting a growing emphasis on sustainability and long-term value creation within the industry (Irfan et al., 2022).

Within the broader framework of sustainability, social sustainability holds a critical position, and under that, the construction industry plays a pivotal role in advancing societal development through the provision of essential infrastructure and public services (Windapo & Moghayedi, 2020). Despite this, existing construction procurement methods often demonstrate limited social impact and insufficient alignment with sustainable principles (Lou et al., 2023). In response, now, there is growing recognition of the value of integrating sustainable procurement models such as Social Procurement (SP) into construction procurement (LePage & Renaerts, 2023). Sustainable procurement integrates environmental, social, and economic considerations into purchasing decisions to achieve long-term value, whereas SP specifically targets the creation of social value (Loosemore et al., 2019; Ludlow, 2016). SP redirects procurement expenditure towards community benefits, primarily by creating employment and training opportunities for marginalised populations such as indigenous communities, refugees, and socially disadvantaged individuals (Loosemore, 2016). It places a strong emphasis on social values in addition to economic gains (Ludlow, 2016). However, implementation remains low across countries due to several barriers. These include limited awareness of SP practices, inadequate resources, training, and technical skills of marginalised communities, and lack of leadership and supporting policies, (Natoli et al., 2023; Troje & Andersson, 2020). Nonetheless, effective SP implementation can create economic value and foster meaningful social outcomes in construction (Loosemore et al., 2019).

When considering construction procurement in Sri Lanka, traditional methods continue to dominate, with the separated method being the most widely adopted, followed by Design and Build under the integrated procurement category (Niriella & Gamage, 2022). Despite increasing global emphasis on sustainability, the focus on sustainable procurement practices within the Sri Lankan construction industry remains limited. However, emerging examples demonstrate a gradual shift. Projects in Sri Lanka such as the Crow Island Beach Park have successfully incorporated sustainable procurement approaches, notably through community-based participatory design (CBPD), which emphasises local engagement and social inclusion (Fernando et al., 2024). Similarly, the ‘Gemidiriya’ project effectively involved the local community in road construction (Yalegama et al., 2016). Such projects create social value, and as a developing country, Sri Lanka stands to benefit significantly from adopting more sustainable procurement approaches. SP represents another viable method in this regard, and there is a clear practical need for its integration into the local construction context.

With respect to the literature gap, this study is the first to explore the integration of SP into the existing procurement methods in Sri Lanka. While several studies have examined SP integration in other countries such as Loosemore (2016) in the United Kingdom, Troje (2021) in Sweden, and Loosemore et al. (2020) in Australia, no study has been conducted

within the Sri Lankan context. Moreover, this study contributes to the limited body of work that distinguishes between different types of SP, a topic addressed only briefly in studies such as Loosemore and Reid (2018), Loosemore et al. (2022), and Furneaux and Barraket (2014). Furthermore, when considering the challenges of SP, several studies including Loosemore et al. (2019) and Natoli et al. (2023) have explored that. However, no study has classified these into each type, and this will be the first.

Accordingly, this study aims to investigate how to integrate SP into the existing procurement methods in Sri Lanka. To achieve this, the study is guided by three objectives: (i) to investigate the limitations to socio-economic advancement in commonly used procurement methods in Sri Lanka; (ii) to assess the types of SP applicable to the Sri Lankan context; and (iii) to examine the specific challenges associated with integrating each type of SP. The remainder of the paper comprises a literature review, methodology, research findings, discussion and finally, the conclusions from the study.

2. LITERATURE REVIEW

This section further explores the concepts of construction procurement and social procurement. It lays the foundation for the findings of the study.

2.1 LIMITATIONS OF EXISTING PROCUREMENT METHODS

Construction procurement methods range from traditional separated approaches to integrated and management-oriented models, extending further to Public-Private Partnerships (PPPs) and emerging innovative procurement strategies (Lou et al., 2023). Separated, integrated, and PPP methods often struggle with cost control, time management, and stakeholder coordination (Eriksson et al., 2019). According to Love et al. (2013), in Australia, nearly 12% of PPP projects experienced significant cost overruns, and 13% encountered schedule delays. Additionally, procurement frameworks like Design and Build often fail to promote genuine collaboration between stakeholders (Lou et al., 2023). Beyond such inefficiencies, existing procurement methods frequently fall short in addressing socio-economic advancement. These methods lack structured mechanisms to promote inclusivity, community engagement, and long-term societal value (Eriksson et al., 2019; Lou et al., 2023). These systems often prioritise financial efficiency over social impact, resulting in marginalisation, gender disparity, and missed opportunities for community empowerment (Windapo et al., 2020). Moreover, rigid procurement structures frequently overlook cultural sensitivity and sustainability, risking the erosion of local heritage and community values (Selviaridis et al., 2023). Thus, in response, the industry is gradually embracing more sustainable alternatives such as SP to improve transparency, equity, and long-term resilience.

2.2 THE CONCEPT OF SOCIAL PROCUREMENT

The concept of SP is recognised as a strategic approach to procurement that extends beyond traditional value-for-money considerations by deliberately aiming to generate positive social outcomes. Furneaux and Barraket (2014) defined SP as the intentional acquisition of goods and services to achieve both direct and indirect social outcomes, while Loosemore (2016) emphasised its role in creating employment and training opportunities for marginalised groups. Moreover, Willar et al. (2020) framed SP as a multidimensional method aligned with sustainability goals integrating cost efficiency, capability, and minimal environmental and social harm. Importantly, SP addresses the

often-neglected social pillar of sustainability, shifting procurement from a purely transactional function to a catalyst for community empowerment and long-term societal value (Hutchins & Sutherland, 2008). It promotes equity, diversity, and inclusion by utilising socially responsible objectives in procurement decisions, empowering marginalised groups such as refugees, people with disabilities, ex-convicts, and long-term unemployed individuals (Troje, 2018). These distinctive features of SP lie in its socio-economic parameters, which include local employment generation, workforce participation of disadvantaged groups, support for social enterprises, and promotion of community well-being, which go beyond the parameters of sustainable procurement, such as resource efficiency, emissions reduction, and responsible supply chains (Loosemore et al., 2019; Ludlow, 2016). Likewise, SP challenges existing traditional procurement methods and positions itself as a necessary reform in sectors like construction, where social impact has traditionally been underemphasised.

2.3 TYPES OF SOCIAL PROCUREMENT

Researchers have identified various types of SP, each addressing distinct social objectives and offering different levels of applicability. Table 1 illustrates these types.

Table 1: Types of SP as per Furneaux and Barraket (2014) and Loosemore and Reid (2018)

Type	Applicability within the industry
Type 1: Procurement of Social Services	Directly involves contracting third-sector organisations to deliver services with clear social outcomes (e.g., health, welfare).
Type 2: Procurement of Public Works with Indirect Social Outcomes	Embeds social value within broader infrastructure or capital works projects.
Type 3: Allocation of Work to Social Enterprises	Dedicates a portion of the procurement to social enterprises to enable workforce participation of disadvantaged groups.
Type 4: Corporate Social Responsibility (CSR)	Focuses on ethical supply chain management, labour rights, and equitable working conditions.

All four types of SP aim to generate social value through purchasing decisions. Types 1 and 3 focus on direct social outcomes, while Types 2 and 4 achieve indirect impacts (Furneaux & Barraket, 2014). Types 1 and 2 are contract-focused (what is being bought), whereas Types 3 and 4 are tender-focused (who is delivering), highlighting a key distinction in procurement strategy (Loosemore & Reid, 2018). Their effective implementation depends on context-specific strategies, stakeholder engagement, and institutional support.

2.4 INTEGRATION OF SOCIAL PROCUREMENT TO EXISTING CONSTRUCTION PROCUREMENT METHODS IN SRI LANKA

Despite the global transition towards sustainable procurement, Sri Lanka's construction industry remains anchored in traditional methods (Niriella & Gamage, 2022). These methods emphasise cost-efficiency over broader socio-economic goals, often neglecting social equity, local employment, and community development. However, studies highlight that the uptake of sustainable procurement, including SP, remains limited in Sri Lanka due to institutional rigidity and lack of policy enforcement (Ekanayake et al., 2024). According to the Central Bank of Sri Lanka (2024), the national unemployment

rate stood at 4.7%, highlighting a need for employment-generating strategies, particularly in sectors like construction that hold significant potential for labour absorption. For this, SP offers a promising solution by embedding social objectives such as inclusive hiring, local enterprise engagement, and skills development directly into procurement practices. Furthermore, with the industry grappling with cost overruns, inefficiencies, and limited stakeholder inclusion (Kavinda & Gallage, 2024), adopting SP offers a way to align project delivery with national goals for inclusive growth. This highlights the need to integrate SP within Sri Lanka's construction procurement practices.

3. METHODOLOGY

This study employed a qualitative research choice. It was deemed appropriate due to the exploratory nature of the research, which seeks to uncover in-depth insights into the experiences, perceptions, and contextual factors influencing SP implementation in Sri Lanka. As noted by Hammarberg et al. (2016), a qualitative choice is particularly valuable when the research aims to investigate meanings, values, and complex processes that are not easily quantifiable. Unlike quantitative approaches that emphasise measurable variables, qualitative inquiry allows for the capture of social, institutional, and behavioural dynamics, which are critical in understanding the evolving nature of SP (McCusker & Gunaydin, 2014). To collect data, semi-structured expert interviews were conducted. This method was selected as it offers a flexible yet focused format, allowing researchers to guide the conversation while also enabling participants to express their perspectives freely (Kallio et al., 2016). Thereafter, the collected data were analysed using manual content analysis as it critically compensates for the interpretive limitations of automated tools by capturing nuanced sentiment and contextual meaning that algorithms often misclassify (Anastasiei & Georgescu, 2020).

A purposive sampling technique was adopted to select participants who possessed specific expertise relevant to the research objectives to ensure that the selected sample reflects the depth of knowledge required to address the research questions (Campbell et al., 2020). A systematic approach was used to determine data saturation, defined as the point where no new second-level categories emerged across two consecutive interviews (Hennink et al., 2019). Saturation was reached by the 13th interview, with no new codes from the 14th and 15th. Thus, a total of 15 expert interviews of 40 to 50 minutes were conducted. A set of selection criteria comprising of mandatory and additional qualifications were set to identify the experts for the interviews ensuring the purposive sampling technique. The experts' profiles are presented in Table 2.

Table 2: Experts' profiles with selection criteria

Code	Designation	Organisation	Mandatory qualifications (At least 2 of 3)			Additional qualifications (At least 4 of 6)					
			Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
R1	PhD Candidate	Research, Consultant	x	✓	✓	✓	x	✓	x	✓	✓
R2	Quantity Surveyor	Contractor	✓	✓	x	✓	✓	x	✓	✓	✓
R3	Quantity Surveyor	Contractor	✓	✓	x	✓	✓	x	✓	✓	✓

Code	Designation	Organisation	Mandatory qualifications (At least 2 of 3)			Additional qualifications (At least 4 of 6)					
			Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
R4	Civil Engineer	Contractor	✓	✓	x	✓	✓	x	✓	✓	✓
R5	Company Director	Client	✓	✓	x	✓	✓	x	✓	x	✓
R6	Senior Lecturer	Client, Research, Consultant	✓	✓	✓	✓	✓	✓	x	✓	✓
R7	Director	Contractor	✓	✓	x	✓	✓	x	x	✓	✓
R8	Director	Contractor	✓	✓	x	✓	✓	x	x	✓	✓
R9	Professor	Research	✓	✓	✓	✓	✓	✓	x	✓	✓
R10	Director	Contractor	✓	✓	x	✓	✓	x	✓	✓	✓
R11	SP Consultant	Consultant	✓	✓	x	✓	x	x	✓	✓	✓
R12	SP Consultant	Consultant	✓	✓	x	✓	✓	x	✓	✓	✓
R13	Director	Contractor	✓	✓	x	✓	✓	x	✓	✓	✓
R14	Social Entrepreneur	Client	✓	✓	x	✓	✓	x	x	✓	✓
R15	Sr. SP Consultant	Consultant	✓	✓	x	✓	✓	x	✓	✓	✓

Mandatory Qualifications

- Q1 - At least 5 years of experience in industry/academia/research (Built Environment)
- Q2 - At least 3 years of experience in industry/academia/research (SP or a related field)
- Q3 - PhD candidate or holder in SP or a related field

Additional Qualifications

- Q4 - A Bachelors' Degree in Built Environment
- Q5 - A Postgraduate Qualification in Built Environment
- Q6 - At least 2 indexed journal publications in SP or related area
- Q7 - Professional qualifications in Built Environment
- Q8 - Involved in at least 2 Social Procurement related projects (Research/ Industry)
- Q9 - Interest in Social Procurement

4. FINDINGS AND ANALYSIS

This section presents and analyses the findings of the expert interviews covering the aim and objectives of the study. The pattern-matching is presented in the 'Discussion' section.

4.1 LIMITATIONS TO SOCIO-ECONOMIC ADVANCEMENT IN PROCUREMENT METHODS COMMONLY USED IN SRI LANKA

Experts were first asked to identify the commonly used procurement methods in Sri Lanka. In response, they identified the separated, integrated, and PPP methods as the most prevalent. Thereafter, they were questioned on the limitations of these methods to socio-economic advancement. The findings based on their responses are presented in Table 3.

Table 3: Integration of SP into the existing procurement methods in Sri Lanka

Method	Limitations of existing methods	Suitable SP types	Challenges to SP integration
Separated	[P1], [P2], [P3], [P4], [P5], [P6], [P7], [P8], [P9], [P10], [P13], [P14], [P19], [P20], [P21], [P22]	Type 1	[C5], [C8], [C12], [C13], [C18], [C20], [C22], [C29]
		Type 2	[C1], [C2], [C3], [C5], [C8], [C11], [C12], [C13], [C14], [C17], [C22], [C23], [C20], [C24], [C25], [C26], [C29]
		Type 3	[C2], [C5], [C6], [C9], [C10], [C11], [C12], [C15], [C16], [C18], [C19], [C21], [C22], [C24], [C25], [C26], [C28]
		Type 4	[C2], [C4], [C5], [C7], [C12], [C14], [C18], [C21], [C22], [C26], [C27], [C28]
Integrated	[P1], [P2], [P4], [P5], [P6], [P7], [P8], [P9], [P10], [P11], [P14], [P15], [P16], [P17], [P18], [P23]	Type 2	[C1], [C2], [C3], [C5], [C8], [C11], [C12], [C13], [C14], [C17], [C22], [C23], [C20], [C24], [C25], [C26], [C29]
		Type 4	[C2], [C4], [C5], [C7], [C12], [C14], [C18], [C21], [C22], [C26], [C27], [C28]
PPP	[P1], [P2], [P3], [P4], [P5], [P6], [P7], [P8], [P9], [P10], [P12], [P13], [P14], [P19], [P21], [P23]	Type 2	[C1], [C2], [C3], [C5], [C8], [C11], [C12], [C13], [C14], [C17], [C22], [C23], [C20], [C24], [C25], [C26], [C29]
		Type 4	[C2], [C4], [C5], [C7], [C12], [C14], [C18], [C21], [C22], [C26], [C27], [C28]

Colour Codes - [Black] Identified from past literature; **[Blue]** Common to all 3 types; **[Red]** Newly suggested by the experts; **[Green]** Common to all 4 SP types; **[Purple]** Newly suggested by experts

Codes for Limitations to Socio-economic Advancement of Existing Procurement Methods - [P1] Unequal development and opportunities; **[P2]** Insufficient focus on social outcomes/growth; **[P3]** Less community engagement; **[P4]** Social marginalisation; **[P5]** Prioritise the lowest price over sustainability; **[P6]** Inequity; **[P7]** Low support for small/med; **[P8]** Low stakeholder engagement; **[P9]** The disturbance of public routes and needs; **[P10]** Subjective evaluation of social criteria; **[P11]** Inadequate evaluation of subcontractors; **[P12]** Lacks strong institutionalisation; **[P13]** Reduced social inclusivity; **[P14]** Lacks public trust; **[P15]** Lack of empowerment; **[P16]** Earnings manipulation; **[P17]** Limit long-term growth for workers; **[P18]** Prioritisation of regulations over social value; **[P19]** Limited citizen influence; **[P20]** Job insecurity; **[P21]** Disputes among the parties; **[P22]** Low chances for the local community; **[P23]** Inability to achieve employee satisfaction

Codes for Challenges to SP Integration - [C1] Lack of meaningful collaboration; **[C2]** Lack of leadership and internal policy; **[C3]** Limited understanding of SP; **[C4]** Low capacity of supply chain partners and small suppliers; **[C5]** Insufficient resources, training, and technical skills; **[C6]** High costs and administrative burden; **[C7]** Lack of universal frameworks and consistent policies; **[C8]** Trust issues of the community towards the government **[C9]** Lack of clarity and consistency in integrating social value into procurement; **[C10]** Difficulty in measuring and monitoring social impacts; **[C11]** Fragmented organisational structure/misalignment between goals; **[C12]** Limited access to funding/financial support; **[C13]** Cultural and language barriers; **[C14]** Challenges in obtaining licenses/certifications; **[C15]** Competitive pressure/preference for larger suppliers;

[C16] Constraints from trade agreements/internal policies; **[C17]** Barriers to subcontractor engagement and compliance with social goals; **[C18]** Geographical/logistical challenges in matching suppliers to projects; **[C19]** Myths and misconceptions about social enterprise costs and competitiveness; **[C20]** Inclusivity and fair compensation; **[C21]** Risk of tokenism in SP implementation; **[C22]** Challenges in engaging marginalised communities; **[C23]** High costs for small suppliers to meet standards and requirements; **[C24]** Limited visibility and marketing opportunities for social enterprises; **[C25]** Weak capacity for social enterprises to measure outcomes; **[C26]** Risk aversion and reluctance to change procurement culture and processes; **[C27]** Poorly designed policies and programmes; **[C28]** Disconnect between organisational purposes and purchasing practices; **[C29]** Legal and administrative delays

The literature review identified 20 limitations to socio-economic advancement, with experts contributing three additional ones (highlighted in red in Table 3). Out of the 23, several were recognised as common to all three procurement methods (highlighted in blue in Table 3). These included unequal development and opportunities, limited focus on social outcomes, social marginalisation, prioritisation of lowest-cost bids over sustainability, weak support for SMEs, low stakeholder engagement, disruption to public needs, unclear evaluation of social criteria, and a lack of public trust. As R3 noted, *"The system still rewards the cheapest bid, not the most responsible one."* R6 added, *"There is no real mechanism for including small players or hearing community voices."* In addition, some limitations were found to be method specific. For integrated procurement, experts highlighted issues such as inadequate subcontractor evaluation, and earnings manipulation, which limit long-term workforce development. In PPPs, the absence of strong institutionalisation was identified as a unique challenge, with R9 stating, *"Without institutional checks, social outcomes in PPPs often become secondary."*

4.2 TYPES OF SOCIAL PROCUREMENT THAT CAN BE USED IN SRI LANKA

Experts were requested to identify use of each SP type (As in Table 1) within the Sri Lankan context for commonly used procurement methods. Firstly, experts highlighted that all four types of SP hold potential applicability within the Sri Lankan construction sector. However, their implementation is not expected to occur uniformly. Experts unanimously agreed that Type 1 and Type 2 offer the most practical starting points as illustrated in Table 3. These types align with existing procurement frameworks and allow for immediate community engagement through services such as site maintenance, landscaping, and welfare facilities. R15 stated, *"We can begin with allocating non-technical or supportive services to community-based organisations without disrupting core construction processes."* Similarly, R1 said, *"You do not need to overhaul the system to start using SP. Just tweak what is already happening, bring in the community for smaller roles and build from there."* Furthermore, experts highlighted that Type 2 practices have already been implicitly applied in projects such as the *Crow Island Beach Park* and the *Lunawa Environmental Improvement and Community Development Project* in Sri Lanka, where local communities participated in the design and implementation phases. These precedents offer a foundation for formalising SP integration, especially through participatory models. R9 noted, *"In Lunawa, the residents contributed to minor works; if this can be scaled, it becomes a structured form of SP."* Furthermore, R6 noted, *"Crow Island was not branded as 'social procurement', but it ticked a lot of the boxes; local labour, community input, long-term value."* R4 said, *"The Crow Island Park is still being maintained by the local community. It creates social value."*

In terms of Type 3, experts viewed it as aspirational but less immediately feasible. This is due to the underdevelopment of registered and construction-ready social enterprises in Sri Lanka. As R2 observed, *"Type 3 is viable, but the ecosystem for credible social enterprises is not mature yet."* Despite this, experts suggested pilot initiatives that allocate minor, low-risk contract segments to marginalised groups under guidance. R11 proposed, *"A portion of municipal construction like paving walkways can be handed to ex-convicts with basic training."* R14 added, *"Even if we don't have big social enterprises now, we can start small. Give 5% of basic tasks to cooperatives or youth groups and see what works."* Experts said that Type 4 is also implementable, particularly for larger contractors. R7 highlighted, *"CSR-type SP can be aligned with existing sustainability mandates; it just needs to be operationalised through tender documents."* Likewise, experts stated that the Sri Lankan construction industry holds the potential to integrate SP into its existing procurement methods.

When considering the integration of these types, experts agreed that Type 1 SP aligns well with the separated method, which allows non-core services to be subcontracted to third-sector organisations. R6 noted, *"There is more room to insert social service providers as ancillary partners."* In contrast, R14 emphasised that integration is harder in traditional models and more effective in alliance contracts, as seen in Australia. Type 2 was viewed as adaptable across all methods but best suited to integrated procurement, where social criteria can be embedded early and sustained throughout the project. R9 explained, *"If you bake in the social criteria during design, it is easier to track and enforce them."* Experts found Type 3 most difficult to apply under PPPs due to rigid structures but saw potential in assigning small tasks to social enterprises during operations. As R11 suggested, *"Even in PPPs, you can earmark small maintenance roles for social enterprises."* Meanwhile, Type 4 was seen as universally applicable, especially when formalised through CSR clauses in contracts. R8 remarked, *"CSR elements don't have to fight the system, they just need to be formalised in the tender docs."* Likewise, the experts noted that among the 3 commonly used procurement methods in Sri Lanka, the separated method offers the most suitable foundation to integrate all 4 SP types. The most compatible SP types for each procurement method are presented in Table 3.

4.3 Challenges of Integrating Each Type of Social Procurement into the Existing Procurement Methods in Sri Lanka

Similar to Section 4.1, the experts validated the findings of the literature review, which initially identified 25 challenges to the integration of SP. In addition, four new challenges were suggested by the experts (highlighted in purple in Table 3). The experts were subsequently asked to classify these challenges according to each type of SP, as presented in Table 1, across the commonly used procurement methods in the Sri Lankan context. Across all four types of SP, several challenges were identified. The common challenges for all the types (highlighted in green in Table 3) include insufficient resources, training, and technical skills, limited access to funding, and challenges in engaging marginalised communities. These shared obstacles reflect deep-rooted structural and socio-cultural constraints that must be addressed to operationalise SP effectively in Sri Lanka. As illustrated in Table 3, for Type 1, the experts cited widespread insufficient training, limited funding, and logistical mismatches between community-based suppliers and project demands. R1 commented, *"Since most of them do not have expertise, the projects are reluctant to try this concept out."* Legal and administrative bottlenecks, particularly

around government procurement cycles, further delay community engagement. Trust was another recurring theme. As R4 noted, *"The ex-convicts and the ones who are going to join would ask; can we trust them? NGOs? Government?"* This lack of mutual confidence between marginalised participants and institutional stakeholders was seen as a unique social constraint limiting the operationalisation of Type 1 within traditional public works. Under Type 2, experts highlighted the lack of internal policy, inconsistent leadership, and fragmented procurement systems as key impediments. R9 observed, *"There can be lots of issues in engaging the local community in the projects,"* especially in areas where cultural, language, or class-based divides exist. The complex nature of construction procurement under *integrated* or *PPP* models also leads to misalignment between project goals and social value delivery. Budget constraints further intensify the problem, with R7 explaining, *"That was the main issue the countries that implemented SP had when introducing the concept costs are the first worry, not impact."* Challenges under Type 3 revolved around social enterprises. R7 said, *"Myths and misunderstandings about social enterprises and the concept of SP are crucial. They have cascading impacts."* R5 said, *"There can be some social concerns. They might not support it. Lack of understanding about the concept, trust issues, and myths may impact that."* In terms of Type 4, many large contractors still lack internal policy direction and struggle with low supplier capacity to meet ethical sourcing standards. As R10 mentioned, *"The hierarchy of the organisations could be another challenge,"* pointing to the inertia within multi-tiered construction supply chains. Fragmented CSR policies, coupled with a lack of universal guidelines, make implementation inconsistent. Moreover, tokenism and the disconnect between organisational values and actual procurement practices continue to undermine the credibility of CSR-linked SP efforts. Unlike other types, Type 4's reliance on broad reporting frameworks often masks the absence of real community impact.

5. DISCUSSION

While previous studies on SP have largely focused on its development and implementation in countries like the UK, Australia, and Sweden (Loosemore, 2016; Troje, 2021; Loosemore et al., 2020), there has been limited attention to how SP can be adapted to developing contexts such as Sri Lanka. This research addresses that gap by identifying that all 4 types of SP can be adapted to Sri Lanka's construction industry. Unlike earlier literature that highlights general SP principles (Furneaux & Barraket, 2014; Barraket et al., 2015), this study offers practical guidance by aligning each SP type with Sri Lanka's existing procurement methods, namely separated, integrated, and PPP models (Niriella & Gamage, 2022). Laying foundation for that, the study identified many limitations to socio-economic advancement going beyond unequal development (Lou et al., 2023), such as inability to achieve employee satisfaction and job insecurity. Unlike earlier research that treats SP types separately, this study identified clear links between SP types and procurement methods, with all four types being more easily adaptable under the separated method, while Type 2 and Type 4 best align with integrated models, and Type 3 can be piloted in PPPs at a smaller scale during post-construction stages. More importantly, while previous research has identified general implementation barriers such as limited funding, unclear policies, and supplier capability gaps (Willar et al., 2020; Denny-Smith & Loosemore, 2018), this study identified a deeper set of context-specific and type-sensitive challenges. These include a lack of technical skills and training among marginalised community members, myths and misconceptions about social enterprises, weak trust between the government and community actors, and fragmented organisational

structures all of which directly hinder the localisation of SP. Particularly for Type 3, where global literature focuses on enterprise readiness and economic viability, this study uncovered cultural resistance and trust issues as more pressing barriers. Meanwhile, in Type 2, the study found that organisational misalignment and weak leadership structures obstruct the embedding of social goals into technical scopes, issues not commonly addressed in international literature. Even in Type 4, where CSR integration is considered the most straightforward, challenges remain due to disconnected procurement and CSR departments, lack of enforcement, and tokenistic implementation. These findings reinforced the notion that while SP is conceptually strong, its success in Sri Lanka hinges on phased implementation, clear institutional commitment, and policy mechanisms that support local adaptation rather than replicate international models blindly.

When considering the impact of this study, it provides a novel contribution by contextualising SP within Sri Lanka's procurement systems and classifying challenges across SP types, offering actionable insights for both academia and industry. For society, the effective integration of SP can promote inclusive economic participation, especially for marginalised groups, thereby addressing social equity through public infrastructure delivery. For regulatory bodies, the findings can inform the development of clearer guidelines, monitoring frameworks, and policy instruments to facilitate the effective implementation of SP within existing procurement regulations.

6. CONCLUSIONS AND RECOMMENDATIONS

As one of the first studies to explore the integration of SP into Sri Lanka's existing construction procurement methods, this research provided a detailed analysis of how each of the four recognised SP types could be applied within the local context. It was also one of the first to classify the challenges to SP integration between these SP types, offering a level of depth not commonly found in existing literature. The study revealed that all SP types could be integrated into the country's three dominant procurement methods; separated, integrated, and PPP, with separated procurement offering the greatest flexibility for early adoption. However, integration was found to be challenged by context-specific barriers. The study identified that insufficient resources, training, and technical skills, limited access to funding, and challenges in engaging marginalised communities are common to all the four SP types. Despite these obstacles, the findings demonstrated that SP holds significant potential to promote social equity, local employment, and community inclusion in Sri Lanka. The success of this integration, however, was shown to depend on a phased implementation approach, beginning with Types 1 and 2, supported by robust policy frameworks, and the gradual development of social enterprise mechanisms.

Future research should examine quantitative impacts of SP implementation, particularly in terms of employment generation and community-level benefits. Studies could also explore how digital tools, such as machine learning, can address the barriers of SP. In terms of limitations, as this is a qualitative study based on expert interviews, findings are context-specific and may not fully represent wider industry views. Furthermore, these findings may be different to the developed countries. Nevertheless, these findings are helpful in promoting SP in developing countries such as Sri Lanka.

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INVESTIGATING BUSINESS MODELS FOR CIRCULAR ECONOMY INTEGRATION IN CONSTRUCTION SECTOR

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ABSTRACT

The growing disparities between the demand and finite resources within the construction section, contribute to market volatility and environmental degradation. The linear business is currently being predominantly employed, which escalates the construction and demolition waste. Unsustainable practices come into play with the take, make, dispose method and pressure the existing resources. In contrast, circular business models advocate for a closed-loop approach, and newer business opportunities with a new and evolving stream of market. The paper investigates the application of circular economy Business model, which can act as a mould for the construction industry. A systematic study of the aspects of CE, which are regulatory and economic difficulties, barriers, innovations, impact on the environment and society, is carried out. The research examines business models for reuse and recycling, and the current demolition waste management. Established data is studied to understand the trends, and variables in the business models. According to this study, despite the economic and environmental benefits of circular business models, there are barriers to implementing them due to factors such as high cost, undeveloped markets, and regulatory restrictions.

Keywords: *Business Model; Circular Economy; Demolition Waste; System Dynamics; Systematic Literature Review.*

1. INTRODUCTION

Land, with its limited availability in the urban areas has resulted in vast brownfield development thereby increasing the amount of construction and demolition waste. Such waste if not managed at the source in time would compromise the Land resource itself, thus, the environment, as it often gets dumped. The construction industry has always been resource-intensive and with more and more brownfield developments the construction industry requires immediate attention and focus on adoption of circular economy (CE) policies to optimize resource use and mitigate damages to the environment (Bestul & Gruis, 2024). Adoption of circular economy in the construction industry is not new, and the research community has already addressed "sustainability", "energy efficiency", "life cycle assessment", "renewable energy", and "recycling" themes (Norouzi et al., 2021).

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However, very few studies were found discussing the scope of CE in businesses in the construction industry.

The "take-make-dispose" attitude present in traditional linear economic models causes waste and resource overexploitation. By contrast, CE focuses on sustainable design approaches, as well as recycling and recovery through reuse (Ossio et al., 2023). (Illankoon & Vithanage, 2023) Circular business models (CBMs) integrate social, economic, and environmental dimensions into business processes and, therefore, can offer practical solutions to reducing waste generation and improving sustainable materials management within the construction industry (Illankoon & Vithanage, 2023). Despite growing awareness, the transition of CE in construction remains limited due to various barriers including, inadequate policy enforcement, fragmented supply chain and lack of technological integration. The paper employs a systematic literature review and aims to identify key themes essential for integrating CE in Business models, followed by development of a system dynamics model to understand interconnection between various aspects of circular business models in the construction industry.

2. METHODOLOGY

This study employs a systematic literature review (SLR) providing an overview of the existing research on circular economy in the built environment and various business models. The goal of systematic literature reviews (SRs) is to synthesize scientific knowledge in a transparent and reproducible way to address a particular research issue by evaluating the quality of all available evidence on a topic (Lame, 2019).

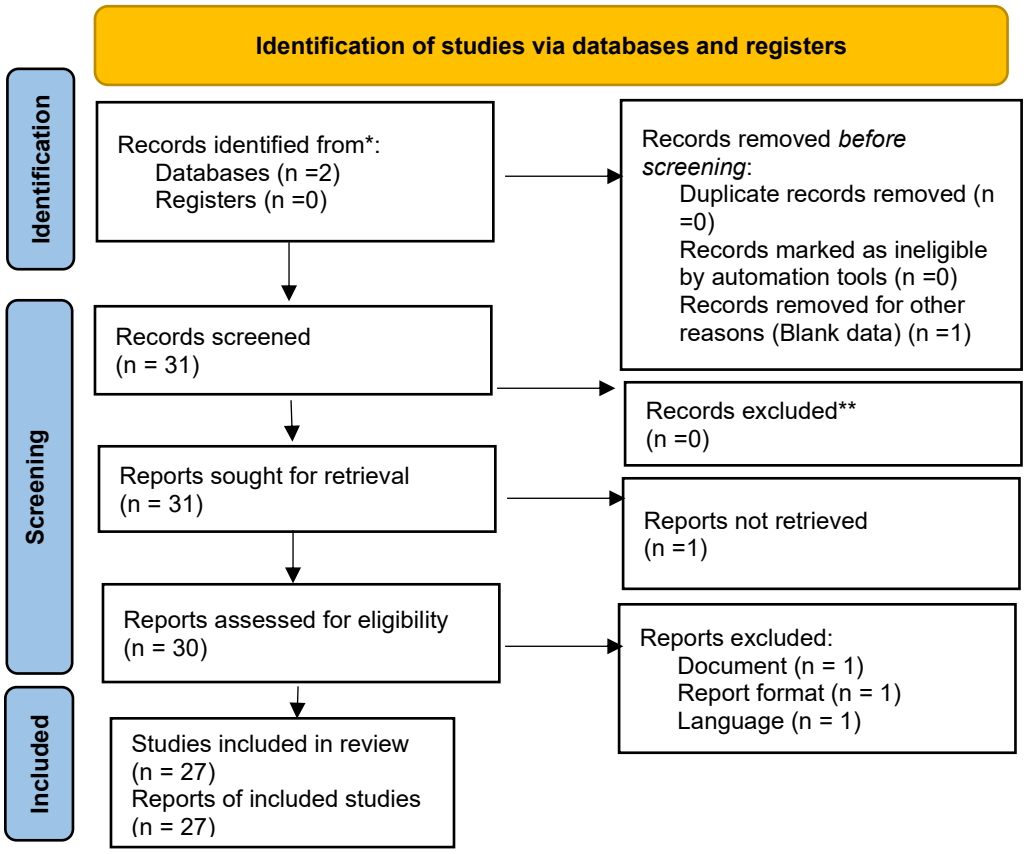


Figure 1: PRISMA 2020 reporting methodology

The Preferred Reporting Item for systematic reviews (PRISMA) approach was employed to review the literature. Due to the limited accessibility to databases, only two databases namely Scopus and JSTOR were used. The initial search query with the keywords (TITLE-ABS-KEY (circular AND economy) AND TITLE-ABS-KEY (demolition AND waste) AND TITLE-ABS-KEY (business AND model)) returned 28 papers from Scopus and 4 papers from Jstor, with the same keywords for both the databases. Papers were filtered on three levels; *first- articles in English were selected*; *second-* articles which are peer reviewed; *third-* relevant data provided in the articles were considered for which the PRISMA statement is presented in Figure 1. In case of unavailability of the full papers, the literature was excluded from the framework. Only literature from articles and documents in addition to the papers were retained.

3. RESULTS AND DISCUSSION

An economic understanding of a business falls under broad three pillars namely- value proposition, value delivery and value capture. This research presents discussion on the business models based on these three pillars by broadly classifying the identified parameters from the systematic literature review as discussed below.

3.1 VALUE PROPOSITION

A business model is built upon a value or business proposition. This type of proposal tackles an issue, an existing need, often undefined requirements. It consists of an ingenious and instantly recognisable mix of products and/or services that meet the needs of a user or customer both directly and indirectly. A proposition may identify potential stakeholders or suggest a target audience. A value's ability to generate an appropriate argument increases with its degree of accuracy (Jonker & Faber, 2021). The value proposition is influenced by various aspects, including, the type of model adopted, social and environmental aspects.

3.1.1 Business Models for Construction and Demolition Waste

Bestul & Gruis (2024) suggest that there are at least six types of organizations that enhance CE in the construction industry namely- deconstruction firms, upcyclers, component specific suppliers, reuse platforms, material resellers, and reuse consulting offices. These above-mentioned models work because they extend product life cycles and networks that resource recovery by-products facilitate. In addition to maintaining material loops, other construction circular business models include waste valorisation, renewable resource adoption, provision of services instead of ownership, and self-sufficiency (Bestul & Gruis, 2024).

Another strategic tool for embedding circularity to large-scale infrastructural projects is the public-private partnership – PPPs. Several of the PPP models, such as design-build-finance-operate (DBFO) and build-own-operate-transfer (BOOT), focus on the redistribution of ownership and responsibility in material management as one of their key defining attributes. Circular PPP infrastructures instead encourage circular behaviour such as sharing, renting, and buyback options rather than contracting the entire liability to life cycle end users (Akomea-Frimpong et al., 2024).

3.1.2 The Impacts of Circular Business Models on the Environment and Society

Circular construction business models enable a variety of sustainability goals, including conservation of resources, reduction in waste, and carbon footprint reduction (Al-Raqeb et al., 2023). The environmental benefits of circular practices have been widely evaluated through life cycle assessments (LCA), which indicate that recycling and material reuse minimize embodied carbon (Ossio et al., 2023). Moreover, circular building models generate new economic opportunities by encouraging the creation of jobs in deconstruction, material recovery, and reverse logistics (Munaro et al., 2020). In addition to employment creation, CE has social benefits through fostering the development of urban circularity initiatives that transform cities into sustainable systems (Dasgupta et al.,2016).

3.2 VALUE CAPTURE

Securing profits from the value given is known as "value capture," and these gains can then be reinvested as input to assist the upcoming transformation efforts (Chen & Thapa, 2025). These can be deviated due to logistical, technical, regulatory, economic, and many such barriers discussed below.

3.2.1 Regulatory and Economic Difficulties

The combination of Circular Economy (CE) and construction and demolition industry is disruptive, and its active usage is prevented due to financial setbacks. It is known that business models that support a circular economy are especially dismantled due to high infrastructure investments in processing, shipment, and storage (Bestul & Gruis, 2024). The competitive stand for recycled items is affine in cross economy regions because of the Intra economic differences in market values, which makes profit for recyclers rather impossible. In addition, the profitability of recycling construction and demolition waste is influenced by the prices charged on secondary material markets, the cost of tipping fees at landfills, and the cost of waste processing (Cho et al., 2022).

Regulations affect profoundly the strategies used in creating new circular construction techniques. Measures such as landfill taxes, sorting laws, and procurement of recycled materials can shift the market towards circularity which in turn can make policies more beneficial (Nußholz et al., 2019). Denmark and other countries have demonstrated that selective demolition accompanied by strong regulatory frameworks enables the development of circular value chains (Christensen et al., 2022). Moreover, steps can be taken towards more advanced sustainability in construction by adding circular concepts to public purchasing policies (Dasgupta et al.,2016).

Investments in new technologies have a positive impact on CE in the building industry. The applications of AI facilitates circularity through RL (reverse logistics), waste predicting, and material selection optimization (Oluleye et al., 2023). In addition, BIM has been increasingly used for integrating CE into construction projects through the provision of digital material passports, monitoring of material flows, and analyzing demolition planning for resource recovery (Kuzminykh et al., 2024). In addition, it is also recognized that efficient waste and material cut strategic targets can be export through the use of prefabrication and modular building techniques (Kit, 2022).

3.2.2 Barriers to the Adoption of the Circular Economy

In spite of the numerous advantages CE principles bring, the construction sector encounters a number of barriers to their implementation. These include organisational, technical, regulatory, as well as economic challenges. Material recovery capacity is constrained by technical problems, including a lack of effective on-site sorting facilities and lack of formalised waste categorisation systems (Ratnasabapathy et al., 2021). Also, market systems that are dominated by few large, powerful firms detract from circular practice incentives by creating resistance towards change (Nußholz et al., 2019). Incentivising waste collection and recovery, and incorporating the reuse of higher value material in construction and demolition waste are a few public policies that help companies address barriers.

Construction firms' reluctance to incorporate secondary materials due to concerns about certification standards and quality assurance is among the significant barriers to circular business model formation. A trustworthy certification framework for recycled material can facilitate increased use of CE practices and developing trust among the industry stakeholders (Nußholz et al., 2019).

3.3 VALUE DELIVERY

Value delivery guarantees that the intended audience receives the promised value in an effective and efficient manner (Chen & Thapa, 2025). Policies play a key role in defining this process and ensures smooth and effective implementation.

3.3.1 Policy Recommendations and Future Directions

Policy measures need to prioritize regulatory incentives, financing, and stakeholder engagement in ensuring that regulatory incentives, financing, and stakeholder engagement are provided top priority to overcome existing challenges and accelerate CE adoption. Imposing stricter landfill bans on non-treated construction and demolition waste, establishing centralized material donation banks, and enforcing circular procurement policies are some means through which governments can encourage CE adoption (Kit, 2022). Investment in environmentally friendly building processes can further be promoted through monetary instruments such as green loans, subsidies on recycling technology, and tax relief to circular businesses (Al-Raqeb et al., 2023).Education and awareness programs are also essential for fostering a circular culture. Architects, engineers, contractors, and other professionals in the field need specialized education in material recovery techniques, business model creativity, and circular design principles (Illankoon & Vithanage, 2023). In addition, research and development efforts to address current technological and financial limitations can be driven by collaboration between academics, business, and policymakers (Kit, 2022). Figure 2 presents the keyword occurrence on the topic, providing the connections between each keyword. Keywords such as circular economy, construction and demolition waste, waste management, and business models hold high strength of network.

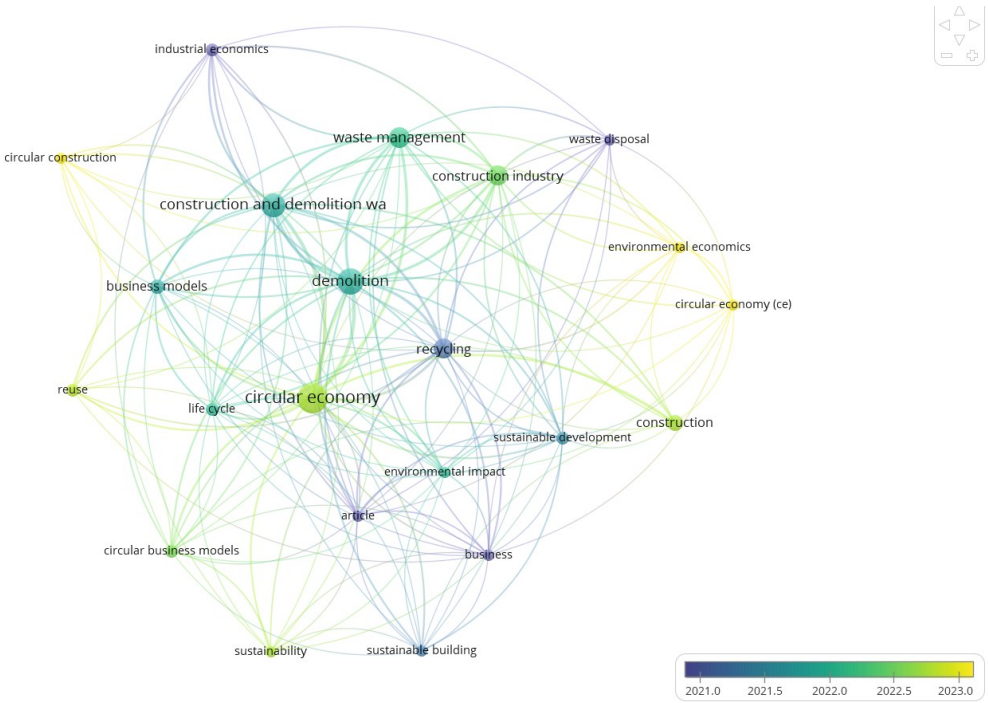


Figure 2: Keyword co-occurrence temporal visualization in VOSviewer

Topics such as recycling, waste disposal and business models are discussed mainly in 2021-2022. This trend reflects a period when research was focused on waste handling and emerging business innovations, aimed at reducing construction related environmental impacts. Keywords such as circular economy, environmental economics, circular construction are terms used post 2022. In contrast, this shift suggests maturing research, that is moving from operational waste management strategies to more systemic and policy driven frameworks. The evolution of newer terms also suggests the long-term sustainability goals. Overall, the keywords underscore a shift from reactive to proactive waste management approach, and economically informed circular practices.

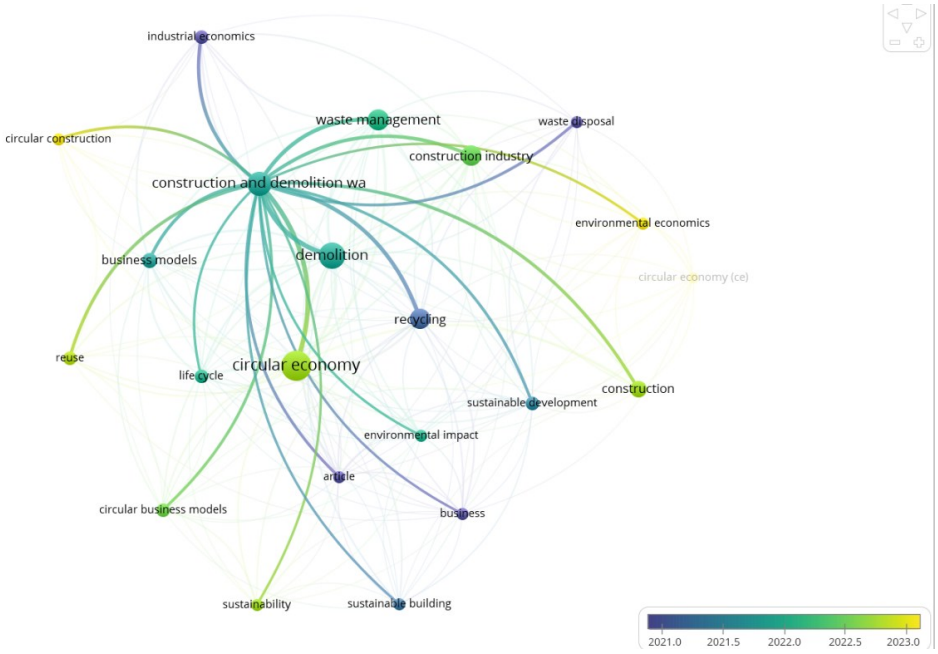


Figure 3: 'Construction and demolition waste' keyword's temporal association with other keywords

Figure 3 shows the connection of the keyword construction and demolition waste to the other keywords. Topics such as circular construction and environmental economics in accordance with construction and demolition waste came up during 2023. Sustainable development and recycling were the topics in relation to it before 2021. This highlights the shift from managing construction and demolition waste after it is generated, to designing it holistically.

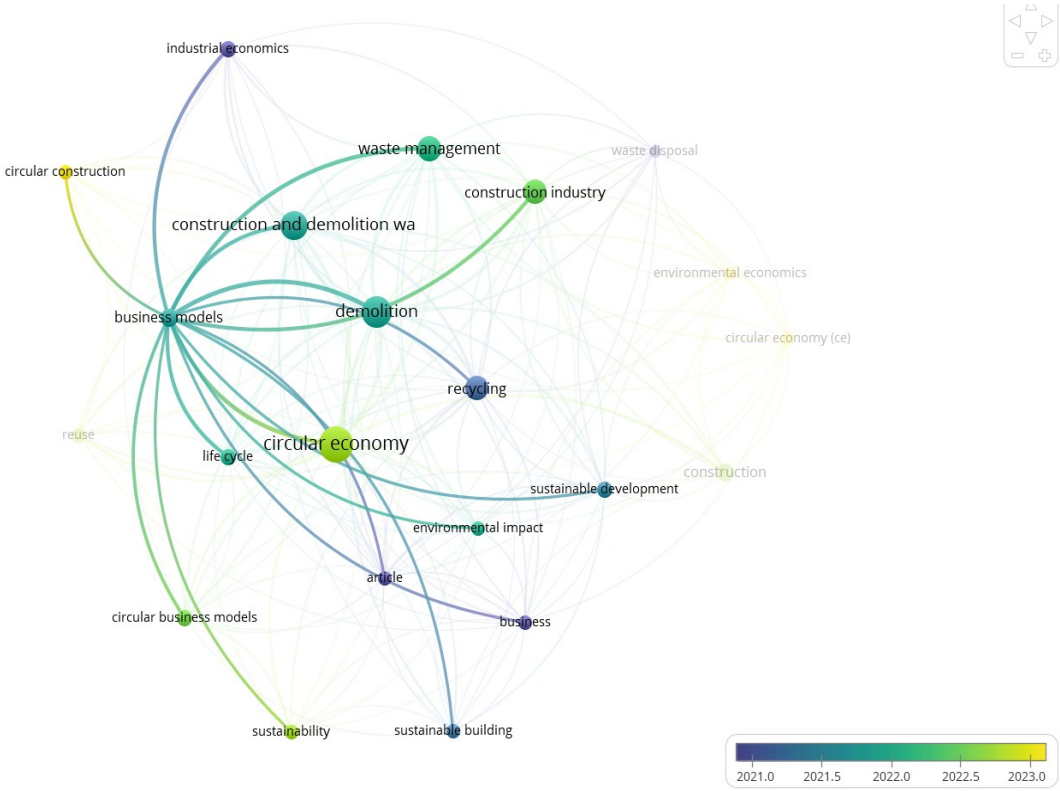


Figure 4: 'Business model' keyword's temporal association with other keywords

Figure 4 shows the connection between business models and other keywords. Recycling was the term used in 2021. Circular economy with respect to business models came up around 2022, whereas circular construction emerged in 2023. This shows the gradual specification of terms and their understanding.

4. UNDERSTANDING BUSINESS MODELS THROUGH SYSTEM DYNAMICS LENS

System dynamics (SD), created by Jay Forrester (1971), provides practical tools for understanding those large, complex management problems. SD is being developed. It is a well-known method based on system thinking for understanding, studying, visualizing, and assessing complex dynamic feedback networks. It is necessary to construct "causal loop diagrams" or "stock and flow diagrams" in order to generate a system dynamics model for applications. The construction and demolition waste management model is an abstract and conceptual model that emphasizes particular elements and theories regarding their interactions. The dynamics of the model are determined by the feedback loops in the causal diagram. A causal loop diagram for this model can be found in Figure 5. Each

arrow illustrates the relationship between two elements. Theories about these influences are based on reviews of the literature (Zhao et al., 2011).

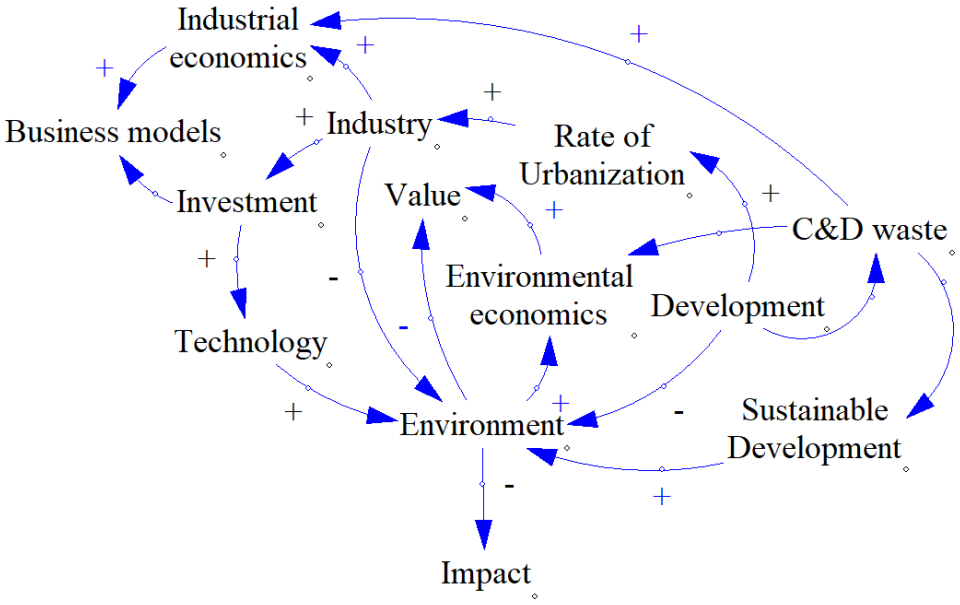


Figure 5: System dynamics model in Vensim summarizing circular business model opportunities

The causal loop diagram. showcases the dynamic relation between the aspects which affects the overall loop. One perspective holds that urbanization aids in the modernization of industrial structures. However, there is a counterargument that urbanization might negatively impact industrial transformation and upgrading. Urbanization frequently leads to rapid population growth and increased economic activity, which can exacerbate environmental pollution and lead to excessive resource use (Wan et al., 2024). Rapid urbanization encourages innovation. A study asserts positive correlation between technological innovation, industrialization, and urbanization. According to it, industrialization and technological development are the main drivers of urbanization and are essential to its progress (Shang et al., 2018). Global infrastructure investment has fundamentally changed as a result of the current stage of the technological revolution and the quick speed of industrial change (Du et al., 2022). A study claims that digital investment enables IT innovation (Nwankpa & Merhout, 2020). The Porter Hypothesis offers a theoretical framework for investigating the previously mentioned question regarding the relationship between environmental performance and technological innovation (Wu et al., 2024). In the current global economic downturn, abundant natural resources don't seem to support economic growth. Given the remarkable environmental degradation taking place on a global scale, turning the "natural resource curse" into the "natural resource blessing" is one of the most significant new issues confronting nations worldwide (Liu et al., 2024). Various impacts have been made on the nature due to rapid industrialization(Choi et al., 2020). The rapid growth of the industry and the economy has been accompanied by environmental degradation (Sehrawat et al., 2015). As the competitive environment evolves, the business model which describes how a company creates, delivers, and gathers value should be reinforced over time and modified either completely or partially to reflect the new conditions (Salfore et al., 2023). Studies assist in finding sustainable and profitable solutions to the global issues we confront, sustainable business models are critical to reaching the SDGs. Thus, while guaranteeing

profitability, sustainable business models can specify sustainable value-creation methods. Accelerating progress towards the SDGs requires sustainable business model innovation, or the process of creating and implementing new sustainable business models, since it can open up new avenues for companies to contribute to a more sustainable future (Gazzola et al., 2024).

5. CONCLUSION

In the construction and demolition sector, the transition towards a circular economy requires a multifaceted approach that involves innovative business models, supportive legal systems, and technology advancements. For closing material loops and minimizing waste generation, circular business models such as material resellers, reuse platforms, and deconstruction businesses, are crucial. However, market transformation strategies, policy shifts, and financial incentives are necessary to overcome economic and technical challenges. The construction sector can optimize resource utilization and facilitate circularity through the use of AI, BIM, and prefabrication procedures. Furthermore, sustainable building practices can be accelerated by legislative measures such as landfill charges, mandated material certification, and green procurement initiatives. Ultimately, systemic collaboration between governments, business, and consumers is required to make circular business models work within the building sector.

Despite the contributions of this paper, several limitations should be acknowledged. The selection of papers was limited to English language, which may have excluded relevant research data. The review was based on data searched from Scopus and Jstor, which while were comprehensive, may have missed pertinent studies from other sources including grey literature and non-English publications, future research could broaden the review's geographic and cultural breadth. It would also be helpful to conduct empirical studies examining the real-world effects of circular construction and demolition business models, and the interdependency of the process on their functioning. Comparing policy frameworks in various places could also help us better understand how regulatory environments impact adoption. A more thorough grasp of the field might be possible with future studies looking at the connection between social business and sustainability.

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IOT-BASED REAL-TIME MONITORING SYSTEMS TO ENHANCE WORKERS' SAFETY IN HIGH-RISE CONSTRUCTION PROJECTS IN SRI LANKA

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ABSTRACT

High-rise construction projects are high-risk ventures and key drivers of economic growth, yet they face severe safety challenges in rapidly urbanizing regions. Despite advancements in IoT-based monitoring systems enabling real-time hazard detection and proactive safety measures, their adoption in developing countries remains limited due to economic, technical, and socio-cultural barriers. This study investigates how IoT technologies can enhance worker safety in Sri Lankan high-rise construction through a qualitative approach, including semi-structured interviews with 17 industry experts (safety officers, project managers, and IoT engineers). Findings reveal pervasive hazards, including falls, scaffold collapses, and electrical risks, which are exacerbated by gaps between formal safety protocols and their on-the-ground implementation. IoT solutions, including wearable sensors, building information modelling (BIM) integration, and drones, show transformative potential, with estimates suggesting a 30% reduction in accidents upon global adoption. However, worker resistance, high costs, and inadequate policy frameworks hinder Sri Lanka's adoption. Experts rated the nation's IoT readiness at a low 2–3 out of 10, indicating considerable scope for advancement. Key challenges identified include public concerns over surveillance, poor durability of devices in harsh monsoon conditions and language barriers. The study advocates for multi-stakeholder collaboration, policy incentives, and phased IoT integration to bridge the gap between international best practices and local realities. By addressing these barriers, IoT can shift Sri Lanka's construction safety paradigm from a reactive approach (post-accident responses) to a proactive one (preventive risk mitigation).

Keywords: *Construction Safety; High-rise Buildings; IoT Technologies; Real-time Monitoring; Sri Lanka.*

1. INTRODUCTION

The construction industry (CI) contributes approximately 6% to the world's gross domestic product (GDP) and supports other industries by offering built infrastructure (Ghosh et al., 2020). CI is also the largest consumer of raw materials and a significant emitter of greenhouse gases (Ghosh et al., 2020). Rapid urbanization is accelerating with over 200,000 individuals entering the cities daily, raising demands for residential houses,

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which is subjecting construction activities to be pressurized (Kamble & Sabanna, 2023). High-rise constructions have emerged to address the shortage of land and population growth while symbolizing the economic advancement (Fakhari & Ünver, 2023). However, high-rise constructions require keen technical and quality controls to mitigate faults and improve safety (Mangaraj et al., 2023). Moreover, construction of high-rise buildings, despite their benefits, poses severe threats to construction safety, including falls from heights, which results from personal, non-personal, and environmental circumstances (Arifuddin et al., 2020).

Statistics of the safety challenges of the CI are supported by global sources. For instance, falls from heights account for approximately 52 deaths a month and 745 deaths a year, 1,000 severe injuries, and 5,000 productivity loss hours per incident (Khan et al., 2023). As well as this, it indicates the significance of human and economic cost, with fatalities representing 20% of workplace deaths (Arifuddin et al., 2020). However, the substantial losses that are preventable with the regulations and construction practices that meet the sustainable development goals are thoroughly investigated (Awolusi et al., 2018). Construction safety precautions play a significant role in helping to save lives and continue the growth of CI within the world via urbanization.

Proper control of safety relies on organisational routines, behaviour of the workers, and environmental controls (Li et al., 2018). However, typical hazards due to scaffolding, lifting, and equipment use still persistently appear (Wang et al., 2024). On the other hand, technical advancements such as Internet of Things (IoT) sensors, wearables, and AI-driven monitoring systems enable real-time hazard detection and data-driven interventions (Wang et al., 2024). These methods offer greater reliability compared to traditional approaches, which heavily depend on variable human compliance (Melagoda & Rowlinson, 2022). As developed countries such as Singapore and the UAE have reduced the fall incidents using digital tools such as building information modelling (BIM) and drones in scaffolding inspections by 40% (Khan et al., 2023). Mobile-based safety platforms help in overcoming resource constraints and increase compliance in risky zones in Sri Lanka (Sandagomika et al., 2020). Such innovations standardize safety protocols, eliminate some persistent hazards, and increase productivity in the same way as the global smart construction practices.

In addition, virtual and augmented reality (VR/AR) enable risk-free safety training, and IoT systems enable the usage of real-time data to avoid risks (Rahman et al., 2023). Issues such as the cost of investments, resistance to change, and limited technical knowledge need to be addressed while implementing modernized technologies in the CI (Tabatabaee et al., 2022). Construction safety in Sri Lanka falls behind as there is a lack of regulations and integration of technology within the industry (Melagoda & Rowlinson, 2022). Moreover, IoT-based models have been proven to yield cost and efficiency benefits globally, even though there are challenges such as economic constraints and unawareness in Sri Lanka (Sandagomika et al., 2020).

This study evaluates the current safety issues encountered in high-rise construction projects in Sri Lanka, examines global best practices in IoT-based safety management systems, and investigates the extent to which such technologies have been implemented locally. By focusing on these areas, the study aims to understand how IoT-driven safety practices can be leveraged to enhance occupational safety performance in Sri Lanka’s

high-rise construction sector, considering the country's unique technological, economic, and regulatory conditions.

2. LITERATURE REVIEW

2.1 SPECIFIC RISKS IN HIGH-RISE CONSTRUCTION

High-rise construction offers a unique set of safety issues that involve immense risk to workers. The issues include typical risk factors, such as prevalent dangers such as falls from heights, exposure to environmental hazards, risks associated with heavy equipment operation, and the potential for fire.

2.1.1 Falls from Heights

Falls are a crucial concern in the construction industry, particularly in high-rise areas. Such accidents are responsible for a high percentage of fatal incidents, involving about 33% of all fatal accidents related to construction work. Falls in 2020 claimed 351 lives in a total of 1008 construction-related deaths in the United States, which emphasizes the need for increased safety measures (Nugroho et al., 2023; Manzoor et al., 2022).

2.1.2 Environmental Hazards

Working environments involving high-rise buildings often expose labour to various environmental hardships, such as extreme weather and harmful air quality (Karthick et al., 2022). The problem of poor air quality is extremely critical, as it is accompanied by the development of severe respiratory diseases and reduced mental functions, which negatively impact both attention and memory in workers (Chen et al., 2022). As estimated by the World Health Organization (WHO), air pollution is the cause of around 7 million deaths annually, and construction workers are most susceptible because they are constantly in contact with harmful chemicals and environments (Chen et al., 2022).

2.1.3 Equipment Safety and Proximity Alerts

The use of heavy machinery and equipment is a distinguishing trait in high-rise building construction, posing significant threats to the safety of labourers (Dhakal & Giri, 2024). Constructions involving contact impacts from objects, which include cases involving touch with movable machinery or falling materials, are a leading cause of deaths, accounting for about 10% of construction worker deaths, as OSHA estimates. The very nature of such operations requires the establishment and execution of stringent safety practices to control such incidents (Nugroho et al., 2023).

2.1.4 Fire Hazards

The fire risk potential is an important concern in high-rise buildings. The use of combustible materials, such as asbestos, in addition to the intricacies surrounding the evacuation corridors in such buildings, escalates the threat of unprecedented fire disasters (Qin et al., 2022). Information supplied by the National Fire Protection Association (NFPA) shows that building construction scenarios are 3.5 times riskier in terms of fire outbreak incidence in comparison to other building types, thus putting in perspective the increased risk present in such environments (National Fire Protection Association).

2.2 MODERN TECHNOLOGIES AND THEIR BENEFITS TO THE CONSTRUCTION INDUSTRY: THE ROLE OF IOT

The construction industry (CI) significantly contributes to global economic growth, accounting for 6% of global GDP and employing over 7% of the workforce (Ghosh et al., 2020; Fei et al., 2021). High-rise construction helps address land scarcity and population growth but introduces complex safety risks due to elevated material handling and multi-trade coordination (Navaratnam, 2022; Nugroho et al., 2023). IoT technologies are increasingly used to manage these risks by enabling real-time monitoring, reducing human error, and supporting early hazard detection (Awolusi et al., 2018; Fang et al., 2024). IoT can predict unsafe scaffolds or equipment failures through automated data collection (Cheng & Cao, 2022; Khan et al., 2023). However, existing studies often overlook the challenges of integrating IoT into current workflows and safety cultures, particularly in developing regions.

In addition to safety, IoT boosts operational efficiency by streamlining processes. Integration with BIM helps project managers anticipate hazards, reducing delays and rework (Wang et al., 2024), while wireless protocols ensure smooth data communication for real-time decision-making (Zidek et al., 2018). Successful implementations in Singapore and the UAE have reduced accidents by up to 30%, improved efficiency, and lowered costs (Khan et al., 2023; Sidani et al., 2023). Nonetheless, these successes largely occur in resource-rich settings, and there is limited analysis of how contextual factors affect IoT adoption across regions. In contrast, countries like Sri Lanka face adoption barriers due to infrastructural, economic, and cultural limitations (Melagoda & Rowlinson, 2022), exposing a gap in the literature that often generalizes IoT's benefits without fully addressing these localized challenges.

2.3 IOT-ENABLED SYSTEMS TO ENHANCE WORKERS' SAFETY

Three technologies from the IoT are improving occupational safety as wearable devices, systems that monitor the environment, and safety platforms located centrally.

2.3.1 Wearable Technologies

Through IoT, smart helmets and Radio Frequency Identification (RFID) tags keep an eye on workers' vital signs (heart rate, body temperature, and fatigue) and their locations (Huang et al., 2020; Okonkwo et al., 2022). When workers get too close to unstable scaffolds or crane operating areas, these devices alert safety managers and immediately send out an emergency notice (Danilenka et al., 2023). In high-rise projects, RFID-enabled vests have helped cut the number of fatalities from falls by 25% by making sure workers are within safe zones (Khan et al., 2023). Despite these benefits, limited research explores worker perception, wearability issues, or resistance to tracking technologies, which could significantly affect practical adoption.

2.3.2 Environmental Monitoring Systems

Scaffolding, cranes, and enclosed spaces now have IoT sensors that report any danger to workers, such as possible damage, bad air, or poor weather. Thanks to strain gauges and vibration sensors, collapses can be detected early, and gas detectors stop suffocation in closed-off areas (Cheng & Cao, 2022; Danilenka et al., 2023). Acoustic sensors in Singaporean high-rises decreased accidents related to equipment by 40% by spotting noises that pointed to possible mechanical problems (Khan et al., 2023). However,

comparative studies evaluating the effectiveness, reliability, and cost-efficiency of these sensor systems in different climates or project scales remain scarce.

2.3.3 Centralized Safety Platforms

All data from drones, AI cameras, and pressure pads can be collected by centralised IoT hubs to find hazards, plan proper resources, and keep safety rules in check (Gambo & Musonda, 2022). As an illustration, using IoT in Dubai cut safety inspection times by half by automating the study of risk trends (Sidani et al., 2023). These systems assume stable power and high connectivity, yet such assumptions may not hold in lower-income regions—an issue often underexamined in case-based literature. Moreover, implementing such systems is challenging for developing countries because they are expensive, have unreliable electricity, and their workforce often objects to being watched (Melagoda & Rowlinson, 2022; Tabatabaee et al., 2022).

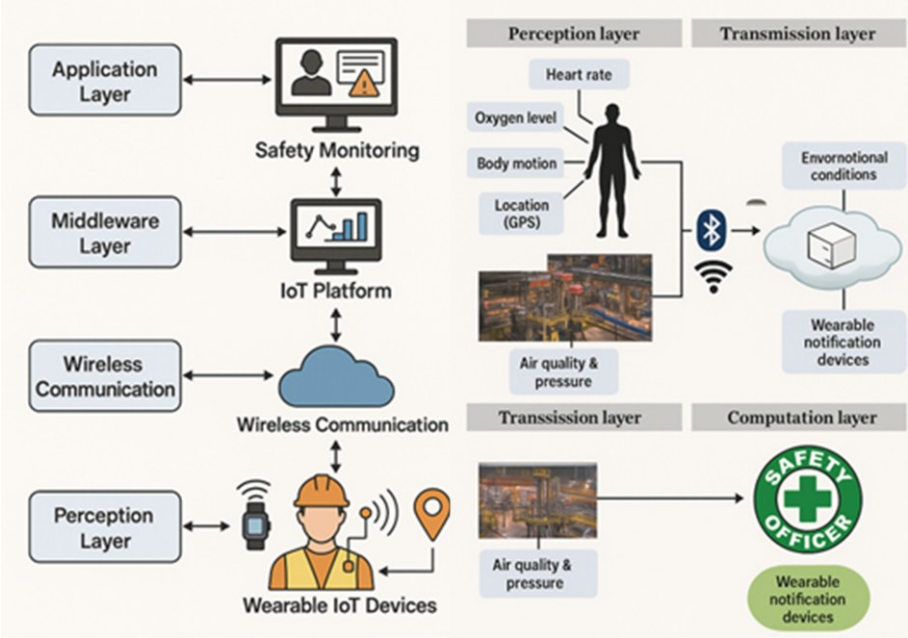


Figure 1: Layered architecture of IoT-enabled safety monitoring system for construction workers

Figure 1 outlines a hierarchical IoT safety system comprising application-level monitoring, middleware platforms, communication protocols, and wearable sensors working together for rapid hazard detection and response. While the architecture is technically robust, real-world deployment demands adaptation to specific local conditions, a factor often overlooked in mainstream models.

Most existing literature fails to account for challenges in countries like Sri Lanka, where IoT devices must be durable and interfaces localized. This study addresses that gap by exploring how IoT systems can be tailored to Sri Lanka's economic and environmental realities, aligning with Sustainable Development Goals 8 (decent work) and 9 (industry, innovation, and infrastructure).

2.4 Integration of IoT Applications in Construction in the Global and Local Context

Globally, IoT adoption in construction has shown transformative impacts. In Dubai, integrating IoT with BIM during the Burj Khalifa project reduced structural inspection

time by 60%. In comparison, Singapore's use of RFID-tagged helmets led to a 25% drop in fall-related incidents. Qatar's use of AI-powered drones during FIFA World Cup stadium construction enhanced site surveillance. These examples showcase IoT's potential but often overlook failed or challenged implementations, limiting understanding of associated risks.

In Sri Lanka, IoT use is still emerging but has shown promise. Pilot projects in Colombo prevented scaffolding collapses using vibration sensors and reduced respiratory issues by 15% with air quality monitors. However, broader adoption is hindered by high costs, staff resistance, and unreliable infrastructure. This contrast underscores the need for adaptive, locally grounded frameworks that go beyond isolated successes to support sustainable, long-term integration.

3. METHODOLOGY

This study adopted a qualitative approach to explore the challenges and enablers of IoT adoption in Sri Lanka's high-rise construction sector. Qualitative methods allow for the exploration of context-specific industry insights (Rampin & Rampin, 2021; Bingham, 2023). A purposive sample of 17 professionals, including project managers, safety officers, quantity surveyors, IoT engineers, and site supervisors, was selected based on experience and relevance to the study (refer to Table 1).

Semi-structured interviews (30–45 minutes) were conducted in person and online. All interviews were transcribed and analysed using manual content analysis. Both predefined categories (e.g., technical, cultural) and emerging themes (e.g., policy, cost) were coded manually. The process involved repeated reading of transcripts, identifying meaningful units of text, assigning codes, and grouping them into themes. Thematic saturation was confirmed after 15 interviews, with two additional interviews validating no new insights.

Table 1: Profile of the experts

Expert Code	Designation	Years of Experience
E1	Quantity Surveyor	11
E2	Project Manager	20
E3	Engineer (IoT specialist)	18
E4	Site Supervisor	13
E5	Quantity Surveyor	12
E6	Quantity Surveyor	19
E7	Safety Officer	10
E8	Quantity Surveyor	12
E9	Safety Officer	16
E10	Engineer	11
E11	Safety Officer	10
E12	Site Supervisor	14
E13	Project Manager	17
E14	Project Manager	10
E15	Safety Officer	15

Expert Code	Designation	Years of Experience
E16	Project Manager	17
E17	Quantity surveyor	18

4. FINDINGS AND DATA ANALYSIS

4.1 SAFETY RISKS IN HIGH-RISE CONSTRUCTION

Interviews with seventeen industry professionals reveal that high-rise construction in Sri Lanka carries extensive risks, with falls from height emerging as the most critical concern. E4 and E8 described hazardous practices such as working atop unstable ledges and treating open lift shafts as routine obstacles. Scaffolding failures during monsoon seasons, cited by E5–E7, account for 68% of preventable accidents. Material handling risks include airborne plywood panels (E5), falling steel beams (E9), and unsafe hoisting rigs made from frayed ropes (E4, E11). Electrical dangers were also widespread, with makeshift waterproofing using plastic bags (E4, E10) and exposed wiring in drainage systems (E11), reflecting a casual attitude toward life-threatening risks.

Other reported hazards included structural collapse during renovations (E1), worker exhaustion (E3), and high-risk explosive activities. E8 observed neglected safety harnesses as symbols of the broader gap between safety rules and real-world practice, while E12 linked this to a cultural perception that safety protocols are too time-consuming. Collectively, the insights show that meaningful safety improvements require more than equipment they demand deep-rooted cultural change and a shift in how risk is perceived and managed on construction sites.

4.2 DAMAGES RESULTING FROM SAFETY FAILURES

Safety failures lead to a cascade of devastating consequences, impacting individuals, projects, and companies. Experts detailed these damages, which range from physical and psychological harm to severe economic and reputational losses. The following Table 2 presents these impacts.

Table 2: Consequences of safety failures

Impact category	Description of damages	Supporting data and expert observations
Physical and Psychological Harm	• Physical Injuries: Fractures, spinal cord injuries, permanent blindness from flying rebar, and fatalities from falls due to worn-out harnesses. • Psychological Trauma: Development of disabling phobias (e.g., fear of heights), suicidal tendencies, and ongoing mental distress among workers forced to continue in unsafe conditions.	E1, E3, E4, E8, E10, E11
Direct Economic Costs	• Incident Costs: Medical and related expenses ranging from Rs 1.8 million to Rs 4.3 million per incident.	E4, E5, E6, E7

Impact category	Description of damages	Supporting data and expert observations
	• Catastrophic Event Costs: A single curtain wall failure resulted in damages estimated at Rs 22 million.	
Project and Business Impacts	• Project Delays: An average delay of 78 days per accident, with some incidents causing delays of up to five months. • Cost Escalation: Delays led to project cost increases of Rs 2.4 million to Rs 3.1 million per day. • Reputational Damage: 63 of clients reportedly blacklisted companies after major accidents, and 72 of subsequent bids from such companies were ignored. This "brand damage" has lasting commercial implications.	E2, E4, E6, E7, E10

4.3 EXISTING SAFETY METHODS AND IMPLEMENTATION CHALLENGES

4.3.1 Current Safety Protocols and Implementation Gaps in High-Rise Construction

Expert insights present a strong theoretical framework for high-rise construction safety, with measures aligned to international standards. E1 emphasized the use of PPE, SWMS, and site assessments, while E2 and E3 advocated for compliance with ISO and ILO standards. Progressive companies, as noted by E4–E7 and E9–E11, are adopting advanced practices like allocating 3.5%–4.5% of project costs to safety funds, enforcing subcontractor safety bonds (5%–7%), and using multi-language presentations to overcome communication barriers. These strategies provide a structured and globally informed approach to safety management.

Despite this, experts pointed to a significant disconnect between policy and on-ground practice. E4 warned of safety being treated as "paperwork does not practice," with support from E5, E7, E9, and E11, who described “safety theatre” as perfect documentation concealing unsafe realities. E5 and E6 reported dangerous behaviours such as workers sharing a single harness, while E7 and E11 observed gear being discarded during unsupervised shifts. This reveals a troubling culture of compliance driven by audits rather than genuine safety commitment.

4.3.2 Systemic and Behavioural Barriers to Effective Safety Implementation

Experts highlighted routine implementation challenges in the construction sector, often rooted in procedural compliance over proactive safety. E8 noted that safety officers prioritize bureaucracy, while incentive schemes mentioned by E2 and E4 may encourage near-miss cover-ups. Though frameworks like the "3E" and "SEE" approaches exist, their impact is limited by poor staff attitudes and tight budgets. E9 illustrated the cost of short-termism through a case where skipping safety measures to save Rs. 200,000 resulted in Rs. 1.5 million in accident-related expenses.

Cultural and behavioural factors further hinder safety compliance. E12 emphasized mandatory safety gear and regular briefings yet found evidence of issue concealment to avoid workflow delays. Language barriers (E4, E10, E11), resistance to safety protocols

(E7, E11), and a prevailing "convenience culture" (E7, E11, E12) all reflect an industry prioritizing ease over compliance. Experts agree that real change requires moving beyond checklists to build a genuine safety culture rooted in behavioural insights, tailored incentives, and strong, context-aware leadership.

4.4 SUCCESSFUL SAFETY MONITORING INTERVENTIONS

4.4.1 Effectiveness of Safety Monitoring Interventions

Both high-tech and low-tech monitoring solutions have proven effective in Sri Lanka. The following Table 3 highlights key success stories.

Table 3: Examples of successful safety monitoring interventions

Project location	Intervention	Cost of intervention	Outcome / averted loss	Expert citation
Marina Square	Strain gauges are installed on structural elements.	Rs.1.2 million	Detected critical stress, enabling evacuation before a collapse. Averted an estimated Rs 150 million in damages and multiple fatalities.	E4
Liberty Plaza/Port City	Tilt sensors and laser alignment systems on cranes and structures.	Rs.450,000−Rs.1.8 million	Prevented potential structural failures and crane collapses, averting losses estimated at ten times the investment cost.	E5, E10
Various High-Risk Sites	Dual-person supervision for critical tasks.	(Operational Cost)	A watchful supervisor averted a fatal accident from a failing beam.	E3, E12
General Application	Smartphone-based app using simple laser levels.	(Low Cost)	Demonstrates that low-tech, accessible solutions can significantly improve safety monitoring.	E8

4.4.2 Drivers and Barriers to Adoption

Experts in high-rise construction in Sri Lanka have highlighted the importance of IoT safety systems in preventing disasters. They highlighted the need for industrial-grade solutions with waterproof enclosures rated IP68 to withstand monsoon conditions, equipment that can endure falls from a height of three feet onto concrete, and user-friendliness. They also advocated for incorporating Sinhala/Tamil voice alerts to assist workers with low literacy levels or limited English proficiency. Alarms must be intuitive, recommending intense audio and visual alerts instead of app alerts.

The life-saving potential of IoT systems is highlighted through example of a monitoring system saving multiple deaths and damages, and a crane collapse in Colombo. Customizing IoT systems to the unique challenges of Sri Lanka is crucial, with proposals for solar-powered capability and strict cost caps. The experts also stressed the need to align with existing accounting principles to deliver verifiable return on investment to contractors.

4.5 PRIORITY OF REAL-TIME DATA TYPES FOR CONSTRUCTION SAFETY MONITORING

Experts identified the most critical data types for real-time monitoring to prevent accidents. The emphasis was consistently on simple, actionable alerts rather than complex analytics. The following Table 4 prioritises these data types.

Table 4: Priority data types for real-time safety monitoring

Monitoring category	Priority data type	Rationale and purpose	Supporting experts
Personnel Monitoring	• Worker location in hazardous zones • Worker fatigue levels	• Enable targeted emergency response. • Predict and prevent human-error accidents.	E4, E5, E6, E7, E8, E10, E11, E12
Environmental Monitoring	• Wind speed• General weather conditions • Air quality in enclosed spaces	• Ensure safe crane operation. • Proactive site shutdowns. • Prevent respiratory hazards.	E1, E3, E4, E5, E10, E11, E12
Equipment and Structural Monitoring	• Vibration patterns in structures • Crane load measurements • Equipment maintenance status	• Indicate imminent structural stress or failure. • Prevent overloading and collapse. • Link maintenance neglect leads to accident risk.	E4, E5, E6, E7, E8, E10

4.6 INTERNATIONAL PRACTICES ADAPTABLE TO SRI LANKA

Experts identified several international best practices that could be successfully adapted to the Sri Lankan context by focusing on simplicity, visual cues, and cultural integration, and these data are summarised under Table 5.

Table 5: International practices on safety

Practice or technology	Origin	Adaptation required	Suggested and supported by
Simplified Digital Systems	Singapore/Dubai	Replace apps with lights/buzzers	E4, E5, E6, E7, E10
Color-Coded Tagging	Dubai	Visual systems without digital dependency	E5, E10, E11
QR Code Inspections	Australia	Paperless but simple interface	E6, E7, E9
Safety Moments	New Zealand	Adapted to tea-break culture	E8, E13

Practice or technology	Origin	Adaptation required	Suggested and supported by
Physical Safety Nets	International	Low-cost visible protection	E12, E15
Automated Compliance	Dubai	Link to payments with simple deductions	E5, E9, E16
Drone Monitoring	Multiple	Focus on hazard mapping, not just progress	E14, E17

4.7 SRI LANKA'S READINESS FOR IOT SAFETY

Experts expressed serious concern about Sri Lanka's preparedness for adopting IoT in construction safety, rating it as low as 2–3 out of 10. Key challenges include resistance from workers who see IoT devices as surveillance tools, sometimes leading to sabotage, and persistent issues with basic safety practices. Managerial reluctance to invest without clear ROI or client demand further stalls progress, creating a paradoxical "catch-22" where adoption is needed to prove value, but value cannot be proven without adoption.

To overcome these barriers, experts recommend a phased, context-specific approach that integrates IoT into existing systems without overwhelming the current framework. Emphasis is placed on training, technological adaptation, economic incentives, and supportive policies. Importantly, solutions must suit Sri Lanka's unique socio-economic context rather than mimic models from more technologically advanced nations.

5. DISCUSSION

The combined literature and expert evidence highlight a clear and significant gap between theoretical safety frameworks and actual practices in high-rise construction. Literature confirms the high-risk nature of such projects, particularly regarding falls, hazardous scaffolding, and material handling (Abbood et al., 2021; Bhilwade et al., 2022), a concern echoed by E4, E8, and E10, who noted the normalization of risky behaviours. Electrical hazards and equipment failures are also well-documented; studies point to unsafe temporary wiring as a major risk (Cai et al., 2020), supported by experts E4, E10, and E11, who observed poor waterproofing and exposed cabling in practice.

Although IoT-based safety solutions like wearable sensors and real-time monitoring show strong potential for incident prevention (Musarat et al., 2022; Wang et al., 2024), their implementation remains inconsistent. Experts E4, E5, and E10 reported failed deployments due to environmental conditions, user resistance, and unclear return on investment (ROI), discouraging management from adopting these systems. While technologies such as BIM and IoT can theoretically reduce incidents by up to 30% (Rodrigues et al., 2022), experts E6, E9, and E12 noted their minimal usage in Sri Lanka, citing high costs, inadequate infrastructure, and a lack of supportive policies.

Cultural compatibility also emerged as a barrier to adoption. E8 emphasized the need for localized adaptations, such as using colour-coded symbols or reinforcing safety during tea breaks, to better align with local practices. Overall, while integrated safety technologies have transformative potential, the findings underscore the need for context-sensitive deployment strategies, cultural alignment, and supportive economic and policy measures to ensure sustainable adoption.

6. CONCLUSION

The research found that even though high-tech safety solutions from IoT (like real-time monitoring and BIM integration) have great potential, they are rarely used in Sri Lanka's high-rise building sector. It is difficult to implement on a large scale because of workforce resistance, inadequate policies, and the lack of a match between global technologies and local economic situations. It is essential to use a phased approach, adapting to culture by using inexpensive IoT devices and providing localised training and interfaces, to shift from being reactive about safety to being proactive. This strategy may prevent many accidents and still suit Sri Lanka's economic and environmental limits.

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IOT IMPLEMENTATION FOR ENERGY MANAGEMENT WITHIN RESIDENTIAL BUILDINGS IN SRI LANKA: DRIVERS AND BARRIERS

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ABSTRACT

Effective energy management is essential to address the growing energy demand and sustainability challenges in Sri Lanka. The Internet of Things (IoT) offers promising solutions by enabling real-time monitoring, automation, and data-driven decision-making to enhance energy efficiency. While IoT adoption has advanced in many developed countries, its application within Sri Lanka's residential building sector remains limited. Existing literature lacks a focused examination of the contextual drivers and barriers influencing IoT adoption in this domain. This study aims to bridge this gap by identifying and analysing the key factors affecting IoT implementation for energy management in Sri Lankan households. Adopting a qualitative research approach, semi-structured interviews were conducted with fifteen industry experts, each possessing over ten years of experience in construction and at least five years in energy management with IoT knowledge. The findings highlight eleven key drivers, including cost efficiency, ease of control, and government support, and ten significant barriers, such as high initial costs, data privacy concerns, and low-quality devices. The study contributes to the academic literature by offering an understanding of IoT adoption in residential building for energy management. Future research should focus on addressing specific technical integration challenges, exploring infrastructure limitations and the integration of renewable energy sources.

Keywords: *Barriers; Enablers; Energy Management; Internet of Things; Residential Buildings.*

1. INTRODUCTION

The increasing demand for energy and the growing concerns for sustainability have led to a global shift towards smarter and more efficient energy management strategies (Mir, 2024). As populations grow and industries expand, the need for reliable, cost-effective, and environmentally sustainable energy systems has become more critical (Ehsanifar et al., 2023). One of the most significant strategies to address these challenges is the integration of the Internet of Things (IoT) into energy systems. IoT technologies enable

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real-time monitoring, automation, and optimisation of energy consumption, leading to more efficient energy management (Bedi et al., 2018). Through the integration of smart devices, sensors, and analytics into energy systems, IoT can transform how energy is produced, distributed, and consumed, resulting in a significant enhancement of energy management (Jia et al., 2024).

IoT-driven energy management solutions have proven to be effective in reducing energy consumption across various sectors by providing real-time insights into energy usage patterns and offering tools for better decision-making (Ehsanifar et al., 2023). These systems offer several benefits, including the ability to track energy usage at the individual device level, automate energy-saving actions, and predict maintenance needs before problems occur (Jia et al., 2024). The widespread adoption of IoT technologies in developed countries has demonstrated substantial improvements in energy efficiency, cost reduction, and the achievement of sustainability goals (Singh et al., 2022). These advancements, however, have not been equally realised in Sri Lanka, where energy management practices in residential buildings are still evolving.

Despite the global momentum in integrating IoT technologies into energy management systems, Sri Lanka remains in the early stages of adopting these solutions, particularly within the residential sector. While numerous studies have explored the potential of IoT in energy management across various construction domains (Kumar et al., 2021; Zhang et al., 2021), residential energy consumption in Sri Lanka continues to rely heavily on traditional, unoptimized practices (Liyanage et al., 2023). This is especially concerning given the rising national energy demand and the urgency for sustainable and efficient energy use (Caldera et al., 2023). Although there is growing interest in smart technologies, academic and practical investigations into IoT implementation specifically within Sri Lankan residential buildings remain scarce. This lack of context-specific research presents a critical gap in understanding the feasibility, challenges, and opportunities of adopting IoT-driven energy solutions in this sector.

To address this gap, this paper aims to identify and analyse the key drivers and barriers influencing IoT adoption for energy management in Sri Lanka's residential buildings. By examining these factors through qualitative research, the study aims to generate insights into the enablers of successful implementation of IoT for energy management, as well as the challenges that may hinder progress. Ultimately, the research also provides targeted strategies to enhance the adoption of IoT technologies in Sri Lankan households, thereby contributing to national energy efficiency and sustainability goals.

2. LITERATURE REVIEW

2.1 IOT IN ENERGY MANAGEMENT

IoT refers to a network of interconnected physical devices that communicate and exchange data through the internet, enabling intelligent monitoring, control, and automation of various processes (Wortmann & Flüchter, 2015). It has transformed energy management by enabling real-time data collection, automation, and predictive analytics (Mudaliar & Sivakumar, 2020). Smart meters, intelligent sensors, and cloud-based platforms facilitate accurate energy monitoring and control, improving efficiency (Bolla et al., 2011). Studies indicate that IoT-based energy management systems can reduce energy consumption by up to 30% in residential buildings (Al-Ali et al., 2017). Recent advancements in IoT technologies, including edge computing, blockchain integration for

energy transactions, and machine learning algorithms for predictive energy management, have significantly improved efficiency and security in energy consumption (Ehsanifar et al., 2023; Jia et al., 2024). These developments allow for better load balancing, real-time fault detection, and seamless integration with distributed energy resources. Smart home systems, embedded with IoT solutions, are gaining popularity globally, as they enable automatic appliance control and provide consumers with real-time feedback on their energy usage, fostering behavioural changes that contribute to energy savings (Yar et al., 2021).

2.2 ENERGY MANAGEMENT PRACTICES IN SRI LANKA

Sri Lanka's energy consumption patterns show a high dependency on non-renewable energy sources, with residential demand accounting for a significant portion of the total electricity usage (Murshed et al., 2020). The government has implemented various initiatives, such as net metering for solar energy, energy-efficient lighting programs, and tiered tariff structures, to promote conservation (De Alwis & Bekchanov, 2020). However, these initiatives primarily target large-scale consumers, leaving a gap in residential energy management. Studies highlight that the lack of smart infrastructure, the absence of policy frameworks, and resistance to new technologies hinder the adoption of advanced energy management solutions (Yahya et al., 2023). Comparative studies with countries such as India and Malaysia reveal that government incentives and public awareness campaigns play a crucial role in encouraging IoT adoption in residential energy management (Zhang et al., 2021).

The adoption of IoT in Sri Lanka's residential sector has been slow, primarily due to affordability concerns and the absence of nationwide digital infrastructure. The energy sector in Sri Lanka heavily depends on centralised electricity distribution, with minimal integration of smart grid technologies (Kumar et al., 2021). Many developed countries have moved towards decentralised energy models, where IoT enables consumers to produce, store, and distribute their own energy efficiently. Lessons from these international case studies suggest that Sri Lanka must adopt a more proactive approach to digital transformation in the energy sector, including investment in IoT-ready infrastructure and smart metering solutions at the household level (De Alwis & Bekchanov, 2020).

2.3 DRIVERS AND BARRIERS FOR IOT IMPLEMENTATION IN RESIDENTIAL BUILDINGS

Studies have identified several key drivers and barriers to the implementation of IoT in energy management. Among these, the most commonly cited drivers are cost efficiency, energy efficiency, real-time monitoring, predictive maintenance, and sustainability goals. Cost efficiency is a major motivator, as IoT systems can reduce long-term energy consumption and operational costs (Bedi et al., 2018; Mishra & Singh, 2023). Energy efficiency is another critical driver, with IoT enabling better management of energy consumption, leading to significant savings (Ahmad & Zhang, 2021; Hossein Motlagh et al., 2020). Real-time monitoring and predictive maintenance offer increased visibility into energy usage, allowing for timely adjustments and improved system performance (Saleem et al., 2022). Additionally, achieving sustainability goals is a significant driver, as IoT technologies contribute to reducing environmental impact through optimised energy use (Mishra & Singh, 2023).

On the other hand, several barriers hinder the adoption of IoT for energy management. High initial investment is a significant obstacle, as the upfront cost of IoT systems can be prohibitive for many residential consumers. Data security and privacy concerns are also critical challenges, as IoT systems require the collection and transmission of sensitive data, raising potential vulnerabilities (Bedi et al., 2018). Integration complexity and lack of standardisation further complicate the implementation process, as IoT solutions often need to integrate with existing systems and adhere to industry standards. Other barriers include reliability and connectivity issues, which can disrupt IoT operations, and the lack of skilled professionals, which hinders the effective deployment and maintenance of IoT systems. Lastly, the lack of awareness among both consumers and policymakers about the benefits and functionalities of IoT technologies poses a significant challenge to their widespread adoption. These barriers must be addressed for IoT to achieve its full potential in residential energy management. The drivers and barriers identified by the various literature have been provided in Table 1.

Table 1: Drivers and barriers for IoT implementation for energy management

Code	Drivers	Sources
D1	Cost efficiency	(Bedi et al., 2018; Mishra & Singh, 2023)
D2	Energy efficiency	(Ahmad & Zhang, 2021; Hossein Motlagh et al., 2020)
D3	Real-time monitoring	(Mudaliar & Sivakumar, 2020; Saleem et al., 2022)
D4	Predictive maintenance	(Han et al., 2021a; Mudaliar & Sivakumar, 2020; Saleem et al., 2022) (Han et al., 2021a; Mudaliar & Sivakumar, 2020; Saleem et al., 2022)
D5	Sustainability goals	(Mishra & Singh, 2023)
D6	Time saving	(Han et al., 2021; Yahya et al., 2023)
D7	Easy control	(Mudaliar & Sivakumar, 2020; Sabit & Tun, 2024)
Code	**Barriers**	**Sources**
B1	High initial investment	(Jia et al., 2024; Khafiso et al., 2024)
B2	Data security and privacy concerns	(Bedi et al., 2018; Jia et al., 2024; Khafiso et al., 2024; Mishra & Singh, 2023)
B3	Integration complexity	(Kumar et al., 2021; Sabit & Tun, 2024)
B4	Lack of standardisation	(Al-Obaidi et al., 2022; Sabit & Tun, 2024; Zhang et al., 2021)
B5	Reliability and connectivity issues	(Al-Obaidi et al., 2022; Kumar et al., 2021; Sabit & Tun, 2024)
B6	Lack of skilled professionals	(Al-Obaidi et al., 2022; Kumar et al., 2021; Marinakis & Doukas, 2018)
B7	Lack of awareness	(Kumar et al., 2021; Sabit & Tun, 2024; Zhang et al., 2021)

3. METHODOLOGY

This study aims to identify the drivers and barriers to the utilisation of IoT in energy management within Sri Lankan residential buildings. Understanding these factors is essential for assessing the feasibility of IoT adoption and its potential impact on energy efficiency in the residential sector. Expert perspectives are critical in developing a comprehensive understanding of the opportunities and challenges related to IoT implementation. Professionals with experience in energy management, construction, and IoT can provide valuable insights into how these technologies can be effectively integrated into Sri Lanka's residential energy landscape. In-depth discussions based on professionals' field experience are necessary to explore the subject comprehensively (Saunders et al., 2023).

A qualitative research approach was adopted to capture detailed insights into the real-world drivers and barriers associated with IoT-based energy management in Sri Lanka. The study is structured around several key components: a literature review to examine global and local trends in energy management and IoT applications, data collection through semi-structured expert interviews, thematic analysis to identify emerging drivers and barriers, and synthesis of findings to propose actionable recommendations for IoT adoption in residential buildings.

According to Guest et al. (2006), data saturation in qualitative research is generally achieved within 6 to 12 interviews, with more than 80% of thematic codes typically emerging in the early stages. In the present study, thematic saturation was observed after the eleventh interview, with four additional interviews conducted to validate the absence of new emerging themes and to ensure robustness in the findings. A total of fifteen (15) semi-structured interviews were conducted with industry experts who possessed more than ten years of experience in the construction sector and at least five years of involvement in energy management, alongside demonstrated knowledge of IoT technologies.

Participants were selected through purposive sampling to ensure the inclusion of individuals with adequate professional or academic expertise relevant to the study's objectives. The experts were selected from the construction industry such that they represent key stakeholders within different stages of the building lifecycle, including both construction and operational phases. As the aim of the study was to examine the key drivers and barriers influencing the IoT adoption for energy management in Sri Lanka's residential buildings, three selection criteria were used to choose the professionals being interviewed, namely, experience in the construction industry, energy management and knowledge and understanding of IoT. For this study, experts such as Engineers, Chief executive officers, quantity surveyors, and assistant operation managers who fulfilled the three selection criteria were selected. These experts offered valuable insights into the real-world challenges associated with IoT adoption in residential energy management, including issues related to infrastructure limitations, regulatory constraints, and technological integration. Through this, the study addressed a significant research gap concerning the practical implementation of IoT-based energy management systems in Sri Lankan residential buildings. A summary of the experts' profiles is presented in Table 2.

Table 2: Profile of interview experts

Expert	Designation	Experience in the construction industry (more than 10 years)	Experience in Energy Management (more than 5 years)	Knowledge regarding IoT
R1	Senior Engineer	✓	✓	✓
R2	Chief Executive Officer	✓	✓	✓
R3	Chief Executive Officer	✓	✓	✓
R4	Lead Consultant	✓	✓	✓
R5	Charted Quantity Surveyor	✓	✓	✓
R6	Chief Executive Officer	✓	✓	✓
R7	Assistant Operations Manager	✓	✓	✓
R8	Senior Engineer	✓	✓	✓
R9	Chief Executive Officer	✓	✓	✓
R10	Charted Quantity Surveyor	✓	✓	✓
R11	Senior Engineer	✓	✓	✓
R12	Senior Engineer	✓	✓	✓
R13	Charted Quantity Surveyor	✓	✓	✓
R14	Chief Executive Officer	✓	✓	✓
R15	Chief Executive Officer	✓	✓	✓

The interviews were conducted in person, each lasting between 30 to 45 minutes. The collected data was analysed using manual content analysis, following a three-stage process. First, all interviews were transcribed to ensure accuracy. Second, the transcriptions were critically reviewed to identify key themes and patterns. Finally, the data were standardised and classified according to both deductive and inductive coding approaches. By following this structured methodology, the study ensures a thorough exploration of IoT's role in energy efficiency, backed by industry expertise and best practices. The insights gained will contribute to developing practical recommendations for implementing IoT-based energy management solutions in Sri Lankan residential buildings.

4. RESULTS AND DISCUSSION

4.1 DRIVERS OF IOT IMPLEMENTATION FOR ENERGY MANAGEMENT

The literature review identified five key drivers for IoT implementation in energy management, including cost efficiency, energy efficiency, real-time monitoring, predictive maintenance, and sustainability goals. Through the expert interviews, six additional drivers were identified, further expanding the understanding of the factors influencing IoT adoption in Sri Lanka's residential energy management sector. Table 3

presents the outcomes of these expert interviews, highlighting the drivers of IoT for energy management in residential buildings.

Among the eleven drivers of IoT for energy management in residential buildings, the cost efficiency, time saving, easy control, and government support emerged as the most frequently mentioned drivers. These factors were highlighted by nearly all of the participants as key drivers that influence the adoption of IoT solutions in residential buildings.

Cost efficiency was identified as a critical driver within the literature (Bedi et al., 2018; Mishra & Singh, 2023), similarly, experts emphasised that IoT systems may seem expensive at the initial stage, but they can lead to long-term savings through energy optimisation and reduction in utility costs. Timesaving was another frequently mentioned driver, as IoT-based systems allow for the automation of energy-consuming devices, reducing the need for manual monitoring and control. The ability to easily control devices remotely via IoT interfaces was also cited as a significant factor, providing convenience to homeowners and improving user engagement with energy management practices. Finally, government support, particularly in the form of incentives and regulatory frameworks, was highlighted as an essential factor in driving the adoption of IoT in residential buildings.

4.2 BARRIERS TO IOT IMPLEMENTATION FOR ENERGY MANAGEMENT

Further, the experts were questioned about the significant barriers that impact the implementation of IoT in energy management. Initially, seven barriers to IoT implementation for energy management were identified through the literature review. However, the interviews revealed three additional barriers, expanding the understanding of the challenges faced in adopting IoT for residential energy management in Sri Lanka. The identified ten barriers are listed in Table 4. Among them, the most frequently highlighted barriers include high initial investment, data security and privacy concerns, lack of awareness, and the use of low-quality devices. These barriers were emphasised by the majority of experts as significant obstacles that hinder the widespread adoption of IoT-based energy management solutions in residential buildings. However, factors such as cost and accessibility of IoT depend on different socio-economic groups. Although is was considered a significant barrier among the majority of the participants, it should be analysed in detail across various socio-economic groups.

4.3 STRATEGIES TO OVERCOME BARRIERS TO IOT IMPLEMENTATION

The expert interviews provided valuable insights into various strategies for overcoming the barriers to IoT implementation in residential energy management. These strategies, proposed by the respondents, addressed the challenges related to cost, awareness, security concerns, and regulatory frameworks. Table 5 presents the strategies identified by the experts, along with the respondents who suggested each solution. These strategies reflect a comprehensive approach that includes government support, developer responsibility, public awareness, expert guidance, and business planning.

Table 3: Drivers of IoT implementation for energy management

	Code	Drivers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
Drivers as per the Literature	D1	Cost efficiency	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	D2	Energy efficiency	✓	✓			✓	✓	✓	✓	✓	✓	✓			✓	✓
	D3	Real-time monitoring	✓		✓	✓			✓	✓	✓		✓	✓		✓	✓
	D4	Predictive maintenance	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓
	D5	Sustainability goals	✓	✓				✓	✓	✓	✓	✓			✓	✓	✓
	D6	Time saving	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
	D7	Easy control	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Additional Drivers	D8	People's interest	✓	✓		✓		✓	✓		✓			✓	✓	✓	✓
	D9	Growing population			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
	D10	Support from the Government	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	D11	Promotions from service providers	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓

Table 4: Barriers to IoT implementation for energy management

	Code	Drivers	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
Barriers as per the literature	B1	High initial investment	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
	B2	Data security and privacy concerns	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
	B3	Integration complexity	✓			✓	✓	✓	✓	✓	✓		✓	✓		✓	✓
	B4	Lack of standards and regulations	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓
	B5	Reliability and connectivity issues	✓	✓				✓	✓	✓	✓	✓			✓	✓	✓
	B6	Lack of skilled professionals	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓
	B7	Lack of awareness	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Additional Barriers	B8	Architectural issues	✓	✓		✓		✓	✓		✓			✓	✓		
	B9	Lack of cost planning	✓	✓	✓					✓	✓	✓		✓	✓		
	B10	Low-quality devices	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 5: Strategies to overcome the barriers to IoT implementation

Code	Strategies to Bridge the Gap	Experts	Related Barriers
S1	Government intervention to reduce the cost of devices	R8	B1, B9, B10
S2	Developers should demonstrate the results of IoT systems to justify the initial investment	R4, R5, R13	B1, B6, B7
S3	Public awareness campaigns by both the government and developers to educate the public about IoT technologies and their benefits	R1, R2, R3. R9. R10	B2, B7
S4	Government-imposed standards for IoT technologies to ensure secure and efficient integration	R1, R6, R7, R12, R15	B2, B3, B4, B5
S5	Providing energy guarantees for energy-consuming equipment to build consumer confidence	R1, R15	B1, B3
S6	Seeking expert guidance before adopting IoT systems to ensure proper implementation	R3, R4, R5, R7	B3, B5, B6, B7
S7	Encouraging collaborative initiatives among stakeholders in the IoT ecosystem	R5, R12	B3, B6, B9
S8	Developing a comprehensive business plan before adopting IoT to ensure alignment with business goals	R14, R15	B3, B9

These strategies indicate a combined approach to overcome the barriers to IoT adoption in residential energy management. The suggestions from the respondents highlight the importance of collaboration between the government, developers, and other stakeholders to reduce the identified barriers, such as cost, lack of awareness, and knowledge regarding IoT for energy management. Tax reductions and cost reduction strategies, such as providing energy guarantees for equipment, aim to tackle the financial barriers identified in the study. Public awareness campaigns and the implementation of IoT standards are crucial to addressing knowledge gaps and ensuring a secure and efficient ecosystem. Furthermore, expert guidance and a well-structured business plan are seen as essential for ensuring proper IoT system implementation and long-term success. These strategies emphasise the need for coordinated efforts to overcome the challenges and unlock the potential of IoT in residential energy management. The outcomes of this study specifically focus on the residential building sector within Sri Lanka and can be generalised for the residential building sector of similar developing countries.

5. CONCLUSION

This study explored the drivers and barriers to the implementation of IoT in energy management within Sri Lankan residential buildings. The findings revealed that key drivers such as cost efficiency, timesaving, ease of control, and government support were the most significant drivers encouraging the IoT adoption. These factors reflect the economic motivations for adopting smart technologies. On the other hand, high initial

investment, data security and privacy concerns, lack of awareness, and the prevalence of low-quality devices were identified as the most significant barriers. To address these challenges, the study identified several strategies, including government interventions in terms of tax reduction and financial aid, public awareness campaigns, standardisation of IoT technologies, and the promotion of expert guidance. These strategies aim to reduce financial and technical gaps that currently impact the IoT adoption. According to the outcomes of the research, it was identified that IoT can significantly enhance energy management practices in residential buildings. This study can be further developed focusing on the specific technical challenges associated with IoT implementation in Sri Lankan residential buildings, such as infrastructure limitations and the integration of renewable energy sources.

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LEAN INTEGRATED BUSINESS MODEL FOR CONSTRUCTION: A SYSTEMATIC REVIEW ON CURRENT PRACTICES AND FUTURE DIRECTIONS

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ABSTRACT

The construction industry plays a critical role in economic and social development but continues to face challenges such as inefficiencies, cost and time overruns, and client dissatisfaction. Lean Construction has emerged as a promising philosophy aimed at minimising waste and maximising value in construction processes. However, widespread adoption remains hindered by barriers such as resistance to change and resource limitations. Integrating Lean Construction principles into Business Models (BM)s referred to as Construction Business Models (CBMs) presents a strategic opportunity to enhance productivity and optimise value creation. Hence there is research gap in construction industry this paper aims to analys the literature on Lean Construction, BMs, and their integration within the construction industry to bridge this research gap. To address this, a systematic literature review (SLR) was conducted, examining publications from databases such as Scopus and Taylor & Francis. Using targeted search terms, 75 documents were initially retrieved, and after filtering, 61 publications were selected for comprehensive analysis. This study explores the integration of Lean Construction within BMs to optimise value in construction projects, offering insights into strategic frameworks that can overcome current inefficiencies. By examining Lean Business Models (LBMs) and their application in construction, the paper contributes to a deeper understanding of how lean principles can drive sustainable business innovation and operational efficiency within the industry.

Keywords: *Business Models (BMs); Construction Business Models (CBM); Lean Business Models (LBMs); Lean Construction.*

1. INTRODUCTION

The construction industry is a key driver of economic and social development, yet it faces persistent challenges such as cost and time overruns, inefficiencies, resource limitations, and client dissatisfaction (Chen et al., 2022; Das et al., 2022; De-Wolf et al., 2023; Kulatunga et al., 2023). To address these issues, innovative management approaches such

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as LC and BMs have gained significant attention (De-Wolf et al., 2023; Goziev, 2022; Rashidian et al., 2023).

Lean Thinking originated in Japan in the 1940s through the Toyota Production System (TPS), developed by Taiichi Ohno. Initially focused on engine manufacturing in the 1950s, it expanded to vehicle assembly in the 1960s and supply chain management by the 1970s (Monden, 2012; Womack et al., 1996). The concept of Lean Production gained global attention by the mid-1980s, aiming to deliver customised products with minimal inventory (Garces & Pena, 2023), and was formalised by Krafcik in 1988. By the 1990s, lean principles extended beyond manufacturing to management and product development (Garces & Pena, 2023), becoming integral to both operational and strategic planning (Lyons et al., 2013).

Lean Construction (LC) evolved from Lean Production as a method to reduce waste and improve project performance (Garces & Pena, 2023; Hamzeh et al., 2021). First conceptualised by Koskela (1992), LC promotes continuous improvement and value delivery (Koskela et al., 2002). It offers a holistic approach focused on reducing waste, enhancing workflow, and meeting client needs (Green & May, 2005). Core LC principles, outlined by Koskela (2004), align with lean thinking and target inefficiencies in construction.

Numerous tools and techniques have been developed to support LC, helping to minimise resource use, time, and cost while maximising value (Zhang & Chen, 2016; Aslam et al., 2022). These tools enhance process efficiency, waste reduction, and project outcomes (Khaskheli et al., 2020; Xing et al., 2021). Studies confirm the effectiveness of LC tools in construction, with over 50 tools identified, varying in application by industry size and project complexity (Li et al., 2020; Issa, 2013; Babalola et al., 2019)

However, the implementation of lean thinking in construction offers a wide range of benefits that contribute to economic, social, and environmental sustainability. Economically, lean thinking promotes continuous improvement in projects and facilitates the timely and cost-effective delivery of products and services by minimising waste (Aslam et al., 2022; Mohammadi et al., 2022). It also helps reduce overall construction costs (Aziz & Hafez, 2013; Babaremu et al., 2022), enhances overall equipment effectiveness (Maradzano et al., 2019), improves project delivery methods and quality (Aslam et al., 2022; Maradzano et al., 2019), and increases both process efficiency and labour productivity (Mohammadi et al., 2022). It further supports managing uncertainties in supply chains (Aslam et al., 2022; Maradzano et al., 2019). Socially, lean thinking strengthens cooperation among stakeholders (Ahmed et al., 2020; Aslam et al., 2022; Maradzano et al., 2019), enhances value creation for improved client and customer satisfaction (Aslam et al., 2022), improves employee satisfaction and supplier relationships (Ahmed et al., 2020; Aslam et al., 2022; Bajjou & Chafi, 2021), and enables the optimal allocation of project resources (Aslam et al., 2022; Maradzano et al., 2019). Environmentally, lean practices promote sustainable development, process optimisation, and waste elimination (Aslam et al., 2022; Maradzano et al., 2019), reduce environmental impacts, and enhance environmental performance (Aslam et al., 2022), while fostering cooperative relationships that support waste reduction (Maradzano et al., 2019; Mohammadi et al., 2022).

Despite the numerous benefits of LC, its implementation is hindered by several interrelated barriers identified across various studies. These barriers can be broadly

categorised into six major groups. Management barriers include poor coordination among project parties (Ahmed et al., 2020; Enshassi et al., 2021; Sarhan et al., 2018), resistance to change by management (Sarhan et al., 2018; Enshassi et al., 2021; Mano et al., 2020), poor project definition (Ahmed et al., 2020; Aslam et al., 2022; Sarhan et al., 2018), and overly centralised decision-making (Ahmed et al., 2020; Babalola et al., 2019; Mohammadi et al., 2022). Financial barriers involve the high cost of implementation (Ahmed et al., 2020; Babalola et al., 2019), the tendency to stick to traditional methods for financial reasons (Moradi & Sormunen, 2023), lack of worker incentives (Ahmed et al., 2020), and issues such as corruption and inflation (Enshassi et al., 2021; Moradi & Sormunen, 2023). Governmental barriers include inadequate support for LC adoption and inconsistent policies (Sarhan et al., 2018; Enshassi et al., 2021). Technical barriers reflect the absence of a long-term philosophy (Sarhan et al., 2018), inadequate planning (Ahmed et al., 2020), and the extended time needed to apply LC techniques (Enshassi et al., 2021). Educational barriers are linked to the shortage of trained professionals, lack of knowledge sharing among organisations, limited interest from academia, and a general lack of awareness and understanding of LC concepts (Moradi & Sormunen, 2023; Musa et al., 2023). Lastly, human-attitudinal barriers stem from employee resistance to change (Huaman-Orosco et al., 2022), lack of client interest (Bashir et al., 2015), and a lack of critical self-reflection to identify areas for improvement (Musa et al., 2023). These multifaceted barriers collectively highlight the organisational, economic, political, technical, educational, and cultural challenges that must be overcome to achieve successful Lean Construction adoption.

To minimise barriers to lean construction implementation, several techniques have been integrated with the lean concept. Among them, BMs can be identified as an innovative method for reducing these barriers, as they serve as strategic frameworks that enable organisations to create, deliver, and capture value (Abeynayake et al., 2022a; Arend, 2013; Das et al., 2023). However, the choice of BM for a specific business depends on various factors, including the nature of the product or service, the target market, and the competitive environment (Ratana et al., 2022). As a result, businesses may either adapt existing BMs to suit their needs or create unique BMs tailored to their specific characteristics and market conditions (Osterwalder et al., 2010; Ratana et al., 2022). The Business Model Canvas (BMC), a widely recognised tool, provides a structured approach to aligning business strategies with operational needs (Barquet et al., 2011; Osterwalder et al., 2010).

The concept of BMs has evolved significantly due to advancements in business practices, technology, and strategic innovation. First introduced in 1957, BMs gained traction in the 1960s (Osterwalder et al., 2005) and became widely recognised in the late 1990s, particularly with the rise of the Internet (Zott et al., 2010). Over time, BMs have extended beyond start-ups, increasingly influencing industries such as construction, where they enhance competitive advantage through technological advancements.

Timmers (1998) made an early contribution by classifying internet-based BMs based on innovation and functional integration. Aho (2013) emphasised that effective BMs incentivise long-term service delivery, align professional goals, and generate sustainable short-term returns. However, BM innovation is often perceived as risky due to potential disruptions, high costs, and uncertain outcomes (Treptow et al., 2022).

BMs in traditional industries like construction play a vital role in reducing inefficiencies and overcoming fragmentation by enhancing value creation and adapting to changing client demands (Girmscheid & Rinas, 2012). The literature identifies key BM components, value proposition, value creation, and value capture as central to delivering and sustaining competitive advantage (Teece, 2018). These are supported by elements such as value offering, target customer, distribution channels, and customer relationships, which shape how value is delivered (Osterwalder & Pigneur, 2010). Operational efficiency is further enhanced through value configuration, partner networks, and core competencies (Kujala et al., 2010). Financial sustainability is addressed via the cost structure, revenue model, and revenue generation logic (Morris et al., 2005), while strategic positioning within the value network ensures long-term relevance and collaboration (Mokhlesian & Holmén, 2012). Together, these elements form a cohesive framework that enables construction firms to create, deliver, and capture value more effectively. However, as a summary, a well-defined BM serves as a comprehensive framework that outlines how organisations create, deliver, and capture value.

In the construction industry there is a requirement to integrating lean principles into construction organisations is essential for reducing waste and enhancing value (Moradi & Sormunen, 2023). However, various implementation barriers persist. A well-defined Lean Business Model (LBM) provides a strategic framework to align value delivery with resource efficiency and customer needs (Balocco et al., 2019; Ramori et al., 2021).

In global context, limited research has explored the integration of LBMs across industries. Existing studies highlight the benefits of applying lean principles within BMs to enhance efficiency and value. For instance, Balocco et al. (2019) proposed a lean framework to optimise digital BMs, while Ramori et al. (2021) demonstrated LBM's potential in the healthcare sector to reduce waste and improve patient outcomes. Similarly, Kates (2014) explored how awards, standards, and lean frameworks can enhance organisational performance and supply chains. Further, Brotcorne et al. (2019) reported improved productivity, client satisfaction, and cost savings through LBM adoption. Sivakumar and Chawla (2022) introduced a decentralised Lean Business Model Canvas, merging lean six sigma and business process management for strategic agility.

In the construction industry, the application of LBMs has been less explored. Therefore, research indicates a need for developing CBMs that integrate Lean principles to enhance productivity and value optimisation in a construction organisation (Abeynayake et al., 2022a). Integrating LC with CBM is crucial for achieving a competitive advantage in the construction sector. However, studies addressing the development of CBMs that are integrated with lean concepts for value optimisation are limited (Abeynayake et al., 2022b; Arend, 2013).

To address the identified research gap, this paper aims to systematically review the implementation of LBMs, the integration of lean construction principles and BMs within the construction industry, with a specific focus on value optimisation for construction companies. By identifying gaps in existing studies, this research contributes to a deeper understanding of integrating lean construction principles through the BM to optimise the value of a construction business. Therefore, this paper consists of the introduction, methodology, the results of the systematic literature review and conclusion.

2. METHODOLOGY

This research employs a systematic review of the literature to evaluate the current state of research on the integration of lean construction and BM concepts in the construction Industry.

To investigate the Integration of BMs in the Construction Industry and optimisation of value through LC implementation, a comprehensive search was conducted across several databases, including Scopus and Taylor & Francis. Scopus and Taylor & Francis were selected for the literature search due to their extensive collections of peer-reviewed journals in construction management, lean practices, and business strategy. Scopus offers broad, multidisciplinary coverage and citation indexing, while Taylor & Francis provides high-quality research in built environment and organisational studies, making both platforms highly relevant to the research focus.

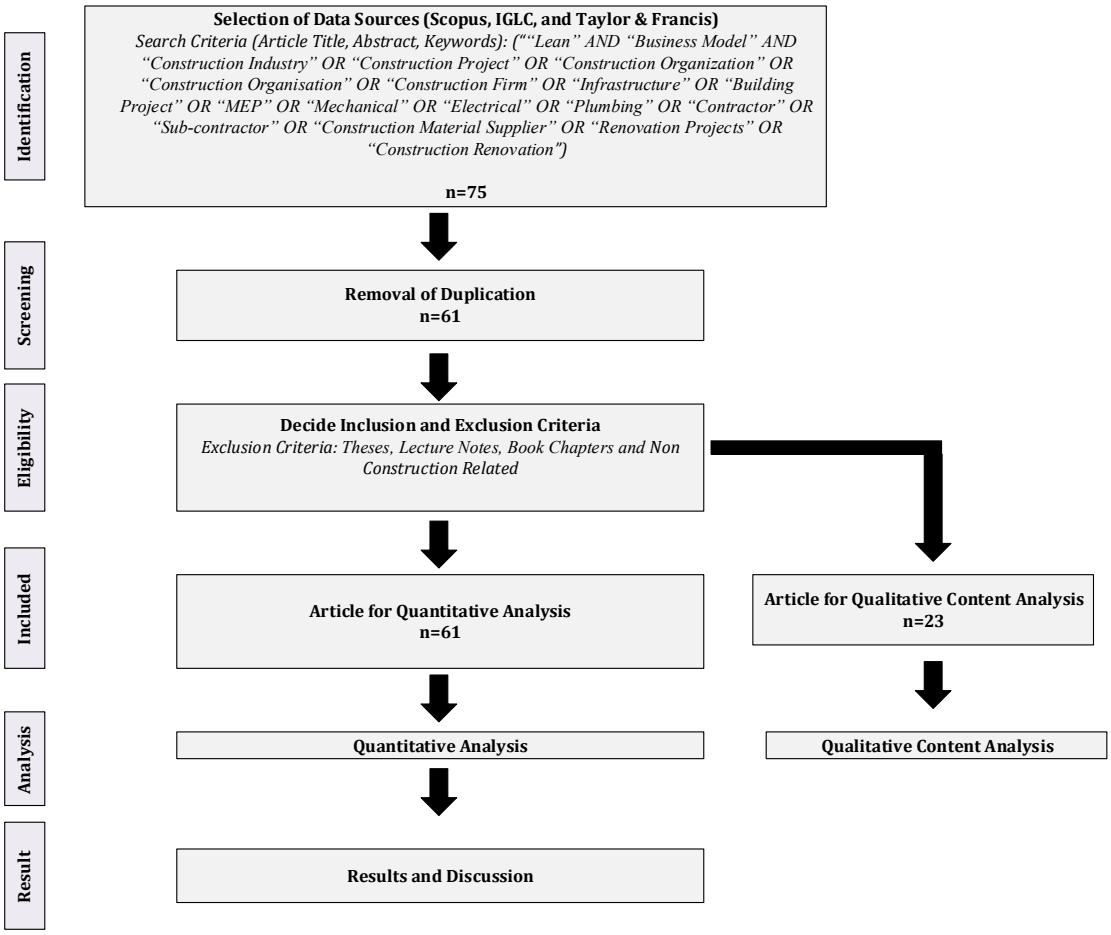


Figure 1: PRISMA protocol for the systematic review process

The initial search, using the terms "Lean" AND "Business Model" AND "Construction Industry" OR "Construction Project" OR "Construction Organization" OR "Construction Organisation" OR "Construction Firm" OR "Infrastructure" OR "Building Project" OR "MEP" OR "Mechanical" OR "Electrical" OR "Plumbing" OR "Contractor" OR "Sub-contractor" OR "Construction Material Supplier" OR "Renovation Projects" OR "Construction Renovation", retrieved 75 documents. After applying additional filtering, 61 unique publications were selected for the SLR. This process excluded duplicates,

theses, book chapters, and lecture materials to ensure the final dataset comprised only peer-reviewed journal articles and conference papers of high academic quality. In the inclusion stage, all 61 articles were subjected to quantitative analysis to examine publication trends, regional distribution, and methodological characteristics, utilising both bibliometric software (VOSviewer) and manual analysis. The overall process is illustrated in Figure 1, which summaries the key steps of the systematic literature review.

3. FINDINGS AND DISCUSSION

This section explores the application of LBMs referring to the integration of lean principles and BMs within the construction industry.

3.1 MAPPING OF RESEARCH WITH PUBLICATION YEARS

Based on the search results, Figure 2 displays the distribution of publications over time, providing a year-by-year analysis of research output.

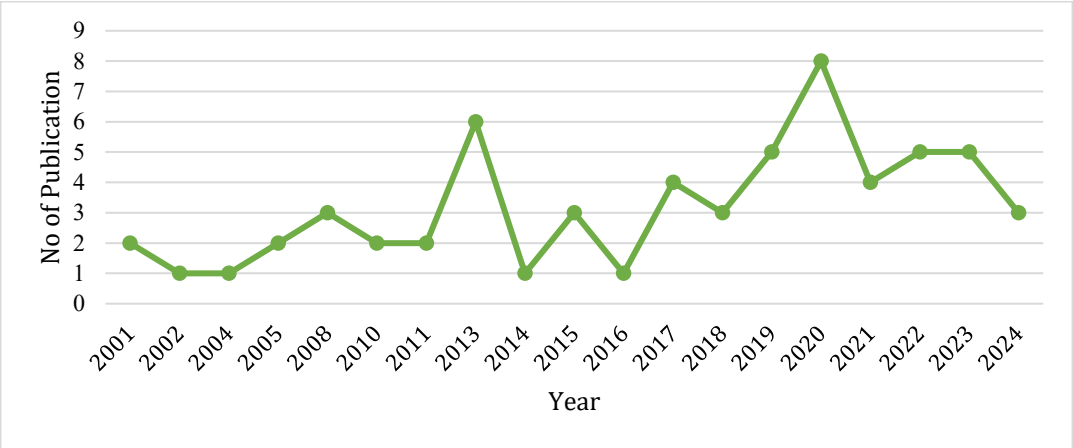


Figure 2: Number of publications over time: trends in lean BM implementation in the construction industry

This figure illustrates the yearly publication trend in different databases from 2001 to 2024. From 2001 to 2011, there was limited interest in the subject area with one (01) to three (03) articles. Since 2013, there has been a noticeable peak in publications, where the number of publications reach seven (07). The period from 2014 to 2019 can be considered as the fluctuating period which annually number of publications varies between one (01) to five (05). According to the graph another peak is shown in the year of 2020, with eight (08) numbers of publications. After the peak in 2020, the number of publications drops slightly and stabilises around three (03) to four (04) publications per year from 2021 to 2023. In 2024, there is a slight decline to two (02) publications, which may indicate a decrease in research output or interest as of this year. However, the shown trend of the publication emphasises that there were two notable peaks (in 2013 and 2020) with periods of fluctuation in between. The publication pattern shown in the graph suggested that this study area has experienced phases of intense research interest, followed by periods of moderate attention.

3.2 MAPPING RESEARCH AREAS ACROSS COUNTRIES

Based on the search results, Figures 3 illustrate the distribution of publications on the implementation of lean BMs in the construction industry across various countries.

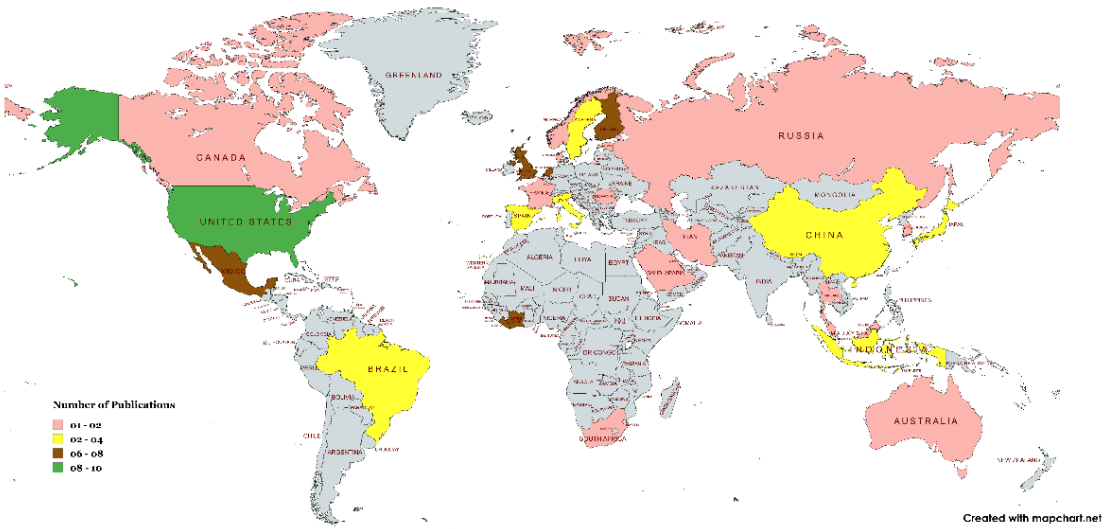


Figure 3: The worldwide spatial distribution of publications on lean BM implementation in the construction industry

The map shows the distribution of lean BM implementation publications in construction sector and is classified according to numbers of publication per country. Highlighted in green, the United States comes out as a major contributor with 9 targeted publications. Brown-highlighted countries are the United Kingdom, Finland and Netherlands, all with 6-7 publications. Yellow indicates countries including Germany and India where there is activity, with 4 to 5 publications from each. Countries with 2 or fewer publication counts (Brazil, China, Spain and Japan) are displayed in light brown. Finally, data from countries like Canada, France and Malaysia is shown in pink. This breakdown provides a spatial perspective of where LC and BM integration research is occurring significant and growing interest in North America, expanding work from Europe, with fledgling contributions emerging out of Asia thereby confirming widespread global attention to the implications of advanced BMs for an industry that has historically been slow to evolve.

3.3 NETWORK MAPPING OF RESEARCH KEYWORDS

A network map of the research area was generated using VOSviewer, emphasising keywords pertinent to this study. To ensure accuracy in the final output, shown in Figure 4, a comprehensive cleaning process was undertaken to eliminate duplicate keywords related to lean BMs.

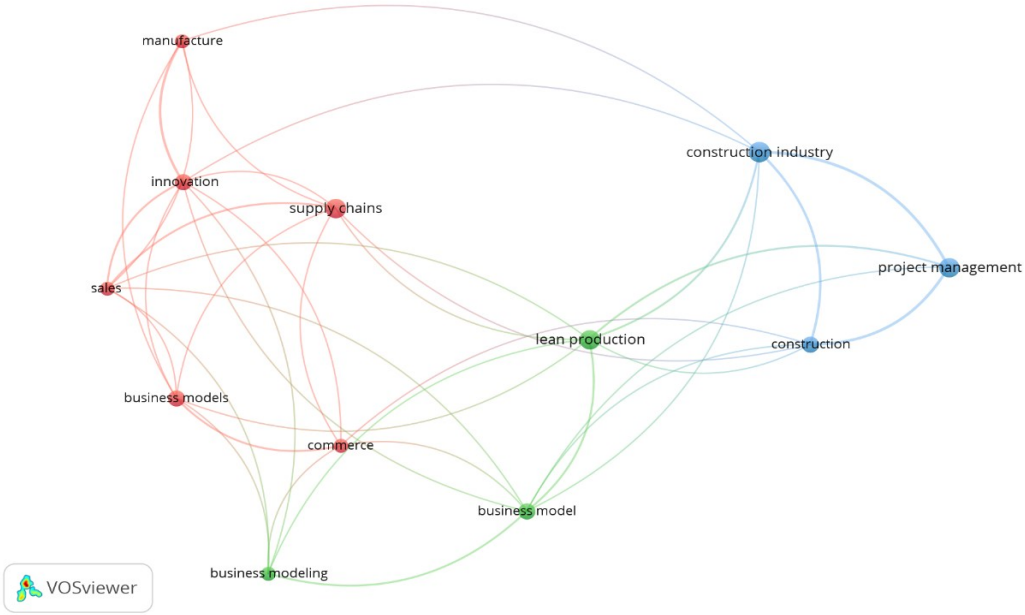


Figure 4: Network visualisation of keywords related to LBM implementation

Figure 4 illustrates a network visualisation of the most frequently used keywords in the selected literature. The size of the nodes reflects the frequency of keyword usage, while the links between them represent the strength of their co-occurrence. The analysis identifies three primary thematic clusters.

Cluster one includes six keywords: BMs, Commerce, Innovation, Manufacture, Sales, and Supply Chain highlighting a research focus on BM innovation within supply chain management and manufacturing processes. Cluster two groups the keywords BM, Business Modelling, and Lean Production, indicating a strong connection between lean principles and BM improvement in construction contexts. Cluster three comprises Construction, Construction Industry, and Project Management, focusing on project execution and management within the sector.

Overall, the network analysis suggests that existing research predominantly addresses the intersection of construction management, lean production, BMs, innovation, supply chains, and manufacturing. However, the diagram also highlights notable research gaps, particularly regarding the integration of lean production and construction management, BM innovation specific to the construction industry, and the combined application of Lean and BM concepts within construction. These gaps suggest significant opportunities for future research aimed at enhancing value creation and operational efficiency through Lean-integrated BMs in construction.

3.4 INTEGRATION OF LEAN BUSINESS MODELS IN CONSTRUCTION INDUSTRY

The concept of the LBM originates from Lean Manufacturing principles, first developed by Toyota in the mid-20th century (Pekuri et al., 2012), and has since evolved into various business contexts, including the Lean Startup methodology. Franke (2004) introduced a lean BM for airline businesses, emphasising cost reduction, revenue generation, and service differentiation. In construction, lean principles require a holistic transformation across value creation, proposition, and revenue systems (Pekuri et al., 2012), exemplified

by Toyota's lean BM approach incorporating business growth, technical coordination, supplier engagement, and waste minimisation. The Lean Startup BM, as discussed by Ide et al. (2015), follows an iterative process for business validation, while Cabrita et al. (2016) explored Lean, Agile, Resilient, and Green (LARG) principles to enhance BM efficiency. Lago et al. (2017) proposed Lean Canvas as a strategic tool for startups, which Balocco et al. (2019) further refined by integrating lean principles into BM change processes. Ghezzi and Cavallo (2020) investigated Lean BM applications in manufacturing and startups, emphasising structured development and value creation. The lean approach has also been applied in healthcare (Ramori et al., 2021), waste management and biofuel production (Moshood et al., 2022), demonstrating its adaptability across industries. Recent advancements include Allen's (2022) Realise Methodology, integrating Design Thinking with lean startups, and Sivakumar and Chawla's (2022) decentralised lean BM utilising blockchain for scholarly communication. In 2024, Tim et al. introduced the Lean Innovation Canvas for SMEs, Zinchenko explored Running Lean in the oil and gas sector, and Reke et al. proposed a Lean Circular BM integrating circular economy principles. These studies collectively illustrate the evolving applications of Lean BM across industries, emphasising efficiency, sustainability, and innovation.

However, existing literature extensively explores LBM implementation across various industries particularly in the context of lean startups limited attention has been given to the construction sector. Given the unique challenges in this industry, integrating BMs with lean construction is crucial for enhancing project value. To address this gap, a systematic literature review SLR was conducted to assess current research and identify areas requiring further investigation. As an initial step in the analysis, a statistical examination is conducted to evaluate publication trends based on two dimensions: publication year and country of origin.

The integration of Lean principles with BMs in the construction industry remains an emerging area of research, with a limited number of studies addressing this intersection. Existing literature highlights various approaches, such as the application of Lean production processes in real-life construction projects through the IKEA BM to optimise construction efficiency (Li et al., 2008) and comparisons between conventional and Lean BMs (Babaremu et al., 2022). Other studies have explored the combination of sustainable BM innovation with user-driven approaches to support Lean startups and examined the role of BMs in construction material recycling in India (Ram et al., 2019). Additionally, the development of the "servitization" canvas has been proposed to help organisations identify new revenue streams in after-sales markets while research has also investigated the integration of Lean principles with platform BMs in Lean startup processes.

The construction industry is undergoing significant transformation, with an increasing emphasis on Lean and sustainable BMs as a means of enhancing efficiency and reducing waste. Furthermore, a growing trend involves integrating Lean principles with BMs to facilitate Lean startup approaches within the sector. The comparative advantages of Lean BMs in minimising waste and improving resource utilisation are further reinforced by their synergy with sustainable innovation and user-driven methodologies, supporting the development of Lean startups in construction (Likita et al., 2022). However, further research is needed to fully explore the potential of Lean BMs in enhancing value creation and optimising construction processes.

4. CONCLUSION

This study underscores the critical role of lean construction and BMs in addressing the longstanding inefficiencies within the construction industry. Lean principles offer considerable economic, social, and environmental benefits, yet their implementation faces several challenges, including management, financial, governmental, technical, educational, and human-attitudinal barriers. The integration of lean principles into CBMs represents a strategic opportunity to enhance value creation and operational efficiency, driving sustainable growth in construction organisations. However, the limited exploration of CBMs in the construction sector implies a need for further research and deeper investigation into how Lean can be integrated with BMs to achieve competitive advantages.

BMs are transforming the construction industry by driving innovation, improving efficiency, and promoting sustainability. Digital, circular, and green BMs are reshaping operations, enhancing value creation, and fostering competitiveness. However, challenges such as resistance to change, skill gaps, financial constraints, and regulatory uncertainties hinder broader adoption. To reveal the full potential of BMs, the industry must focus on innovation, workforce development, and supportive policy frameworks.

The integration of LBMs in the construction sector offers significant potential to enhance efficiency, reduce waste, and foster innovation. While Lean principles have been widely studied in other industries, their application in construction remains relatively underexplored. Existing research suggests that LBMs can optimise value creation, particularly when combined with sustainable practices and user-driven approaches. However, significant gaps remain in fully understanding the potential of LBMs within the construction industry. Therefore, future research should focus on bridging these gaps, exploring practical applications, and developing frameworks that will enable construction businesses to effectively integrate Lean construction principles into their operations, ultimately enhancing both operational efficiency and long-term value creation.

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LEAN INTEGRATED CIRCULAR ECONOMY IN THE SRI LANKAN CONSTRUCTION INDUSTRY: A QUALITATIVE DELPHI STUDY

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ABSTRACT

The construction industry is known for its significant environmental impact and waste generation. To address this issue, the concept of Circular Economy (CE) has emerged, aiming to minimise waste and maximise resource utilisation. However, there are several barriers which impede the implementation of the CE concept in the construction industry. Therefore, this research aims to incorporate the lean concept to overcome the barriers of CE implementation in the construction industry. Therefore, this research develops a framework for a lean-enabled CE in the construction industry. The qualitative approach is used for this paper, and the Delphi technique was adopted. Purposive sampling was used to select the experts for the study, and data were analysed through manual content analysis. The findings revealed 10 benefits from CE and 12 benefits from Lean were identified, along with 8 benefits of CE and Lean integration. Furthermore, 19 barriers were identified towards this integration, and 12 strategies were identified to overcome these barriers. This study also provides a comprehensive mapping between CE and Lean implementation benefits, their integration benefits and barriers, and strategies. In addition, integrating lean and CE for the construction industry can lead to many significant benefits, such as cost savings, improved environmental performance, and enhanced stakeholder engagement.

Keywords: *Benefits; Circular Economy; Construction Industry; Lean Construction; Sri Lankan.*

1. INTRODUCTION

The construction industry is one of the industrial sectors that significantly contributes to many negative impacts on the environment, such as carbon emissions, resource depletion,

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waste generation, land degradation, and loss of biodiversity (Ryłko-Polak et al., 2022; Viknaruban et al., 2024). To overcome these negative impacts, at present, various sustainable practices have been introduced to the construction industry. Among them, CE (Circular Economy) holds a significant place, and it can be identified as a shift towards a closed loop instead of the ordinary linear method of construction holds an important place as it reduces the extraction of natural resources whilst managing the construction and demolition waste (EMF, 2015; Peck, 2023; Pomponi & Moncaster, 2017; Wang et al., 2019). Further, according to Valencia et al. (2023), the CE plan aims to extend the valuable existence of materials and components through repair, refurbishment, or remanufacturing, and then recycling once the end-of-life is unavoidably reached. However, the construction industry's effective application of CE is still in its early stages (Adams et al., 2017; Leising et al., 2018).

Many researchers highlighted the barriers to the CE, which can be summarised as cultural, financial, technological, regulatory, and environmental (Campbell-Johnston et al., 2019; Hart et al., 2019). Thus, these barriers caused budget and upfront costs (Adams et al., 2017; Guerra et al., 2021), schedule and project timeline (Hart et al., 2019), lack of awareness and change resistance (Benachio et al., 2020), and the current construction business model (Guerra & Leite, 2021) and a lack of regulations and implementation guidelines (Valencia et al., 2023) for the execution of certain circular strategies. To overcome these causes for the proper implementation of CE in the construction sector, lean is an appropriate approach to tackle this circumstance, as many surveys and empirical investigations have shown that the most adaptable lean methods can be applied to overcome barriers (Bajjou et al., 2017; Tezel & Aziz, 2017). On the other hand, Nadeem et al. (2019) emphasised that although lean construction and CE use distinct methods for their two primary shared aspects of "waste elimination" and "value creation," their combination appears natural to complement each other and considerably benefit the CE to be realistic, simple, and easy. According to Ciliberto et al. (2021), one of the matrices showed the existence of a strong, positive interaction between CE principles and lean strategies.

Accordingly, the CE aims to increase the management of building materials by treating them as valuable resources even after a building reaches the end of its life cycle, thereby reducing waste generation. Lean construction focuses on advancing building value by minimizing waste and increasing productivity. Thus, the synergy between these two concepts indicates that their integration could offer significant improvements to the construction industry (Benachio et al., 2021). Still, this combined approach has received limited attention in the construction industry, emphasizing the need for further investigation. Therefore, analysing and exploring the CE and lean combination in the construction industry will make a fresh approach.

The connections between lean and CE allow their integration, likely to deliver improvements to the construction industry (Benachio et al., 2021) because the integration of lean with the CE permits the design of a new "sustainability-oriented" business strategy, with the financial aim of the construction industry (Ciliberto et al., 2021). However, several studies have explicitly discussed lean construction (Parameswaran & Ranadewa, 2024; Ranadewa et al., 2021; Uhanovita et al., 2025) and CE (Bekchanov & Mirzabaev, 2018; Wijewansha et al., 2021) in the Sri Lankan construction industry, but there is a lack of research explicitly linking lean construction to the CE, and they are focused on lean principles and CE principles (Benachio et al., 2021; Nadeem et al., 2019).

Hence, this paper aims to develop a framework integrating Lean and CE towards achieving a sustainable construction industry. To achieve the aim of the study the study followed four objectives as; to investigate benefits of implementing CE and Lean in the Sri Lankan construction industry, to investigate the benefits of integrating lean into the CE in the construction industry, to analyse the barriers to integrate Lean into the CE in the construction industry, to propose strategies to overcome the barriers to integrate lean to the CE in the construction industry. This paper consists of a comprehensive literature review followed by the methodology adopted, findings, and the analysis of them, as well as the conclusion and recommendations of the study.

2. LITERATURE REVIEW

2.1 BENEFITS OF CE IMPLEMENTATION IN THE CONSTRUCTION INDUSTRY

The concept of CE has been grabbing traction in the construction industry because applying its principles can significantly reduce a building's negative environmental effects (Smol et al., 2015). However, its use in the construction sector is still in its early stages (Pomponi & Moncaster, 2017). According to the industry's current trends and practices, the CE may help ensure the sector's sustainability (Awan et al., 2021). Given that the CE may play a significant role in lowering the environmental impact of construction operations, the first step is to comprehend how the CE could benefit the construction sector (Ghisellini et al., 2018). Table 1 comprises the benefits of the CE in the construction industry.

Table 1: Benefits of the CE in the construction industry

No	Benefits	References
1	Reducing waste	[1], [2], [4], [5], [8], [10]
2	Time savings	[1], [2], [3], [5], [8], [10]
3	Cost savings	[1], [2], [4], [6], [8], [9]
4	Increasing the productivity of materials	[5], [7], [8], [1]
5	Maintaining or increasing the value of materials	[4], [5], [8], [9], [10], [11]
6	Increased resilience	[6], [8], [9]
7	Regulatory compliance	[8], [9], [11]

[1] - (Zuofa et al., 2023), [2] - (Barnabè & Nazir, 2022), [3] - (Campbell-Johnston et al., 2019), [4] - (Barón et al., 2020), [5]- (Charef, 2022), [6] - (Rahla et al., 2021), [7] - (Adams et al., 2017), [8] - (Merli et al., 2018), [9] - (Mangialardo & Micelli, 2018), [10] - (Quedou et al., 2021), [11] - (Charef et al., 2021)

Overall, Table 1 provides a concise and clear overview of the benefits of the CE approach, which can be helpful for individuals or organisations who are considering adopting this approach. However, it should be noted that the list of benefits is not exhaustive and that the actual benefits may vary depending on the specific context and implementation of the CE practices. Moreover, there is a variety of R principles to incorporate the CE into the construction industry. Finally, the CE approach in the construction industry can lead to significant environmental, economic, and social benefits (Zuofa et al., 2023). However, achieving a CE in the built environment will require collaboration among stakeholders and policy support from governments (Mhatre et al., 2023).

2.2 BENEFITS OF IMPLEMENTING LEAN IN THE CONSTRUCTION SECTOR

Construction projects frequently experience challenges, including cost overruns and schedule delays (Aziz & Hafez, 2013; Bajjou et al., 2017). Additionally, the construction industry experiences significant problems with low quality (Marhani et al., 2012), inadequate construction safety (Young et al., 2016), and negative environmental effects (Parameswaran et al., 2024). Moreover, lean construction has gained significant popularity in recent years as construction organisations seek to improve their operations and deliver projects more effectively (Parameswaran et al., 2025). In this context, it is important to understand the benefits of lean construction to appreciate why it has become a preferred approach in the construction industry. Some of the key benefits of lean construction include improved efficiency, cost savings, increased quality, better safety, and enhanced team morale (Bajjou & Chafi, 2018; Ghisellini et al., 2018). By adopting lean construction principles, construction organisations can achieve better project outcomes, reduce waste and costs, and increase their competitive advantage (Aslam et al., 2020). Many researchers highlighted benefits and improvements by adopting lean construction within construction projects, as shown in Table 2.

Table 2: Benefits of lean construction in the construction industry

No	Benefits	References
1	Lower costs and faster turnover of construction projects	[1], [2] [3] [4] [7] [9]
2	Improving the quality	[3] [4] [6] [8] [9] [10]
3	Better planning and scheduling	[3] [5] [6] [8]
4	Better risk and safety management	[1] [4] [5]
5	Improving the safety of workers	[2] [5] [10]
6	Improving the environmental performance	[4] [6] [7] [9] [10]
7	Reducing the total project duration	[1] [2] [3] [8] [9] [10]
8	Greater customer satisfaction	[2] [5] [8]
9	Increased team productivity	[6] [8] [9][10]
10	Better management of changing priorities	[1] [5] [6][7]
11	Real-time access to relevant information	[3] [7] [8][10]

[1] - (Salem et al., 2005), [2] - (Aziz & Abdel-Hakam, 2016), [3] -(Bajjou et al., 2017), [4] - (Sarhan et al., 2017), [5]- (Marhani et al., 2012), [6] - (Bajjou & Chafi, 2018), [7] - (Oakland & Marosszeky, 2017), [8]- (Hyatt, 2011), [9] - (Saieg et al., 2018), [10] - (Eriksson, 2010)

The provided Table 2 appears to be a list of benefits associated with a certain approach or method for construction projects. The references cited for each benefit suggest that the approach has been studied and tested in various contexts and has been found to yield positive results. According to Table 2, lower costs, improving the quality and reducing the total production are highly mentioned by authors. Overall, the information suggests that the approach in question has the potential to improve construction project outcomes across multiple dimensions significantly. This could be of great interest to stakeholders in the construction industry, as well as to policymakers and others concerned with promoting sustainable and efficient building practices (Ahmed et al., 2021). Moreover, lean techniques are adding more value by adopting lean construction into the construction sector.

2.3 INTEGRATION OF LEAN CONSTRUCTION INTO THE CE

When it comes to their two main components of "waste elimination" and "value creation," lean and the CE take distinct approaches (Nadeem et al., 2019). The CE employs a closed-loop system, which the lean approach does not, and is not as comprehensive as it is.

Lean's emphasis on process optimisation is restricted to a single supply chain. However, the supply chain is enlarged to a much larger viewpoint under the circular economy's perspective of systems effectiveness and thinking, where value identification and the stream are not restricted to one life cycle of the product or supply chain but instead continue to evolve (Benachio et al., 2021). The lean construction idea of mapping the value stream in the resource, establishing flow inside the closed loop system, and pursuing excellence via continuous enhancement can help realise the circular economy's emphasis on protecting and increasing natural capital. Similarly, closed-loop flow can be established by generating only what is needed, and resource yield optimisation can be accomplished while pursuing perfection through continual improvement (Nadeem et al., 2019). Lean's philosophy of mapping value streams within resources and producing flow within a closed-loop system, combined with the pursuit of perfection through continuous improvement, can be applied to achieve the circular economy's focus on preserving and increasing natural capital. The resource yield optimisation can be accomplished similarly by creating pull by just producing what is needed, and again by building closed loop flow while pursuing excellence through continuous improvement (Nadeem et al., 2019).

2.4 BENEFITS AND BARRIERS FOR THE INTEGRATION OF LEAN CONSTRUCTION INTO THE CE

Table 3 consists of a summary of the literature discussed on the benefits and barriers of CE and Lean integration.

Table 3: Benefits of the integration of CE and lean in the manufacturing industry

Benefits	Barriers	References
Reduction of waste and resource consumption	Reluctant to change	(Salibi et al., 2022; Hartini et al., 2021)
Cost savings	Lack of awareness and understanding	(Kurdve & Bellgran, 2021; Lim et al., 2022)
Enhanced product quality and customer satisfaction	Poor documentation and tracking of materials and processes across the supply chain	(Salibi et al., 2022; Lim et al., 2022)
Compliance with regulations and standards	Limited research and innovation	(Salibi et al., 2022; Kurdve & Bellgran, 2021)
Improved reputation and brand image		(Hartini et al., 2021)

Table 3 summarises the benefits of integrating CE and lean in the manufacturing industry based on several references. The integration of CE principles and lean manufacturing practices can provide numerous benefits to the manufacturing industry. These benefits include reduced waste and resource consumption, cost savings, improved product quality and customer satisfaction, compliance with regulations and standards, and enhanced

reputation and brand image. The studies cited in the table provide evidence for these benefits and suggest that companies can achieve these advantages through various approaches such as eco-design, product lifecycle management, closed-loop supply chains, and waste reduction programs (Salibi et al., 2022). Overall, the adoption of CE and lean principles can help companies improve their sustainability, competitiveness, and overall business performance. Although there are inadequate researchers who highlight the convergence between lean and CE in the construction sector, this convergence remains underexplored. So, with the help of these benefits, there is a possible chance for adopting a lean integrated CE into the construction industry.

3. RESEARCH METHODOLOGY

To achieve the aim of this study, an in-depth study was conducted to determine the aforesaid factors. Therefore, this study adopted a qualitative approach as it is best suited to obtain human expertise and opinions on a subject matter from different perspectives (Malterud, 2016). Further, the Delphi technique was used to collect the qualitative data to develop a set of experts' opinions (Hsu & Sandford, 2007). Generally, a Delphi study consists of two or three rounds of interviews, whereas this study is limited to two interview rounds (Aghimien et al. 2020; Ameyaw et al. 2016). Thus, a two-round Delphi technique was used to achieve the objectives of the study. Experts were selected using purposive sampling, as it is optimal for qualitative studies (O'Reilly & Parker, 2013). Purposive sampling is more closely aligned with the research aims and objectives, as it involves selecting individuals who possess substantial experience/knowledge related to the topic. The selection criteria used for the purposive sampling are shown in Table 4. Further, studies adhere to a predefined set of criteria when selecting experts, as the reliability of the results largely depends on the quality of expert recruitment, as shown in Table 4. Accordingly, all experts were selected through purposive sampling, ensuring their relevant expertise and familiarity with lean and CE within the construction industry were taken into account. Manual context analysis was used to analyse the collected data from two interview rounds, as it helps to analyse qualitative data more effectively (Denscombe, 2014).

Table 4: Expert selection criteria

	Delphi round objectives
Delphi Round 1	Phase I – Identify the benefits of implementing CE in the construction industry in Sri Lanka Phase II – Identify the benefits of implementing Lean in the construction industry in Sri Lanka
Delphi Round 2	Phase I – Investigate the benefits of integrating CE and Lean in the construction industry Phase II – Identify the barriers towards integrating CE and Lean in the Sri Lankan construction industry Phase III - Investigate the strategies to overcome the barriers towards CE and Lean integration in the Sri Lankan construction industry and map the benefits of CE and Lean implementation.

Expert selection criteria								
Expert code	**Discipline**	**Qualifications:**		**Industry experience more than 8 years in construction**	**Awareness of the concepts:**		**Delphi round 1**	**Delphi round 2**
		Academic - Having at least a BSc degree in the Built Environment	**Professional – Obtaining a charter in the relevant field**		**Lean construction (Min 5 years)**	**CE (Min 5 years)**		
E01	General manager	✓	-	✓	✓	✓	✓	✓
E02	Senior Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓
E03	Senior Quantity Surveyor	✓	-	✓	✓	✓	✓	✓
E04	Senior Quantity Surveyor	✓	-	✓	✓	✓	✓	✓
E05	Civil Engineer	✓	✓	✓	✓	✓	✓	✓
E06	Civil Engineer	✓	✓	✓	✓	✓	✓	✓
E07	Civil Engineer	✓	✓	✓	✓	✓	✓	✓
E08	Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓
E09	Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓
E10	Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓
E11	Project Manager	✓	-	✓	✓	✓	✓	✓
E12	Associate Director	✓	✓	✓	✓	✓	✓	✓
E13	Project Coordinator	✓	✓	✓	✓	✓	✓	✓
E14	Project Engineer	✓	-	✓	✓	✓	✓	✓
E15	Site Engineer	✓	-	✓	✓	✓	✓	✓
E16	Project Manager	✓	-	✓	✓	✓	✓	✓

4. RESEARCH FINDINGS AND ANALYSIS

4.1 BENEFITS OF IMPLEMENTING CE AND LEAN IN THE CONSTRUCTION INDUSTRY

The literature review revealed 7 benefits of implementing CE in the construction industry. During the Delphi Round I – Phase I (DRI-PI), experts were given these benefits and asked whether they apply to the Sri Lankan context and asked to identify further benefits within the Sri Lankan construction industry. The literature review revealed 11 benefits of implementing Lean in the construction industry. During the Delphi Round I – Phase II (DRI-PII), experts were given these benefits and asked whether they apply to the Sri Lankan context and asked to identify further benefits within the Sri Lankan construction industry in terms of Lean implementation. Newly identified benefits are presented in *italics* in Table 5, and any changes to the benefits identified from the literature review have been indicated by **bold letters**.

Table 5: Benefits of implementing CE and Lean

Benefits of implementing CE in the construction industry – DR I -PI	Benefits of implementing Lean in the construction industry – DRI -PII
C1- Construction waste management	L1 - Lower costs and faster turnover of construction projects
C2 - Time savings	L2 - Improving the quality
C3 - Cost savings	L3 - Better planning and scheduling
C4 - Increasing the productivity of materials	L4 - Better risk and safety management
C5 - Maintaining or increasing the value of materials	L5 - Improving the safety of workers
C6 - Increased resilience	L6 - Improving the environmental performance
C7 - Regulatory compliance	L7 - Reducing the total project duration
C8 - Resource efficiency and reduction of resource extraction	L8 - Greater customer satisfaction
C9 - Reduction of carbon emissions	L9 - Increased team productivity and improved collaboration
C10 - New business opportunities for different stakeholders	L10 -Better management of changing priorities
	L11- Real-time access to relevant information
	L12 - Increased Client Satisfaction

The experts highlighted three new benefits from implementing CE in the Sri Lankan construction industry, apart from the seven benefits identified from the literature review. Further, experts renamed "reducing waste" to "**Construction waste management"** as shown in Table 5. E10 stated that "*One of the major benefits of CE is resource efficiency and reducing the amount of natural resource extraction*". E12 and E15 experts also confirmed the same by stating different keywords such as "closed loop", "R-principles". Furthermore, E09 highlighted a significant environmental benefit through CE implementation, specifically the reduction of carbon emissions. Another major fact

highlighted by experts was new business opportunities for stakeholders, specifically for profit seeking organisations.

4.2 BENEFITS AND BARRIERS OF INTEGRATING LEAN INTO THE CE IN THE CONSTRUCTION INDUSTRY

The literature review revealed 5 benefits which can be obtained through Lean and CE integration, while only four literature facts were available for barriers to integrating Lean and CE in the construction industry. During the DRII-PII, 15 new barriers were identified towards Lean and CE integration, and 3 new benefits of this integration were identified during DRII-PI interviews. Newly identified facts are presented in *italics*.

Table 6: Barriers and benefits of integrating Lean and CE

Barriers to integrating Lean into the CE in the construction industry – DRII-PII	**Benefits of integrating Lean into CE in the Sri Lankan construction industry DRII-P1**
BLC1 - Reluctant to change	BeLC1- Reduction of waste and resource consumption
BLC2 - Lack of awareness and understanding	BeLC2- Enhanced Project Time and Cost Performance
BLC3 - Preference for immediate gains over long-term sustainability benefits	BeLC3- Enhanced product quality and customer satisfaction
BLC4- Poor collaboration between departments and stakeholders hampers holistic implementation	BeLC4- Compliance with regulations and standards
BLC5- Incompatibility of processes	BeLC5- Improved reputation and brand image
BLC6- Lack of standardised practices	*BeLC6- Design for deconstruction and reuse*
BLC7- Poor documentation and tracking of materials and processes across the supply chain	*BeLC7- Enhanced stakeholder collaboration and engagement*
BLC8 - High upfront costs	*BeLC8- Regulatory and market advantages*
BLC9- Uncertain return on investment (ROI)	
BLC10- Funding constraints	
BLC11- Existing policies may not support or even hinder CE and Lean initiatives	
BLC12- Inconsistent standards	
BLC13- Weak implementation or monitoring of environmental and efficiency standards	
BLC14- Lack of training and education	
BLC15- The Workforce may lack the expertise to implement integrated Lean-CE strategies	
BCL16- Limited research and innovation	
BLC17- Difficulty coordinating circular and lean practices across diverse stakeholders	

Barriers to integrating Lean into the CE in the construction industry – DRII-PII	**Benefits of integrating Lean into CE in the Sri Lankan construction industry DRII-P1**
BLC18- Low stakeholder engagement	
BLC19- Weak mechanisms for learning and continuous improvement	

4.3 STRATEGIES TO OVERCOME THE BARRIERS TO INTEGRATING LEAN INTO THE CE IN THE CONSTRUCTION INDUSTRY

During DRII-PIII, experts suggested twelve strategies to overcome the barriers to integrating Lean and CE into the construction industry. Moreover, the recommended strategies are as follows.

Leadership commitment and vision (S1), Education and training (S2), Develop Expertise (S3), Pilot projects (S4), Data and metrics (S5), Collaboration and partnerships (S6), Capacity-building workshops (S7), Promote transparent data-sharing platforms (S8), Develop a certification scheme for Lean-CE integration (S9), Encourage long-term supplier and contractor partnerships (S10), Engage employees early with collaborative planning and feedback loops (S11), Emphasise the waste reduction cost savings from Lean processes (S12). Figure 1 illustrates the mapping of benefits from implementing CE and Lean in the construction industry, highlighting the connection between their integrated implementation and the strategies and barriers involved.

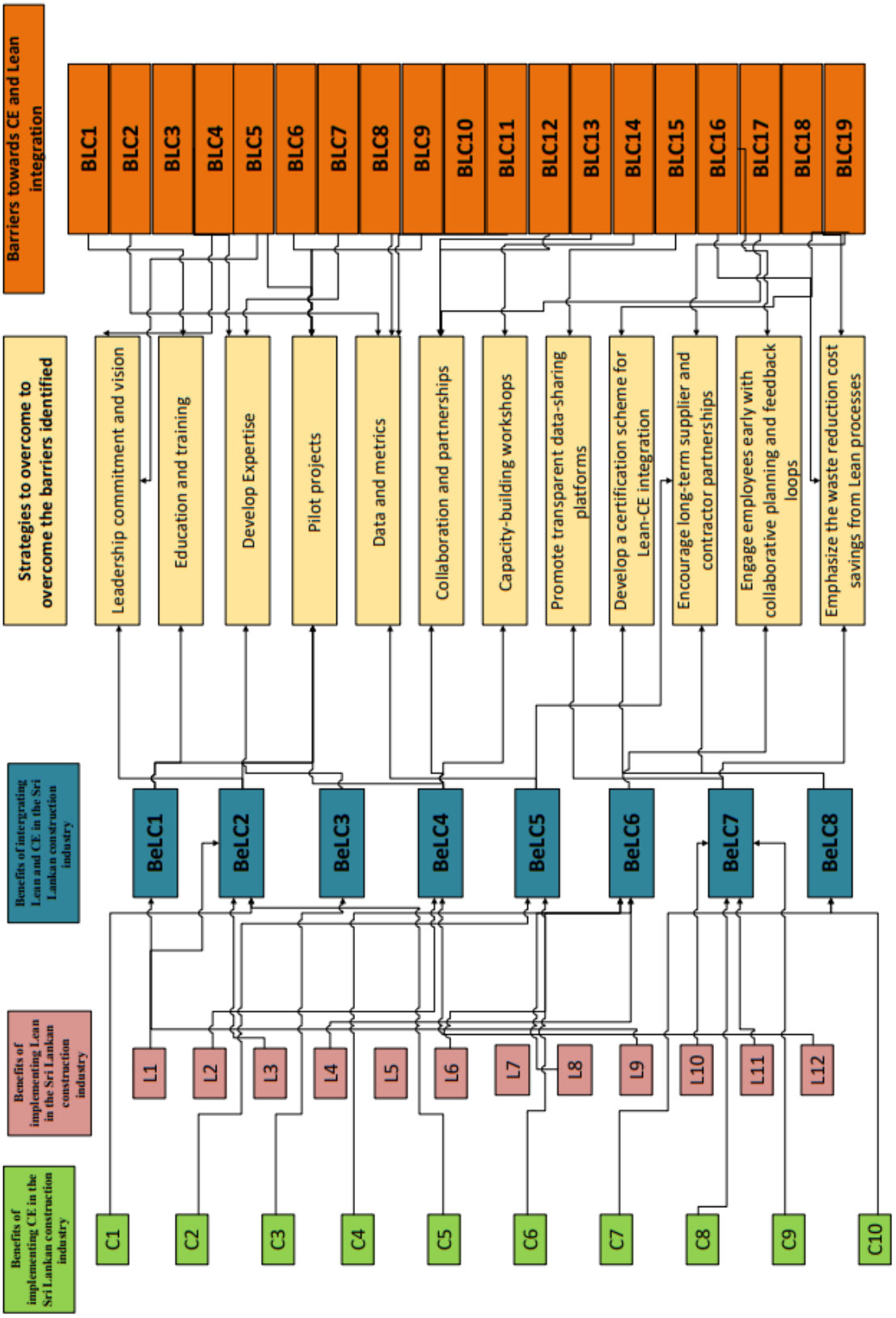


Figure 1: Final framework of the study

5. CONCLUSION AND RECOMMENDATIONS

In this research study, the CE for the construction industry was discussed. According to this study, the Sri Lankan Built environment can gain sufficient ideas. This study provides a list of the benefits of implementing CE and Lean in the construction sector and the connection between the benefits of integrating these two concepts. Further, this study analyses the barriers towards integrating CE and Lean and the strategies to overcome the barriers. To overcome those barriers, lean concepts and techniques were introduced in this research. Further, the study provided a framework that integrates Lean and CE to promote sustainability in the construction industry. In the Sri Lankan context, construction professionals lack knowledge regarding lean, lean techniques and CE as well. Through this research study, participants can enhance their understanding and skills related to lean and CE principles. The economic crisis has created project funding issues for the Sri Lankan construction industry; therefore, threats can be reduced by implementing a CE for the Sri Lankan construction industry. This study stands out among other studies as it is the only one to map various aspects, including the benefits and barriers of CE and Lean integration, along with strategies to overcome and enhance these integrations. Furthermore, the research contributes to the body of knowledge about the benefits and barriers of integrating Lean into the CE in the construction industry and strategies to overcome the barriers to integrating Lean and CE in the construction industry. As the scope of this research is conducted in the Sri Lankan construction industry, it can be developed for a specific type of construction, for example, road construction, building works, civil works and pile construction as well, because the types of wastages differ for one construction from another. Several barriers to implementing the CE were identified in this study. Future studies could focus on a specific barrier and explore methods to overcome it.

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LEAN THINKING FOR GREEN BUILDING: BARRIERS FOR LEAN INTEGRATED SUSTAINABLE CONSTRUCTION

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ABSTRACT

Green building has become a central focus in modern construction discourse, representing a practical and measurable approach to achieving sustainable construction in response to the thriving need for the construction industry to adopt sustainable construction practices, particularly in response to the persistent challenges that characterise the sector, such as excessive material waste, high energy consumption, environmental degradation, inefficient resource utilisation, and the generation of significant carbon emissions. Despite the well-known benefits of sustainable construction, most countries are still widely familiar with the traditional construction, due to the bottlenecks that hindered the widespread adoption of sustainable construction. Subsequently, lean thinking has been identified as a foremost solution for the effective implementation of sustainable construction, owing to the close conceptual alignment between the two approaches, as well as the extensive benefits offered by lean principles in reducing waste, enhancing efficiency, and promoting value-driven processes. However, the implementation of lean integrated sustainable construction is obstructed by numerous barriers. Therefore, this study aims to investigate the barriers to lean integrated sustainable construction. The study employed a quantitative research approach using a questionnaire survey, through which a total of 120 responses were gathered via snowball sampling. Findings revealed a total of 32 highly significant barriers to lean integrated sustainable construction, from a total of 94 barriers identified through the literature review and data collection. Out of these, the most significant barriers include employees' resistance to lean, resistance to change, lack of incentives and motivation, shortage of manpower, and an unfriendly organisational culture, which collectively highlight a deep-rooted human-centricity in lean thinking. The study provides empirical insights for practitioners, including the identification of relevant barriers and the highlighting of their significance, enabling enhanced practices and informed decision-making, thereby contributing to address a gap in the literature.

Keywords: *Barriers; Green Buildings; Lean Construction; Sustainable Construction.*

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1. INTRODUCTION

Construction industry has evolved through several chronological stages, starting with ancient shelters constructed from stone to the multifaceted international construction projects (Ngowi et al., 2004). Despite its dominant role in economic growth and social improvement, the construction industry has significant unfavourable impacts, with the buildings and construction sector responsible for 21% of global greenhouse gas emissions, and 37% of energy and process-related CO_2 emissions in 2022 (United Nations Environment Programme, 2024), and numerous indirect environmental consequences including, significant waste generation (Chandrappa & Das, 2024), noise pollution (Bouzir et al., 2024), and urban heat island effect (Iungman et al., 2024). These negative consequences highlight the thriving need for implementing a strategic approach aimed at minimising the negative impacts of the construction industry, where the concept of sustainability has emerged through the construction industry.

Sustainable construction has rapidly been implemented in recent years due to its remarkable potential to address numerous issues in the construction industry, with a central focus on the proper distribution of global resources (Cuesta et al., 2022), waste minimisation (Djokoto et al., 2014), optimum resource utilisation (Lima et al., 2021), and reuse and recycling practices (Pearce, 2006). Nevertheless, sustainable construction remains a challenging task, hindered by numerous obstacles, and requires an effective approach for successful implementation (Singh, 2016). Importantly, lean construction can serve as a holistic approach to enhance the successful realisation of sustainable construction, being a philosophy based on the underlying principles of waste minimisation, value maximisation, and continuous improvement (Akanbi et al., 2019). However, lean integrated sustainable construction faces significant implementation challenges (Marhani et al., 2012), necessitating a strong need to properly identify these barriers within the construction industry. Therefore, concerns arise regarding the barriers to the integration of sustainable construction and lean construction. Moreover, the lack of research investigating the barriers to lean integrated sustainable construction has contributed to limited lean implementation within the construction sector (Madhushani et al., 2024). Consequently, there is a clear need to investigate the significance of the barriers to lean integrated sustainable construction, in order to enhance the implementation of lean construction and thereby drive sustainable construction. This research is therefore aimed at investigating the barriers to lean integrated sustainable construction. Achieving this aim will bridge the theoretical gap and provide insights for practitioners to effectively implement both lean construction and sustainable construction, ultimately contributing to the sustainability of the global construction sector. The paper starts with an introduction to the topic and research gap followed by a comprehensive literature review on sustainable construction and lean construction. The methodology section outlines the research process, and the findings are presented with a discussion. Subsequently, research implications are provided followed by future research areas.

2. LITERATURE REVIEW

2.1 NEED OF SUSTAINABLE CONSTRUCTION

Initially, Kibert (1994) proposed the first definition of sustainable construction as "the creation and responsible management of a healthy built environment based on resource efficient and ecological principles." Notably, Baloi (2003) emphasised that there is a

worldwide concern regarding the alignment of the construction industry with sustainable construction due to the significant negative impacts of construction activities. Importantly, financial issues such as insufficient financial resources, and late payments (Abdul-Rahman et al., 2014), disrupt the efficient operations of projects while the issues such as unforeseen site conditions (Amarasekara et al., 2018), poor site management (Alaghbari et al., 2007) cause project delays. Moreover, as many studies have identified, stakeholder-related human problems (Thapanont et al., 2018), quality problems (Zou et al., 2007), health and safety problems (Kadiri et al., 2014) and environmental problems (Gangolells et al., 2009) contribute to inefficiencies including time and cost overruns, and low-quality outcomes, which hinder the industry's long-term sustainability.

As a solution, several studies highlight the driving factors of sustainable construction in a more comprehensive manner, where the environmental drivers include greater energy efficiency (Darko et al., 2017), improved indoor environmental quality (Darko & Chan, 2017), and land-use regulations, while the economic drivers are identified as the value for money in project delivery (Whang & Kim, 2015), and support for the local economy (Pearce, 2006), and the social drivers of sustainable construction are identified as service quality (Abidin, 2010), and security (Whang & Kim, 2015). Ultimately, all these aspects collectively emphasise the urgency of widespread adoption of sustainable construction practices to achieve a more sustainable built environment.

2.2 CHALLENGES IN IMPLEMENTING SUSTAINABLE CONSTRUCTION

Despite the well-known benefits of sustainable construction practices, most countries are still widely familiar with the traditional construction industry, due to the bottlenecks that hindered the widespread adoption of sustainable construction practices (Davies & Davies, 2017). Consequently, financial issues such as higher initial costs and long payback periods (Ahn et al., 2013) discourage many contractors, especially in regions with weaker economies. Political factors such as limited government promotion (Aghimien et al., 2018), and weak regulations (Mosly, 2015) further hinder the implementation of sustainable construction. Additionally, managerial barriers, including a lack of coordination and communication between stakeholders significantly restrict the adherence to sustainable construction (Serpell et al., 2013). Moreover, knowledge gaps, including a lack of training and understanding of sustainability concepts (Abraham & Gundimeda, 2018) create significant obstacles to widespread adoption of sustainable construction, which is compounded by social-cultural barriers where cultural change resistance (Enshassi & Mayer, 2005) and the tendency to maintain current practices further disrupt the smooth transition to sustainable construction. Similarly, technical barriers, including shortages of skilled labour and inadequate sustainability measurement tools (Häkkinen & Belloni, 2011), along with physical constraints such as scarcity of green materials, equipment, and technologies (Darko & Chan, 2017), create substantial restrictions to the effective implementation of sustainable construction. Collectively, these barriers hinder the adoption of sustainable construction worldwide. Therefore, there is a growing need to explore better ways to ensure the successful adoption of sustainable construction. Consequently, lean construction can be considered a foremost solution for effective implementation of sustainable construction within the construction industry.

2.3 NEED OF LEAN CONSTRUCTION FOR SUSTAINABLE CONSTRUCTION

The origin of lean philosophy is related to the industrial process, where this innovation business approach has changed the paradigm and management concepts of the 20th century (Kelendar, 2020). With the rapid advancement of technologies, many industries experience a growing prominence of the application of lean production principles in various sectors (Akanbi et al., 2019). Koskela (1993) introduced the first reference to apply lean principles in the construction industry as a solution to chronic issues of industry such as insufficient quality, low productivity, inadequate safety, and poor working conditions. Delving further into this notion, Marhani et al. (2012) defined lean construction as "the concurrent and continuous improvement of the construction project by reducing waste of resources and, at the same time, increasing productivity and securing a better health and safety environment to fulfil the client's requirements, as well as contributing towards a sustainable and greener environment". With the widespread adoption of lean construction, many researchers emphasised that lean construction serves as a holistic approach to solve most issues in the construction industry. Accordingly, the major economic benefits of lean construction include reduced rework, improved quality, (Besklubova & Zhang, 2019), value achievement (Opoku et al., 2024), project and labour cost reduction (Parfenova et al., 2020), whereas the social benefits of lean construction include enhanced teamwork and transparency, collaborative communication among stakeholders, reduced conflicts and disputes (Jagannathan et al., 2024), while the environmental benefits of lean construction include more controllable material storage, improved safety measures, enhanced quality of environment, reduced pollution and emissions (Pejić et al., 2023), water conservation , energy consumption savings (Shaqour, 2022). Collectively, these lean construction benefits demonstrate their extensive potential to achieve the sustainable construction, simultaneously emphasising the importance of lean integrated sustainable construction implementation for the advanced achievement of construction goals.

2.4 BARRIERS FOR LEAN INTEGRATED SUSTAINABLE CONSTRUCTION

Albalkhy and Sweis (2021) emphasised that despite the evident benefits of lean construction, numerous hindrances arise when amalgamating the lean principles into construction projects. Moreover, various studies have identified the barriers to implement lean integrated sustainable construction, focusing on different categories. Accordingly, Demirkesen et al. (2019) classified them as political barriers, economic barriers, workforce barriers, cultural barriers, managerial barriers, communication barriers, and technical barriers. In contrast, Alinaitwe (2009) analysed the barriers to implement lean construction by dividing them into three different aspects: management, organisation, and design-related factors. On the other hand, Moradi and Sormunen (2023) stated, "People are the main root cause of the barriers, enablers, and implications of lean construction adoption and implementation." Similarly, numerous studies highlighted that people are the most crucial factor in enabling lean practices, where social barriers including workforce, cultural, managerial, communication, and educational challenges collectively identified as the major obstacles to sustaining a long-term lean implementation (Sarhan & Andrew, 2012; Shang & Pheng, 2014). Therefore, there is a need to thoroughly investigate the barriers to lean integrated sustainable construction, to secure a better future for the construction industry.

2.5 NEED OF THE RESEARCH

Focusing on existing literature clearly indicates that the critical issue faced by many construction firms is the absence of proper prioritisation of the barriers to lean integrated sustainable construction (Madhushani et al., 2024). Moreover, there is a notable lack of research aimed at identifying the potential to minimise the barriers to green buildings through lean implementation. Most existing studies tend to address lean construction and sustainable construction separately, failing to provide a comprehensive understanding of the combined implementation challenges. This lack of clarity poses a significant gap for both researchers and industry practitioners, making it difficult to develop targeted strategies. Therefore, this research aims to fill this gap by investigating the key barriers to lean integrated sustainable construction, contributing both to academic knowledge and practical improvements in the construction sector.

3. METHODOLOGY

A comprehensive literature review was initially conducted by referring to journal articles, books, theses and dissertations, reports, web pages, other online sources, and conference papers to identify the barriers to lean integrated sustainable construction. Accordingly, a total of 80 barriers were identified under nine categories, as presented in Table 1. Subsequently, data collection for the study was conducted using a questionnaire survey to identify the most significant barriers to lean integrated sustainable construction. According to Östlund et al. (2011), quantitative research is effective for identifying patterns, testing hypotheses, and ranking factors based on empirical data, which is critical for understanding widespread industry challenges. In answering this research question, the authors adopted a quantitative method by conducting a questionnaire survey, utilising



Figure 1: Profile of the sample

snowball sampling as the sampling technique. The survey was distributed via Google® Forms to 150 industry professionals working in the construction industry who are knowledgeable about lean integrated sustainable construction, resulting in the collection of approximately 120 responses. The questionnaire consisted of 24 questions aimed at gathering data on the significance level of barriers to implementing lean integrated sustainable construction in the construction industry. The primary objective of this survey was to identify and prioritise the most significant barriers to implementing lean integrated sustainable construction. Moreover, Figure 1 illustrates the professional backgrounds of the respondents along with their educational and professional qualifications.

Accordingly, the innermost layer represents the professional designations of the respondents, the middle layer represents their educational qualifications, and the outermost layer indicates their professional qualifications. The composition of the sample reflects a diverse group of construction-related professionals with high levels of expertise, enhancing the overall proficiency of the sample and the reliability of the responses gathered.

Quantitative data need to be analysed using mathematical techniques together with statistical concepts (Weyant, 2022). Therefore, quantitative data gathered from the questionnaire survey analysed using Weighted Mean Rating (WMR) method and Standard Deviation (SD). The mean, which is also known as the average, is the most frequently used measure of central tendency for numerical variables (Manikandan, 2011). It provides a comprehensive representation of the data set by analysing every value within it, thereby offering valuable information and reliable interpretations (Sial & Abid, 2023). Mean score of a particular item is derived as,

$$Mean = \frac{\sum_{i=1}^{5}(x_i \times f_i)}{n} \qquad Equation\ (1)$$

where, fi = frequency of responses and n = number of responses.

Moreover, standard deviation can be identified as a statistical measure for quantifying the dispersion or spread of data in relation to its mean (Przystupa et al., 2022). Thus, it was used in this study to determine the spread of findings on the participants' knowledge and opinions regarding the significance of the barriers. Accordingly, the following formula was used for that standard deviation.

$$Standard\ Deviation = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n}} \qquad Equation\ (2)$$

Where: x_i = Weightage given to each variable based on the level of agreement; $\overline{x}$ = Mean of the data set; n = Number of respondents.

Furthermore, Cronbach's alpha calculation is generally used as a measure of internal consistency and reliability (Tavakol & Dennick, 2011). Accordingly, Cronbach's alpha was used to measure the consistency of the Likert scale data obtained through the questionnaire survey.

$$Cronbach's\ Alpha\ (\alpha) = \frac{k}{k-1}\left(1 - \frac{\sum V_i}{V_t}\right) \qquad Equation\ (3)$$

Where α = Cronbach's alpha coefficient; k =Number of items in the scale; $\sum V_i$ = Sum of the variances of each individual item; V_t= Total Variance of the total scale. In this research, IBM SPSS Statistics 26 software was used to calculate statistical measures.

4. FINDINGS AND ANALYSIS

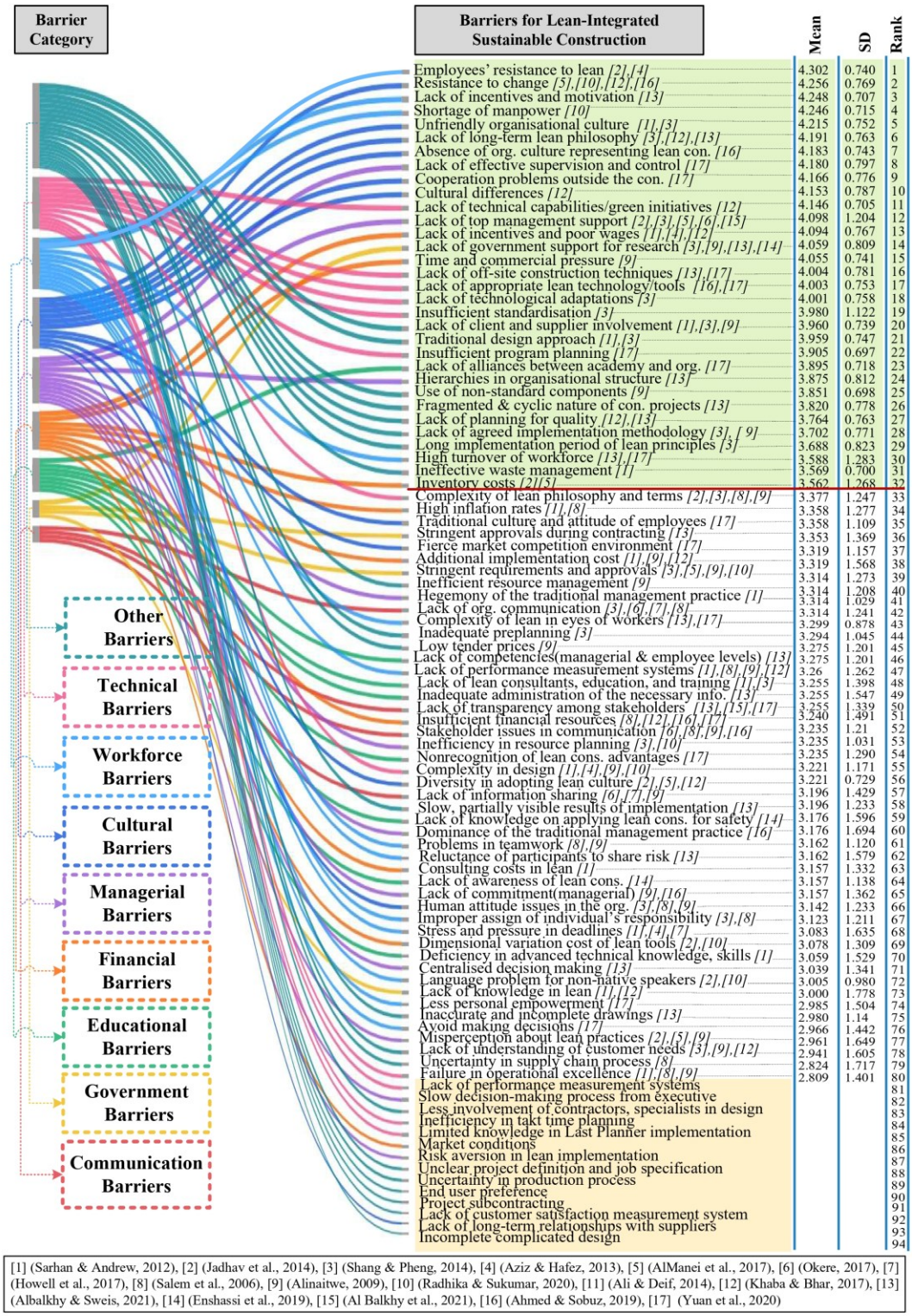
4.1 BARRIERS OF LEAN INTEGRATED SUSTAINABLE CONSTRUCTION

Through an extensive literature review, a total of 80 barriers to lean integrated sustainable construction were initially identified. Additionally, a structured questionnaire survey revealed 14 new barriers reported by industry respondents, bringing the total to 94 distinct challenges. With the aim of identifying the most significant barriers, respondents were asked to rank the level of significance of each barrier using a five-point Likert scale, between "Not Significant" and "Highly Significant". Maree and Pietersen (2016) suggested that Cronbach's alpha value of 0.90 indicates high reliability, 0.80 indicates moderate reliability, and 0.70 indicates low reliability. Accordingly, a reliability test was conducted for all the barrier variables used in this study. Consequently, the reliability test conducted on the 94 variables revealed Cronbach's alpha coefficient of 0.893, reflecting a high level of reliability, and confirming that the measurement instrument used in this study is dependable and consistent. Subsequently, the weighted mean rating method was applied to evaluate the relative rankings of each barrier, in descending order of significance, with the results summarised in Figure 2.

These barriers ranged from 'Employees' resistance to lean' (mean = 4.302; SD = 0.740) which is the highest ranked to "Incomplete complicated design" (mean = 1.471; SD = 1.155) which is the least ranked. In line with the threshold recommended by Olanrewaju et al. (2020), a mean score of 3.50 or higher was used as the benchmark to identify the most critical barriers, especially in construction related research. Accordingly, 32 of the 94 barriers surpassed this threshold and were considered highly significant in hindering the implementation of lean integrated sustainable construction practices. The results indicate that employees' resistance to lean implementation, emerged as the most critical barrier, with a WMR of 4.302. This highlights a deep-rooted behavioural and cultural challenge within construction organisations. Closely following are resistance to change and the lack of incentives and motivation, both pointing towards the critical influence of organisational culture and human resource management. The persistence of these barriers implies that the successful adoption of lean integrated sustainable construction is not only a technical or procedural challenge but a deeply human-centric one. Furthermore, barriers such as manpower shortages (WMR = 4.246), unfriendly organisational culture (WMR = 4.215), and the lack of a long-term lean philosophy (WMR = 4.191) further reinforce the argument that workforce-related and cultural factors are pivotal. It is evident that even in technologically capable environments, without strong managerial backing, continuous training, and cultural realignment, lean sustainability efforts may remain superficial or unsustainable. Moreover, barriers such as 'lack of technical capabilities/green initiatives', 'lack of top management support', and 'lack of government support for research', each with a rounded mean rating of 4.1, highlight the importance of government support, managerial commitment, and technical capability in enhancing lean implementation. This underscores the multidisciplinary and collaborative nature of a lean construction.

Conversely, the barriers fall below the WMR benchmark of 3.4 include external and project specific constraints such as market conditions, unclear project definitions, subcontracting practices, and incomplete designs. Though less critical, these issues still represent practical impediments, especially under complex or large-scale project conditions. The wide spread of standard deviations across these items suggests varying perceptions among respondents, likely influenced by contextual differences across

construction environments. Overall, these findings emphasise the need for a systemic transformation that integrates behavioural change, institutional learning, and participative leadership as key pillars for driving lean culture in pursuit of sustainability in construction.



Barriers for Lean-Integrated Sustainable Construction	Mean	SD	Rank
Employees' resistance to lean [2],[4]	4.302	0.740	1
Resistance to change [5],[10],[12],[16]	4.256	0.769	2
Lack of incentives and motivation [13]	4.248	0.707	3
Shortage of manpower [10]	4.246	0.715	4
Unfriendly organisational culture [1],[3]	4.215	0.752	5
Lack of long-ferm lean philosophy [3],[12],[13]	4.191	0.763	6
Absence of org. culture representing lean con. [16]	4.183	0.743	7
Lack of effective supervision and control [17]	4.180	0.797	8
Cooperation problems outside the con. [17]	4.166	0.776	9
Cultural differences [12]	4.153	0.787	10
Lack of technical capabilities/green initiatives [12]	4.146	0.705	11
Lack of top management support [2],[3],[5],[6],[15]	4.098	1.204	12
Lack of incentives and poor wages [1],[4],[12]	4.094	0.767	13
Lack of government support for research [3],[9],[13],[14]	4.059	0.809	14
Time and commercial pressure [9]	4.055	0.741	15
Lack of off-site construction techniques [13],[17]	4.004	0.781	16
Lack of appropriate lean technology/tools [16],[17]	4.003	0.753	17
Lack of technological adaptations [3]	4.001	0.758	18
Insufficient standardisation [3]	3.980	1.122	19
Lack of client and supplier involvement [1],[3],[9]	3.960	0.739	20
Traditional design approach [1],[3]	3.959	0.747	21
Insufficient program planning [17]	3.905	0.697	22
Lack of alliances between academy and org. [17]	3.895	0.718	23
Hierarchies in organisational structure [13]	3.875	0.812	24
Use of non-standard components [9]	3.851	0.698	25
Fragmented & cyclic nature of con. projects [13]	3.820	0.778	26
Lack of planning for quality [12],[13]	3.764	0.763	27
Lack of agreed implementation methodology [3], [9]	3.702	0.771	28
Long implementation period of lean principles [3]	3.688	0.823	29
High turnover of workforce [13],[17]	3.588	1.283	30
Ineffective waste management [1]	3.569	0.700	31
Inventory costs [2],[5]	3.562	1.268	32
Complexity of lean philosophy and terms [2],[3],[8],[9]	3.377	1.247	33
High inflation rates [1],[8]	3.358	1.277	34
Traditional culture and attitude of employees [17]	3.358	1.109	35
Stringent approvals during contracting [13]	3.353	1.369	36
Fierce market competition environment [17]	3.319	1.157	37
Additional implementation cost [1],[9],[12]	3.319	1.568	38
Stringent requirements and approvals [5],[5],[9],[10]	3.314	1.273	39
Inefficient resource management [9]	3.314	1.208	40
Hegemony of the traditional management practice [1]	3.314	1.029	41
Lack of org. communication [3],[6],[7],[8]	3.314	1.241	42
Complexity of lean in eyes of workers [13],[17]	3.299	0.878	43
Inadequate preplanning [3]	3.294	1.045	44
Low tender prices [9]	3.275	1.201	45
Lack of competencies(managerial & employee levels) [13]	3.275	1.201	46
Lack of performance measurement systems [1],[8],[9],[12]	3.26	1.262	47
Lack of lean consultants, education, and training [1],[3]	3.255	1.398	48
Inadequate administration of the necessary info. [13]	3.255	1.547	49
Lack of transparency among stakeholders [13],[15],[17]	3.255	1.339	50
Insufficient financial resources [8],[12],[16],[17]	3.240	1.491	51
Stakeholder issues in communication [6],[8],[9],[16]	3.235	1.21	52
Inefficiency in resource planning [3],[10]	3.235	1.031	53
Nonrecognition of lean cons. advantages [17]	3.235	1.290	54
Complexity in design [1],[4],[9],[10]	3.221	1.171	55
Diversity in adopting lean culture [2],[5],[12]	3.221	0.729	56
Lack of information sharing [6],[7],[9]	3.196	1.429	57
Slow, partially visible results of implementation [13]	3.196	1.233	58
Lack of knowledge on applying lean cons. for safety [14]	3.176	1.596	59
Dominance of the traditional management practice [16]	3.176	1.694	60
Problems in teamwork [8],[9]	3.162	1.120	61
Reluctance of participants to share risk [13]	3.162	1.579	62
Consulting costs in lean [1]	3.157	1.332	63
Lack of awareness of lean cons. [14]	3.157	1.138	64
Lack of commitment(managerial) [9],[16]	3.157	1.362	65
Human attitude issues in the org. [3],[8],[9]	3.142	1.233	66
Improper assign of individual's responsibility [3],[8]	3.123	1.211	67
Stress and pressure in deadlines [1],[4],[7]	3.083	1.635	68
Dimensional variation cost of lean tools [2],[10]	3.078	1.309	69
Deficiency in advanced technical knowledge, skills [1]	3.059	1.529	70
Centralised decision making [13]	3.039	1.341	71
Language problem for non-native speakers [2],[10]	3.005	0.980	72
Lack of knowledge in lean [1],[12]	3.000	1.778	73
Less personal empowerment [17]	2.985	1.504	74
Inaccurate and incomplete drawings [13]	2.980	1.14	75
Avoid making decisions [17]	2.966	1.442	76
Misperception about lean practices [2],[5],[9]	2.961	1.649	77
Lack of understanding of customer needs [3],[9],[12]	2.941	1.605	78
Uncertainty in supply chain process [8]	2.824	1.717	79
Failure in operational excellence [1],[8],[9]	2.809	1.401	80
Lack of performance measurement systems			81
Slow decision-making process from executive			82
Less involvement of contractors, specialists in design			83
Inefficiency in takt time planning			84
Limited knowledge in Last Planner implementation			85
Market conditions			86
Risk aversion in lean implementation			87
Unclear project definition and job specification			88
Uncertainty in production process			89
End user preference			90
Project subcontracting			91
Lack of customer satisfaction measurement system			92
Lack of long-term relationships with suppliers			93
Incomplete complicated design			94

[1] (Sarhan & Andrew, 2012), [2] (Jadhav et al., 2014), [3] (Shang & Pheng, 2014), [4] (Aziz & Hafez, 2013), [5] (AlManei et al., 2017), [6] (Okere, 2017), [7] (Howell et al., 2017), [8] (Salem et al., 2006), [9] (Alinaitwe, 2009), [10] (Radhika & Sukumar, 2020), [11] (Ali & Deif, 2014), [12] (Khaba & Bhar, 2017), [13] (Albalkhy & Sweis, 2021), [14] (Enshassi et al., 2019), [15] (Al Balkhy et al., 2021), [16] (Ahmed & Sobuz, 2019), [17] (Yuan et al., 2020)

Figure 2: Barriers of lean integrated sustainable construction

To deepen the analysis of challenges in lean integrated sustainable construction, the identified key barriers were clustered according to the categories identified in the literature, as illustrated in Figure 3 below.

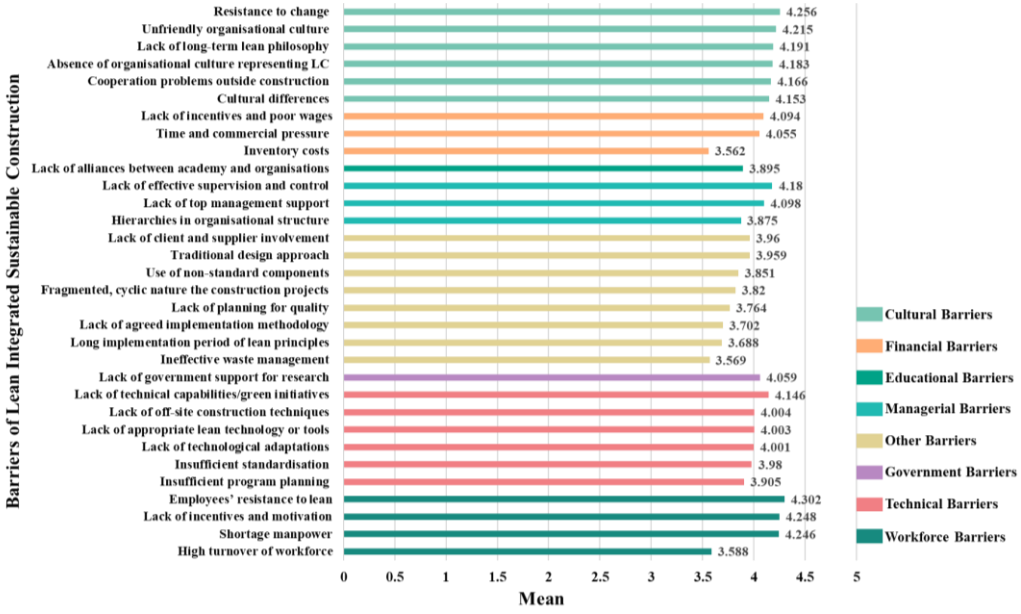


Figure 3: Clustering of key barriers of lean integrated sustainable construction

The visual clustering reveals a clear dominance of socially rooted barriers across the highest rated challenges. Cultural barriers such as resistance to change, and unfriendly organisational culture consistently ranked among the most critical, alongside workforce issues like low motivation, high turnover, and skill shortages. Managerial barriers particularly lack of top management support and ineffective supervision also emerged prominently. These clusters demonstrate that the core impediments to lean integrated sustainable construction are not technical or procedural in isolation but rather embedded in the organisational mindset, human behaviour, and leadership practices. Crucially, the interconnectedness of these categories reflects their shared foundation in broader social dimensions, because cultural, managerial, workforce, and educational barriers are not merely operational or technical; they are deeply rooted in the broader social fabric. This confirms the centrality of human dimensions in advancing sustainable construction.

5. DISCUSSION

As indicated in the lower section of the barriers in Figure 2, the study identifies 14 barriers to lean integrated sustainable construction, in addition to the 80 barriers identified in the literature. Moreover, the empirical findings of the study align closely with the literature findings, affirming that the most critical barriers to lean integrated sustainable construction are deeply embedded within social, human dimensions. The prominence of barriers such as employee resistance to lean, resistance to change, and lack of motivation strongly resonate with the conclusions of Moradi and Sormunen (2023), who assert that "people are the main root cause of the barriers, enablers, and implications of lean construction adoption." Similarly, the dominance of cultural, managerial, and workforce-related barriers in the findings corroborates the categorisations offered by Demirkesen et al. (2019) who identified these social categories as core impediments to lean integrated sustainable construction. The finding that technical or project-specific barriers ranked

significantly lower aligns with the view of Sarhan and Andrew (2012), who argued that lean failure often stems not from technical deficiencies, but from inadequacies in leadership, training, and cultural readiness. Furthermore, Alinaitwe (2009) supported this narrative by underlining the persistent organisational and managerial constraints that hinder lean integration, despite its acknowledged benefits. Collectively, these parallels confirm that the empirical insights generated in this research are not isolated but rather form part of a broader, consistent pattern within contemporary construction literature.

5.1 IMPLICATIONS OF THE RESEARCH

This study significantly contributes to the theoretical understanding of the barriers impeding the successful integration of lean integrated sustainable construction. By identifying 32 critical barriers, with a focus on social aspects, the study offers new insights into the complex interplay of behavioural, managerial, and workforce challenges in lean thinking. From a practical standpoint, the study highlights the critical barriers that practitioners and organisations must address to successfully implement lean practices in sustainable construction projects. Collectively, organisations can utilise these findings to tailor their lean implementation strategies, focusing on human resource development, cultural realignment, and leadership engagement for more sustainable outcomes.

5.2 THE WAY FORWARD

The identified human-centric barriers present opportunities for future research to examine their impact in real-world construction settings. Researchers can further investigate how factors like leadership, culture, and workforce engagement influence the success of lean integrated sustainable construction adoption. These insights can contribute to developing an integrated framework for assessing organisational readiness and maturity in implementing lean integrated sustainable construction.

6. CONCLUSIONS

Green building is a key enabler of sustainable construction, as it translates sustainability principles into measurable practices focused on environmental performance, energy efficiency, and resource optimisation. When integrated with lean construction, it creates a comprehensive approach to achieving sustainability in the construction industry. This study reveals that the primary obstacles to successful lean integrated sustainable construction implementation are rooted in organisational culture and human factors. Key challenges include resistance to change, insufficient leadership, and misaligned incentive structures, all of which hinder the adoption of lean integrated sustainable construction. These findings emphasise the need of fundamental shift in organisational mindset, prioritising cultural adaptation, stakeholder collaboration, and continuous education. By addressing these human centric barriers, the construction sector can unlock the full potential of lean integrated sustainable construction, paving the way for more sustainable and efficient project delivery. Future research should explore practical frameworks for creating organisational readiness and overcoming cultural resistance to these innovative approaches. Strengthening the alignment between green building practices and lean thinking will not only improve environmental and economic outcomes but also contribute to long-term industry resilience. As the demand for sustainable infrastructure continues to rise, this integrated approach stands as a critical pathway toward achieving global sustainability targets and transforming the construction industry's future.

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LEARNING FROM NATURE: BIOMIMICRY-INSPIRED BUILDING DESIGN FOR CARBON REDUCTION IN URBAN LIVING

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ABSTRACT

The built environment contributes significantly to global carbon emissions, with urban construction accounting for over one-third of total CO_2 emissions. With increasing urbanisation and climate concerns, effective methods for reducing building emissions are essential. This research evaluates biomimicry-inspired designs in reducing carbon emissions in urban high-rise residential buildings. A comparative analysis was conducted between a conventional 35-storey residential tower and a biomimicry-inspired model based on the human femur's structural efficiency and tree trunks' aerodynamic shape. Autodesk Carbon Insight was employed to assess carbon emissions, controlling variables such as material use, occupancy patterns, climatic conditions, and mechanical systems. The biomimicry-inspired design achieved a 48.76% reduction in embodied carbon and a 47.8% reduction in operational carbon, leading to an overall carbon emission decrease of 61%. These reductions were mainly due to structural optimisation, improved passive ventilation from stack effects, and effective solar shading. This study offers new theoretical insights by integrating form-driven design with carbon analysis at early design stages. The use of Autodesk Carbon Insight not only facilitates precise carbon quantification but also bridges a critical gap in evaluating biomimetic architecture beyond aesthetics or energy modelling. Practically, the findings introduce a replicable and scalable strategy for urban development that aligns construction with natural principles. As the urban environment continues to grow, the path forward must not resist nature but emulate it, because, as nature has long demonstrated, form follows function. This approach reframes design as a dialogue with the biosphere, marking a necessary shift toward regenerative and carbon-conscious architecture.

Keywords: *Autodesk Carbon Insights; Biomimicry; Carbon Emissions; Urbanization.*

1 INTRODUCTION

Urban centres are major zones of resource consumption (Secretariat of the Convention on Biological Diversity, 2012), and their continuous growth accelerates biodiversity loss and ecosystem degradation (Güneralp et al., 2013). Urban activities produce pollutants including wastewater, carbon emissions, smoke, dust, and solid waste, contributing

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significantly to environmental decline (Li et al., 2022). Fuel combustion further adds to atmospheric pollution, with notable emissions such as Sulphur dioxide (SO_2), particulate matter, and carbon dioxide (CO_2) (Liu & Wang, 2017). Urban environments are estimated to generate around 70% of global carbon emissions and are central to a range of socio-environmental challenges (United Nations Human Settlements Programme (UN-Habitat), 2022). Urban dwellers face heightened risks from the urban heat island (UHI) effect, with city regions registering higher temperatures than their rural counterparts (Patel et al., 2022). This is exacerbated by land use patterns, particularly energy consumption, transportation, and industrial processes, which intensify greenhouse gas emissions (Pataki et al., 2007). Urban areas, therefore, form a critical arena for addressing climate change (Hoornweg et al., 2011).

In response, design approaches such as biomimicry have gained traction as viable strategies for climate change mitigation in cities (Araque et al., 2021). Biomimicry involves applying principles observed in nature to inform the design of built systems (Pawlyn, 2019), offering pathways for sustainable architecture, urban planning, and infrastructure (Zari, 2021). It shifts design thinking by leveraging evolutionary intelligence embedded in biological systems, which have adapted to complexity, constraint, and efficiency over millennia. Biomimicry, therefore, not only informs resilient design but also realigns built environments with ecological processes. By studying organisms and ecosystems, designers can model urban forms capable of regenerating environmental health and responding flexibly to dynamic urban challenges (Zari, 2021). Despite its potential, biomimicry remains underexplored in the context of urban residential construction. While its application in other domains of the built environment is documented (Pawlyn, 2019; Woodward, 2023), its systematic integration into high-density housing remains limited. Yet, as Aanuoluwapo and Ohis (2017) suggest, nature offers tested solutions to disorder and complexity, traits now intrinsic to urbanization and climate volatility. Consequently, leveraging Biomimicry to mitigate the climatic impacts resulting from increasing urbanization and carbon emissions holds significant potential in the contemporary global context. Thus, this study investigates:

"How effective are biomimicry-inspired approaches in urban residential building construction projects for achieving net zero outcomes in the built environment?"

This study intends to assess the viability of biomimicry in the design and construction of urban residential towers by evaluating its capacity to reduce carbon emissions and contribute to scalable, low-impact construction solutions aligned with both ecological logic and net-zero carbon goals.

2 LITERATURE REVIEW

2.1 CARBON EMISSIONS IN THE BUILT ENVIRONMENT

According to the UN Environment Programme (UNEP) (2025), the construction sector in 2023 consumed 32 percent of global energy and was responsible for 34 percent of global carbon dioxide emissions. Operational emissions reached a peak of 9.8 gigatons, while embodied carbon emissions were approximately 2.9 gigatons. Although there was a slight reduction in embodied carbon emissions and an increase in renewable energy usage, which accounted for 17% of total building energy consumption in 2023, these efforts remain insufficient to achieve the goals of the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) (2011) projected the sector's

emissions would rise from 31% in 2020 to 52% by 2050. As a key driver of economic growth and resource consumption, construction significantly influences emissions, particularly through materials like cement and steel, which account for 18% of global emissions and generate substantial waste (Zhang et al., 2019). Notably, 2023 marked the first time since 2020 that emissions from the building sector plateaued despite ongoing growth, reflecting a 10% reduction in energy intensity and a 5% increase in renewables in final energy demand (Molloy, 2023). Looking forward, the sector could deliver 11% of global mitigation potential by 2035, roughly 4.2 gigatons of avoided CO_2 emissions, if aligned with the 1.5°C climate goal. Achieving this requires retrofitting existing buildings and designing new ones for sustainability. Biomimicry has emerged as a promising solution to support these efforts (Kennedy et al., 2015).

2.2 THE CONCEPT OF BIOMIMICRY IN THE BUILT ENVIRONMENT

Biomimicry offers a promising approach to reducing energy consumption and carbon emissions across various scales, from materials and components to entire buildings and cities (Pacheco-Torgal, 2015). In architecture and urban design, it supports sustainable and regenerative development (Hes & du Plessis, 2014). Nature operates on the principle of utilizing free energy, with most ecosystems relying on contemporary sunlight, which is recent solar energy converted into biomass through photosynthesis. Examples include seed pods dispersed by wind using air currents and marine mammals migrating by taking advantage of ocean currents (Zari, 2021). These systems serve as models of energy efficiency (Aanuoluwapo & Ohis, 2017), providing strategies to reduce fossil fuel dependence and emissions. Zari (2021) suggests designing urban environments to mimic ecosystem functions, which could help restore local ecosystems. Dicks et al. (2021) have proposed a forest as a model for urban planning and designing. Using trees as models for buildings not only suggests fitting each building with solar panels but also opens possibilities for advancements in biomimicry solar technologies. This includes water-splitting technologies that replicate many of the functional properties of leaves (Liu & Wang, 2017). Biomimicry also involves replicating the structure and function of biological forms, such as nests, focusing more on performance than aesthetics (Januszkiewicz & Alagoz, 2020; Uchiyama et al., 2020). This method enhances building performance by aligning with material efficiency and optimizing lighting and heating (Buck, 2017). The European Commission recognizes biomimicry as a key innovation area for climate adaptation and mitigation (Blanco et al., 2021).

2.3 BIOMIMICRY AS A SOLUTION FOR ENERGY EFFICIENCY AND CARBON REDUCTION

Enhancing the thermal performance of building envelopes, particularly facades, is essential for reducing operational energy use while ensuring occupant comfort (Liao et al., 2022). Biomimicry offers nature-inspired strategies to lower energy demands for heating, ventilation, and lighting (Yuan et al., 2017). Badarnah (2015) introduced a framework for integrating biomimicry into building skins, addressing energy, comfort, water management, materials, and waste. Passive cooling and ventilation, another key application, draw on nature's efficiency (Khelil & Zemmouri, 2019). Zari (2021) notes that ecosystems demonstrate how energy-efficient systems can function without fossil fuels. For instance, researchers at the University of Rochester mimicked super-wicking plant leaves to enhance evaporation in cooling systems, achieving up to 500% greater efficiency (Smith et al., 2015). In the 1990s, biomimetic architecture gained prominence

through landmark projects such as Zimbabwe's Eastgate Centre (1996). Emulating termite mounds to maintain stable indoor conditions without mechanical HVAC, Eastgate's use of natural ventilation and thermal mass reportedly reduced its energy consumption by roughly 90% relative to conventional buildings (Chayaamor-Heil et al., 2018). Another relevant example is London's 30 St Mary Axe ("The Gherkin"), which employs a passive ventilation system inspired by marine sponges to enhance energy efficiency (Aboulnaga & Helmy, 2022). However, such biomimetic innovations have seen limited application in high-density urban residential towers. This gap is particularly notable in light of rapid urbanization and the proliferation of high-rise housing, underscoring the need for further research on biomimetic strategies for high-density urban housing.

3 METHODOLOGY

This study adopted a phased methodological framework, progressing through four key stages. First, a comprehensive literature review was conducted to identify how biomimicry principles have been previously applied to reduce carbon emissions in the built environment. The second stage involved selecting a representative case study. The third phase focused on the digital development of two comparative building models: a conventional residential tower and a biomimicry-inspired counterpart. The final stage outlined the carbon quantification process using a performance-based analytical tool to assess both embodied and operational carbon emissions in a controlled simulation environment.

3.1 SELECTION OF THE CASE STUDY

A 35-storey apartment building located in the United States of America (USA), with a gross floor area of 28,000 m², was selected. This building is a standalone building where the structural system is reinforced concrete, and the external envelope consists of a double-glazed curtain wall façade. Figure 1 shows the architectural layout of the selected building, showcasing elevation, site plan, unit layout, and ground floor design.

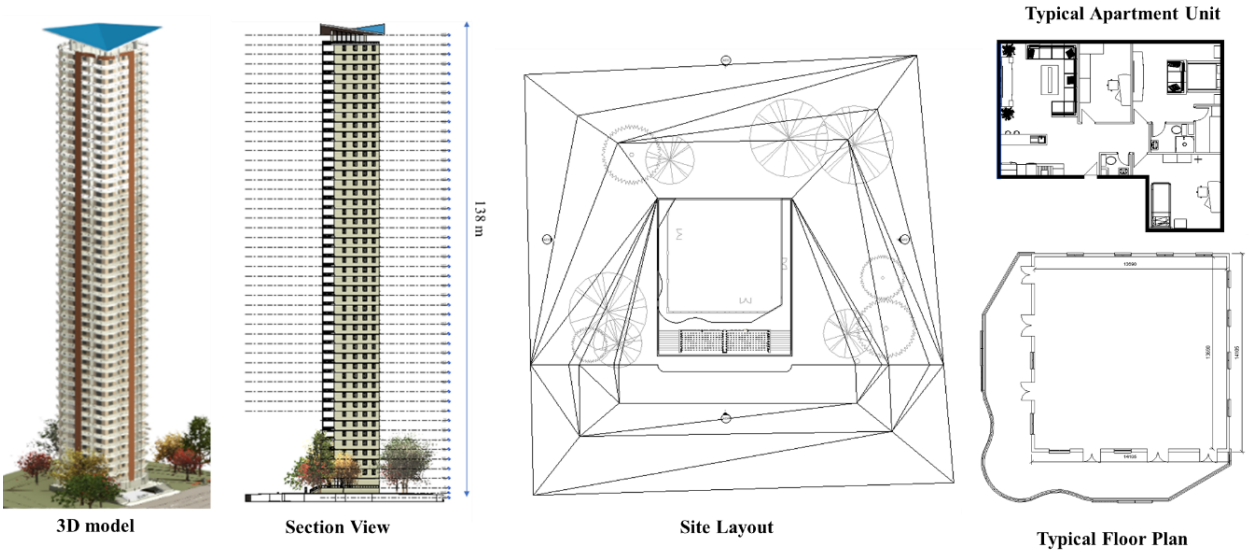


Figure 1: Architectural layout of the selected building, showcasing elevation, site plan, unit layout, and ground floor design

The choice of this building in the USA as a case study was guided by three principal considerations. First, the square form reflects a dominant typology in contemporary high-rise construction due to its structural simplicity, spatial efficiency, and adaptability (Steadman, 2006). Second, the selection of a USA based project aligns with the Autodesk Carbon Insights tool, which incorporates the EC3 database developed by the Carbon Leadership Forum in Seattle (Molloy, 2023). As this database relies on USA specific Environmental Product Declarations (EPDs), it enables a more precise assessment of embodied carbon within the local construction context. Lastly, the availability of comprehensive carbon data further supports the feasibility and relevance of this case study.

3.2 DEVELOPMENT OF THE BUILDING MODELS

Among different Building Information Modelling (BIM) software, Autodesk Revit was used to develop detailed digital representations of both the conventional and biomimicry-inspired designs. Geographic and climatic settings were adjusted in each model to simulate accurate carbon performance within a consistent environmental context. To maintain internal validity, identical building functions and spatial allocations were retained across both models.

3.2.1 Inspiration for the Biomimicry Building Model

A problem-based biomimicry approach was used to address the carbon-intensive nature of high-rise construction. This involved identifying carbon reduction as the central design challenge and analyzing natural systems for analogous solutions. The resulting design drew on the structural logic of the human femur and the aerodynamic form of tree trunks, both of which exhibit inherent efficiencies in load distribution and environmental adaptability. This translation of biological logic into architectural form was guided by structural engineering constraints and environmental performance objectives. Figure 2 shows the development process of the biomimicry inspired building model.

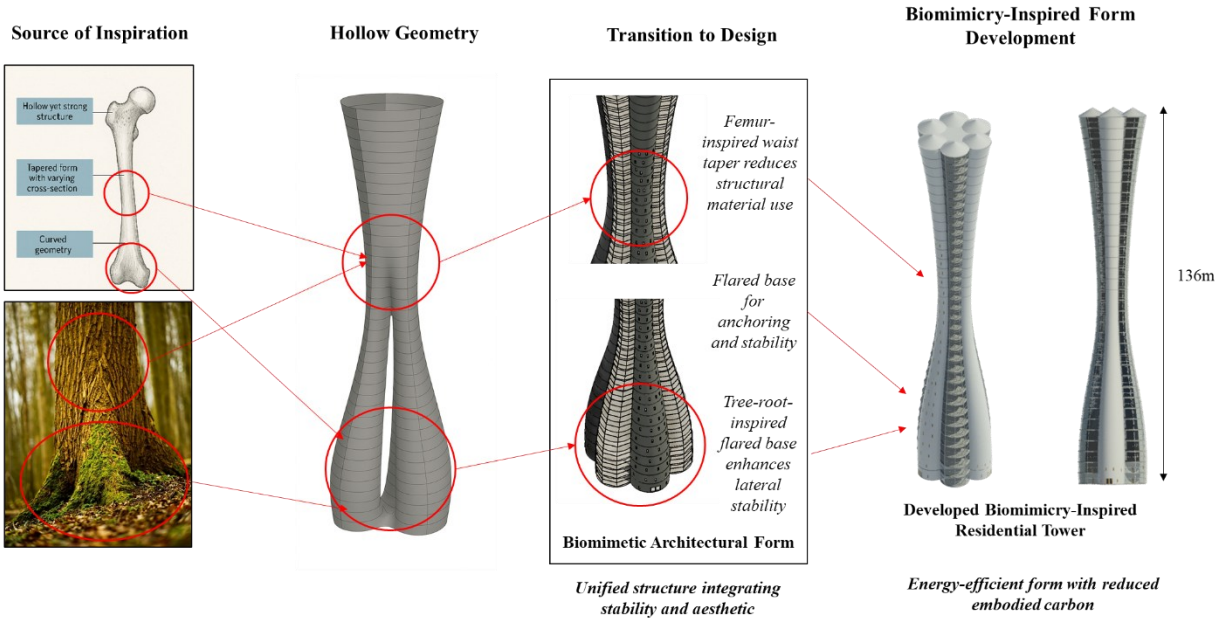


Figure 2: Development process of the biomimicry inspired building model

Figure 3 shows the floor plans and the roof plan views of the building.

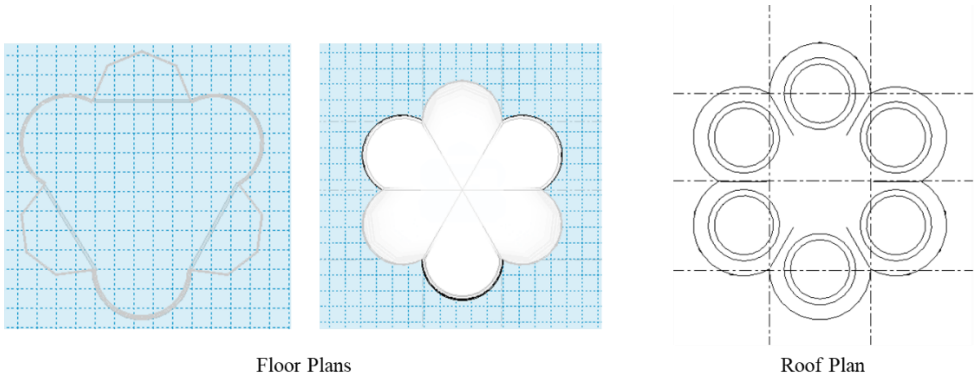


Figure 3: Biomimicry inspired building model: Floor plans and the roof plan views of the building

3.2.2 Architectural Features

The femur's hollow, tapered shaft and expanded ends exemplify how material can be distributed efficiently for maximum strength with minimal mass. This structural logic informed a building form with a narrow waist to reduce material demand and flared base and crown to enhance resistance against lateral forces such as wind and seismic loads. Meanwhile, the tree trunk, shaped by wind and gravity over time, inspired an aerodynamic and vertically optimized form, promoting passive ventilation, reducing wind pressure, and enhancing overall environmental responsiveness.

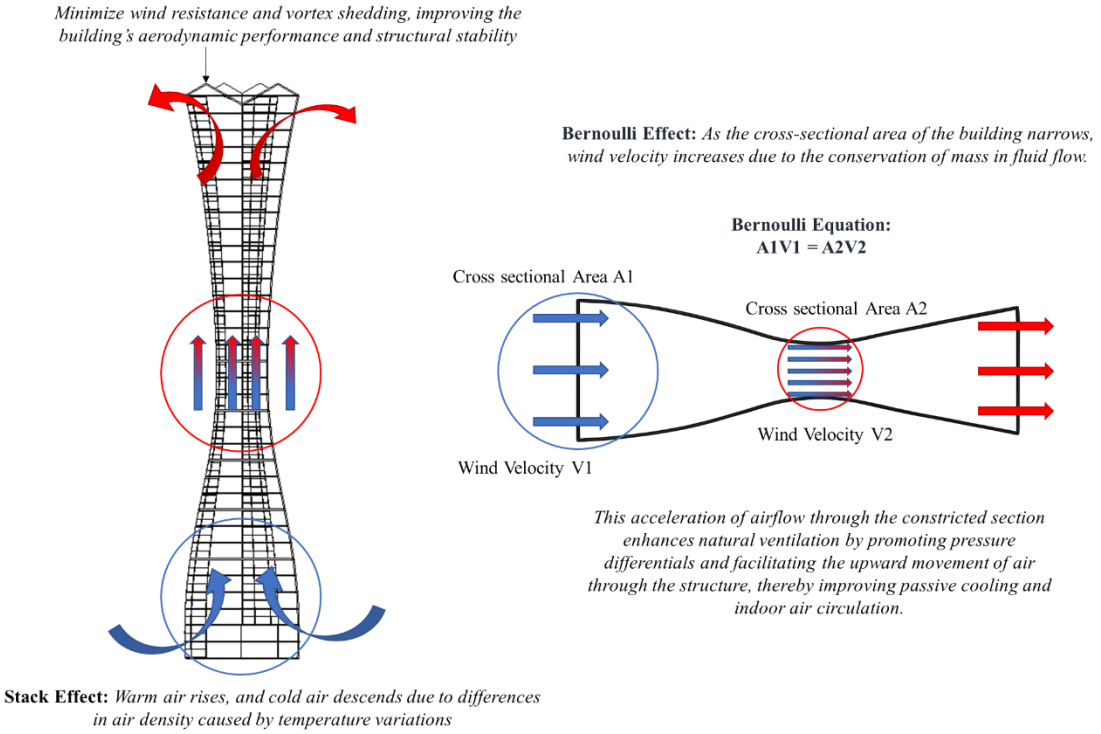


Figure 4: How the building form supports natural ventilation

Morphologically, the form supports natural ventilation via the stack effect, facilitated by the narrowing waist (see Figure 4), while the curved façade geometry minimizes solar gain. Inspired by spiral growth patterns in trees and bones, the building's subtle torsion facilitates wind redirection to enhance cross-ventilation. Orientation adjustments

optimize daylight penetration and limit solar exposure on thermally sensitive façades, reducing reliance on artificial lighting and mechanical cooling. Collectively, these strategies embody a passive design logic derived from nature, where form and function converge to meet structural and environmental performance goals without relying on energy-intensive active systems.

3.3 Assumptions and Limitations

The analysis assumes consistent operational parameters for both models, including identical occupancy profiles, HVAC systems, lighting setups, and energy demands. Climatic conditions were held constant by applying a single weather dataset across both models. This controlled comparison allows isolation of the impact of form and structural logic on carbon performance.

3.4 Assessment of Total Carbon Emissions

Carbon quantification was performed using Autodesk Carbon Insight (Molloy, 2023), which integrates with Revit to evaluate both operational and embodied carbon metrics. The tool draws on data from the EC3 database, which aggregates third-party verified EPDs and material carbon intensities. By extracting quantities from the BIM models, it enables accurate forecasting of carbon outcomes at both design and procurement stages. Interactive dashboards provided by the platform support comparative assessment and facilitate informed decision-making on carbon reduction strategies. This capability is particularly valuable in early-stage design, where major decisions on form and materiality are made.

4 RESEARCH FINDINGS AND DISCUSSION

4.1 Comparison of Carbon Emissions between Conventional and the Biomimicry Inspired Building Models

Figure 5 and 6 illustrates the embodied, operational, and total carbon emissions calculated from Autodesk carbon insights for the two building models.

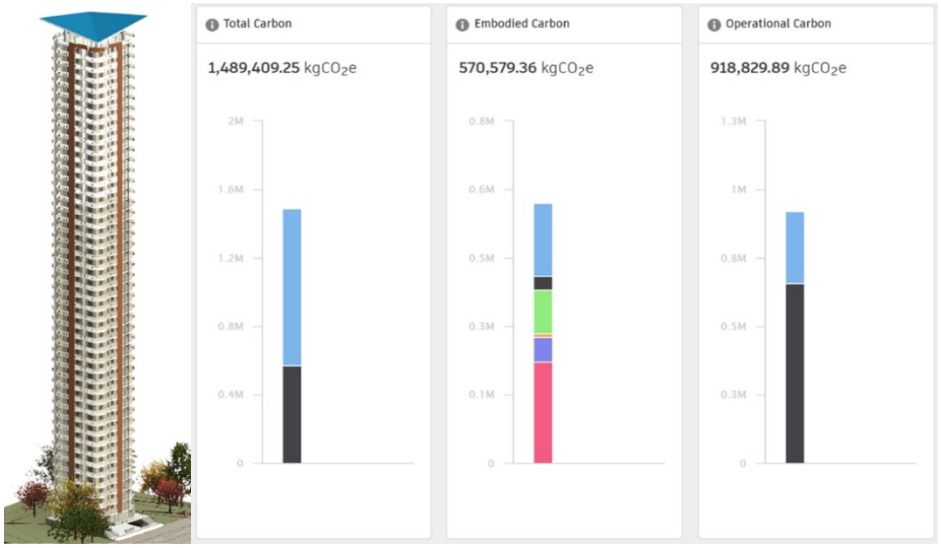


Figure 5: Embodied, operational, and total carbon emissions of the conventional building

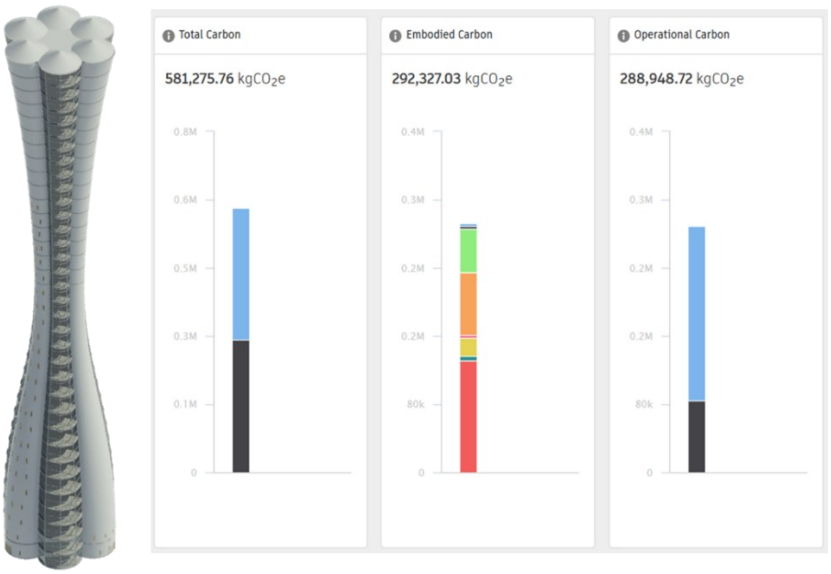


Figure 6: Embodied, operational, and total carbon emissions of the biomimicry inspired building

A comparative analysis of carbon emissions between the two models, based on data obtained from Autodesk Insights, is presented in the following sections.

4.1.1 The Comparison of Embodied Carbon Emissions

Figure 7 illustrates the embodied carbon emissions from the two building models.

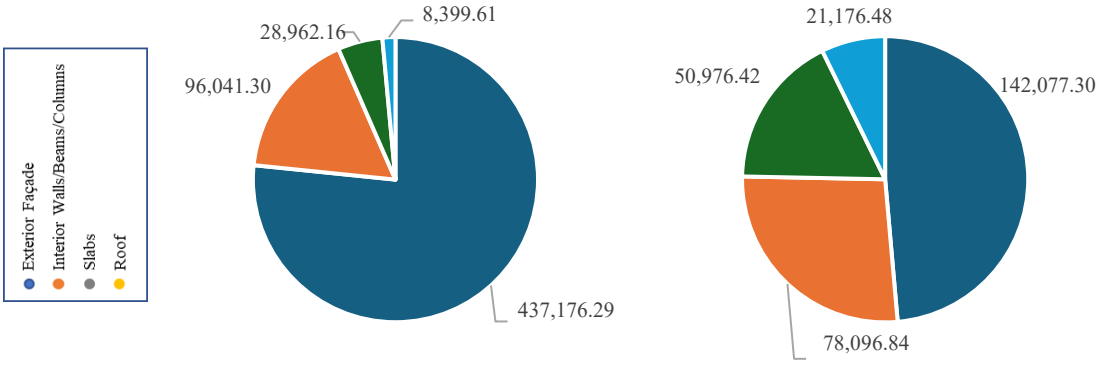


Figure 7: Embodied carbon emission from the two building models: Conventional building (Left) and biomimicry inspired building (Right)

The embodied carbon analysis shows a 48.76% reduction in the biomimicry-inspired design, with total emissions dropping from 570,579.36 kgCO₂e to 292,170.23 kgCO₂e (refer figure 5 and 6). Significant savings were achieved in the building envelope and structural elements like walls, beams, and columns. Although slab and roof emissions increased by 76% and 150% due to complex biomimetic geometries, the overall outcome highlights improved material efficiency through nature-inspired structural optimization.

4.1.2 The Comparison of Operational Carbon Emissions

Figure 8 illustrates the operational carbon emissions from the two building models.

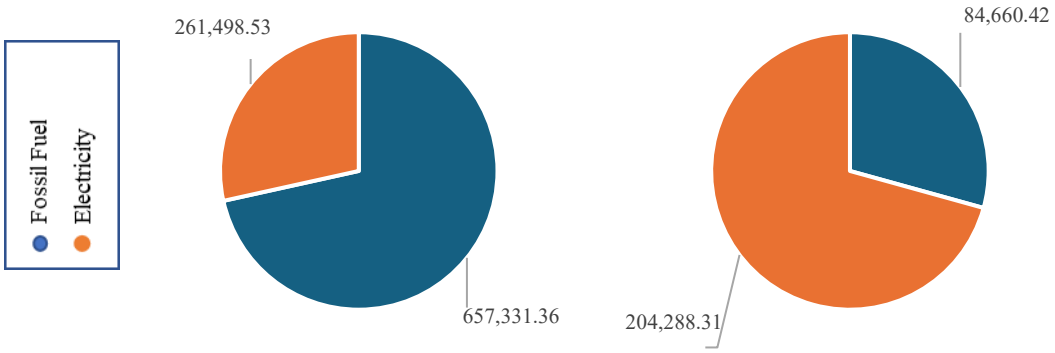


Figure 8: Operational carbon emission from the two building models: Conventional building (Left) and biomimicry inspired building (Right)

Operational emissions analysis shows that the biomimicry model reduced fossil fuel emissions by 87% (from 657,331.36 to 84,660.42 kgCO_2e) and electricity emissions by 22% (from 261,498.53 to 204,288.31 kgCO_2e). These reductions stem from passive design strategies, enhanced stack ventilation, solar shading from the flared crown, and optimized daylighting, achieved through geometric adaptation rather than mechanical systems.

4.1.3 The Comparison of Total Carbon Emissions

Figure 9 illustrates the total carbon emissions from the two building models.

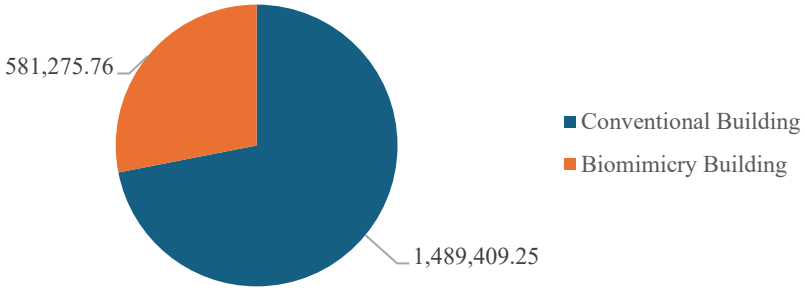


Figure 9: Total carbon emissions from the two building models

The cumulative carbon emissions underscore the impact of design form. The conventional model emitted 1,489,409.25 kgCO_2e, while the biomimicry-inspired counterpart emitted 581,275.76 kgCO_2e. This represents a total carbon reduction of 61%, reinforcing the potential for biomimetic design to influence both embodied and operational performance simultaneously.

4.2 DISCUSSION

These findings contribute to the emerging discourse on form-driven design as a primary vector for decarbonising the built environment. The 48.76% reduction in embodied carbon aligns with the assertion by Gu et al. (2024) that building form and structure have a direct influence on material-related emissions. Unlike most conventional studies that emphasise material substitution or efficiency at the procurement stage, this study isolates form as the primary variable. The use of the same materials, systems, and environmental conditions across both models reinforces the validity of this attribution. This isolation of form offers a rare empirical instance where geometry itself becomes the key

decarbonising agent, an approach that remains underexplored in current lifecycle-based research methodologies. Comparatively, exemplar projects such as the Gherkin (Küçük & Arslan, 2020), Eden project (Woodward, 2023), and Sinosteel building project (Pawlyn, 2019) have demonstrated similar principles, using form to minimize material demand. However, these precedents often incorporate a combination of passive and technological strategies. What distinguishes the present study is its focus on form as a singular intervention, suggesting that biomimetic geometry alone, without significant changes in materials or building systems, can lead to substantial carbon reductions.

In contrast to integrated design approaches that blur the contribution of form with systems innovation, this model foregrounds the idea that the spatial and structural logic of nature, when translated into architectural massing, can independently drive carbon optimization. This reorients biomimicry from a symbolic or aesthetic discourse to one grounded in quantitative performance. Operational carbon results (refer to Section 4.1.2) further reinforce this. While much of the existing literature attributes energy efficiency to technological upgrades or system-level interventions, the findings of this study reinforce the argument made by Hanafi (2021) and Sudhakaran et al. (2017): that building form itself can regulate energy demand. Precedents such as the Esplanade Theatre, Eastgate Building, Sinosteel Plaza, and the Gherkin demonstrate similar outcomes, though only a few, including the latter two, attribute their efficiency primarily to aerodynamic and daylight-responsive geometries (Bijari et al., 2025). The Gherkin and Sinosteel projects report 80% and 75% energy improvements respectively comparable to the 47.8% operational carbon reduction achieved in this study. Crucially, these results are obtained without altering occupancy patterns, systems, or climatic conditions, underscoring the underexplored potential of early-stage morphological decisions in passive carbon mitigation. Notably, the biomimicry model integrates multiple passive functions, stack ventilation, solar control, and daylight optimisation, within a single, morphologically coherent form. This multifunctionality mirrors ecological principles, where natural structures often perform more than one function simultaneously, offering a resilient and adaptive logic for urban design.

Taken together, these findings challenge the current paradigm that treats architectural form primarily as an aesthetic or spatial determinant. Instead, they position form as a measurable variable in carbon performance modelling, with implications for lifecycle analysis, building codes, and early-stage design decision-making. This reframes biomimicry not as a conceptual exercise, but as a quantifiable design logic that may bridge the gap between ecological inspiration and environmental performance.

5 CONCLUSION

This study set out to examine the effectiveness of biomimicry-inspired architectural form as a mechanism for reducing carbon emissions in urban high-rise residential construction and contributing to net-zero objectives in the built environment. In the context of accelerating urbanization and intensifying ecological stress, the findings affirm that translating nature's structural and environmental logics into architecture is not only conceptually sound but demonstrably effective. Using a problem-based biomimetic approach, the study developed a tower form inspired by the human femur and the functional morphology of tree trunks. Carbon performance simulations using Autodesk Carbon Insight revealed a 48.76% reduction in embodied carbon and a 47.8% reduction in operational carbon, achieved without any modification to material specifications,

systems, or occupancy parameters. These results isolate form as a critical, and often overlooked, determinant of environmental performance.

The study reinforces the central thesis that architectural morphology, when grounded in ecological intelligence, can supplant reliance on energy-intensive technologies by enabling inherent efficiencies. Passive shading, enhanced stack ventilation, and optimized structural load paths emerged not as afterthoughts, but as embedded outcomes of the building's biologically informed geometry. This aligns with successful precedents such as the Gherkin, Sinosteel Tower, and Eastgate Centre, positioning biomimicry as both scalable and practicable. Crucially, this research contributes to the growing body of knowledge in built environment that biomimicry transcends symbolic mimicry; it is a quantifiable, high-impact strategy with measurable environmental gains.

Future research may advance the potential of biomimicry by combining parametric simulations and multi-objective optimization techniques to explore how evolutionary geometries can shape scalable frameworks for decarbonized urban design. This approach positions biomimicry not as a niche innovation, but as a legitimate and reproducible strategy within the mainstream carbon discourse in construction. Further exploration into the integration of biomimetic geometry with advanced materials, modular construction methods, and responsive envelope systems could unlock additional performance gains.

Overall, this study advocates for biomimicry not as an optional aesthetic gesture, but as a strategic framework for design, one that repositions buildings as participants in natural systems rather than disruptors of them. As urban environments become the front line of climate mitigation, learning from nature offers not just a model for efficiency, but a philosophy of survival. In the pursuit of lasting, regenerative futures, it is time the built environment ceased to dominate nature and began to emulate it.

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MAPPING CIRCULARITY PARAMETERS: A LITERATURE REVIEW OF POLICY PLANNING IN THE BUILT ENVIRONMENT

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ABSTRACT

The construction industry is amongst the major consumers of natural resources, resulting in an exponential increase in overall waste generation, especially construction waste. The current approach to design in the construction industry is linear, involving take, make, dispose strategy, which has led to a significant depletion of resources and in turn to environmental degradation. The need for human shelter will remain inevitable; thus, there is an urgent need to integrate a circular economy approach within design and construction practices, which gives back to the environment it takes from. This change from linearity to circularity is a complex process, influenced by several factors. Government policies can be highly influential for this change from linear to circular approach in design, construction and management of the built environment. In the process of change, these policies need to be assessed and checked for every part that supports the circular economy principles. This systematic literature review critically examines the role of existing government policies in supporting circular economy principles and identifies key regulatory gaps that restrict their implementation. The primary gap lies in the implementation process. The suggestive nature of the frameworks hinders the implementation of such policies on a larger scale. Through the existing literature, 10 circular economy parameters were identified across 3 different construction phases, with the help of which key government policies will be analysed in the future. This study will identify the existing gap within the legal framework barring circular economy implementation in the construction sector.

Keywords: *Built Environment; Circular Economy; Policies; PRISMA; Systematic Literature Review.*

1. INTRODUCTION

The construction industry is low in resource efficiency worldwide (Shooshtarian et al., 2022). This has led to high levels of construction and demolition waste, high greenhouse gas emissions, air and water pollution, and resource depletion. Circular economy approach refers to giving back to the environment from which it takes, hence, closing the loop. This is a significant shift from the regular linear approach to design, which involved

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a take, make, dispose strategy. The construction industry produces substantial waste, which demands a more circular approach in the design stage. In response to the growing environmental crisis, several international organizations and national governments have introduced policy frameworks aimed at promoting circular economy principles in the built environment.

Arora and Mishra (2019) notes that the 2030 Agenda for Sustainable Development outlines the need for economic security and environmental sustainability, but the only three countries that have managed to achieve one-third of the Sustainable Development Goals are Sweden, Denmark and Finland. The need for the world to come together and act upon these goals is inevitable. All countries need to have their own policy frameworks for this overarched goal to be attained. "*The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 countries at the UN Climate Change Conference (COP21) in Paris, France*." (United Nations Framework Convention on Climate Change, 2018) According to this Agreement, countries must work on a five-year action plan. They are required to submit their national climate action plans in order to hold them accountable. The United States of America is the second-largest contributor to greenhouse gas emissions but has exited the Paris Agreement recently. The EU Waste Framework Directive and Circular Economy Action Plan 2020 set ambitious targets for waste reduction, recycling, and resource efficiency, promoting sustainable production, eco-design, and circular business models. This comprehensive framework aims to accelerate the circular economy transition, reduce environmental impact, and drive sustainable growth (Bragança et al., 2025).

However, all these frameworks and action plans seem to be in place on an international level and how they percolate down to the grassroot level has not been linked in the current available literature. Thus, an in-depth analysis of current regulations and the identification of potential areas for regulatory frameworks on various levels of governance is necessary to support the shift from a linear to a circular economy. A thorough analysis of the policy literature can be used to evaluate the efficiency of the laws in place, identify best practices from nations that have effectively used the concepts of the circular economy, and suggest changes that would improve compliance. The research paper aims at critically analysing how government regulations support the circular economy's principles in the building sector through thorough a systematic literature review. It analyses important policy provisions, assesses their effects, and identifies the obstacles to their implementation through a methodical literature study. This study also offers insights into policy actions that can accelerate the transition by examining national and international policy frameworks.

2. METHODOLOGY

This study uses a systematic literature review (SLR) to provide an overview of existing research on circular economy principles in the built environment and their integration into policy frameworks. The SLR follows a structured approach to evaluate and synthesize relevant literature, aiming to highlight key findings and research gaps in the field (Turner et al., 2025).

2.1 DATA COLLECTION

The literature search was conducted using Scopus, a widely recognized database for peer-reviewed research. Due to limited accessibility to databases, only one database was

analysed. The search utilized the following keywords: “built environment,” "circular economy," and "policy" (TITLE-ABS-KEY (built AND environment) AND TITLE-ABS-KEY(circular AND economy) AND TITLE-ABS-KEY (policy)) AND (LIMIT-TO (LANGUAGE,"English"). The data extraction was performed on 29th of May 2025, retrieving an initial data set of 172 papers. While conducting the search by keywords, the query was specific with the use of asterisks.

2.2 SCREENING AND SELECTION

A multi-stage filtering process was applied to systematically review and filter the dataset. The first stage was Keyword Analysis, out of the 172 papers, 75 papers were excluded as they lacked direct relevance to circular economy and policy frameworks keywords. Secondly, of the remaining 97 papers, papers with abstracts not explicitly addressing both policy frameworks and the built environment were removed, resulting in the elimination of 36 papers from the dataset. Lastly, after the systematic screening, 61 papers were deemed relevant and included in the final review. The screening and selection process was done with the PRISMA Framework (Page et al., 2021) as shown in Figure 1. Due to a lack of resource availability, only one database (Scopus) was used to retrieve records.

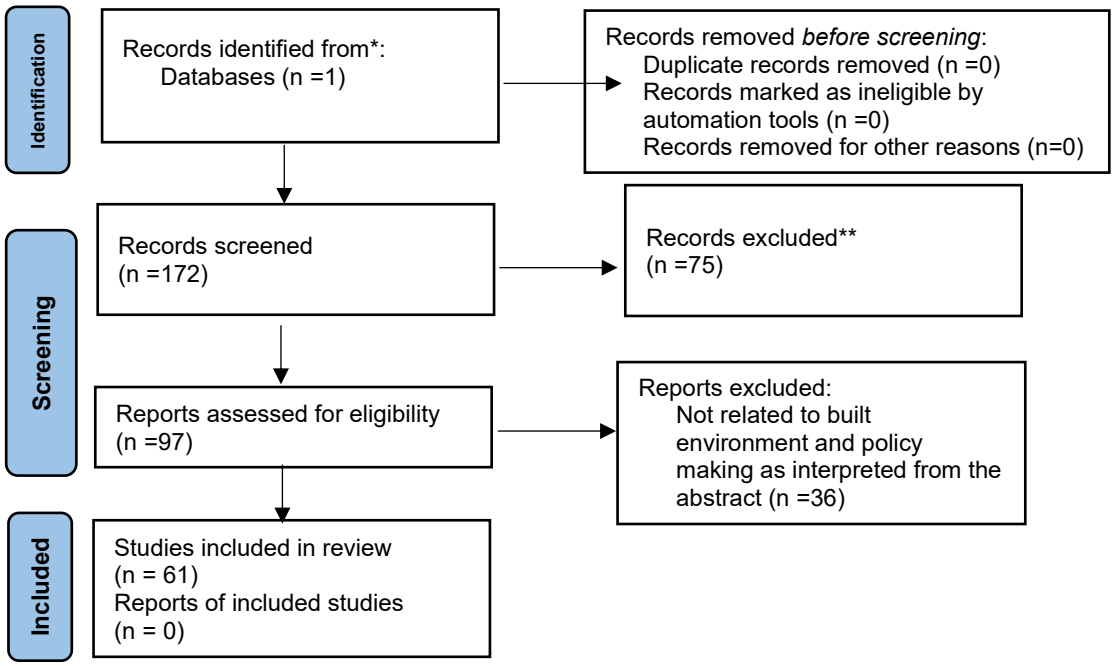


Figure 1: Screening process using PRISMA framework

This structured methodology ensures a rigorous and unbiased selection process, allowing for a comprehensive analysis of policy-driven circular economy practices in the built environment. The conclusions of these studies reveal valuable insights into existing policy frameworks and highlight challenges and opportunities for further research and study on newer policy frameworks. Table 1 highlights the country-wise distribution of publications in the given domain with their respective citations counts. The United Kingdom is leading and sustains itself regarding research output and influence on circular economy in construction, followed by high contributions from the United States of America, Australia, and The Netherlands. Hong Kong and India display fewer publications, but their strong post-screening retention suggests targeted, significant

research. Emerging interest is demonstrated by India, while countries like Ghana, Sweden, and South Africa reflect developing, context-specific circular economy research environments. With regional significance, nations like Germany, Italy, and Turkey make consistent contributions.

Table 1: Country wise distribution of circular economy publications before and after screening

Country	Before screening (n: 172)	After screening (n: 61)	Country	Before screening (n: 172)	After screening (n: 61)
United Kingdom	31	11	Greece	5	1
Spain	13	2	Ghana	7	2
Germany	9	3	Hong Kong	6	3
Austria	8	1	Denmark	5	0
Italy	14	3	South Africa	8	1
United States	20	5	Turkey	6	3
Switzerland	7	1	Sweden	6	1
Netherlands	19	10	Australia	16	5
China	11	2	Finland	5	1
Portugal	10	3	India	6	3
Belgium	7	0			

Note: The total number of documents on addition before screening may exceed 172, as research papers addressing multiple countries have been counted under each relevant country.

2.3 KEYWORD ANALYSIS BEFORE SCREENING

Before applying the PRISMA framework, 172 papers were analysed with their keywords. For this analysis, both author and indexed keywords were used as the query was too specific. Using VOSviewer, a keyword analysis diagram was generated. **Error! R eference source not found.** is a graphical representation of trends in keyword use within the initial research database showing frequency of use, interrelation with other keywords, and the temporal pattern of usage over the years.

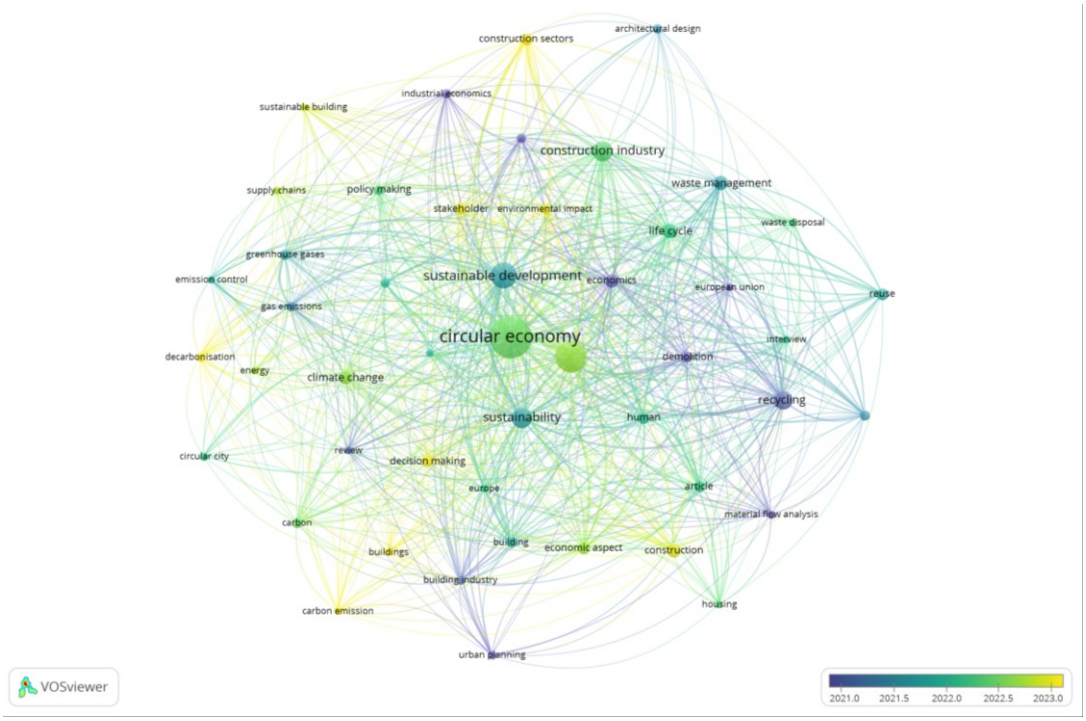


Figure 2: Keyword analysis before applying the PRISMA framework for 172 papers

There are four prominent keywords: "circular economy", "built environment", "sustainable development", and "sustainability". These are the core concepts derived from the dataset retrieved from Scopus. Keywords such as "recycling", "reuse", "life cycle assessment", and "construction industry" are topics that were prominent in earlier years. In contrast, keywords such as "policy making", "urban planning", "climate change", "carbon emissions", and "decarbonisation" have emerged in recent years, indicating a growing focus on governance and system-led integration. This change indicates an emerging interest in actual applications of circular economy concepts across industries such as construction, housing, and resource management, an indication of the increasing pertinence of circular approaches to urban planning and policymaking. Furthermore, "policy making' is linked to greenhouse emissions.

2.4 KEYWORD ANALYSIS AFTER SCREENING

Each of the 61 chosen papers was evaluated in a systematic manner to evaluate how far these parameters were included. Comparative assessment was done to identify trends, gaps, and policy implications concerning circular economy adoption. The results were synthesized to identify the prevalence and distribution of circular economy parameters in policies, the domains where policy structures strongly favour circularity, the most significant gaps in current policies and suggestions for improvement. With a systematic screening and analysis methodology, this approach guarantees a systematic and thorough assessment of the integration of circular economy principles into policy structures in the built environment.

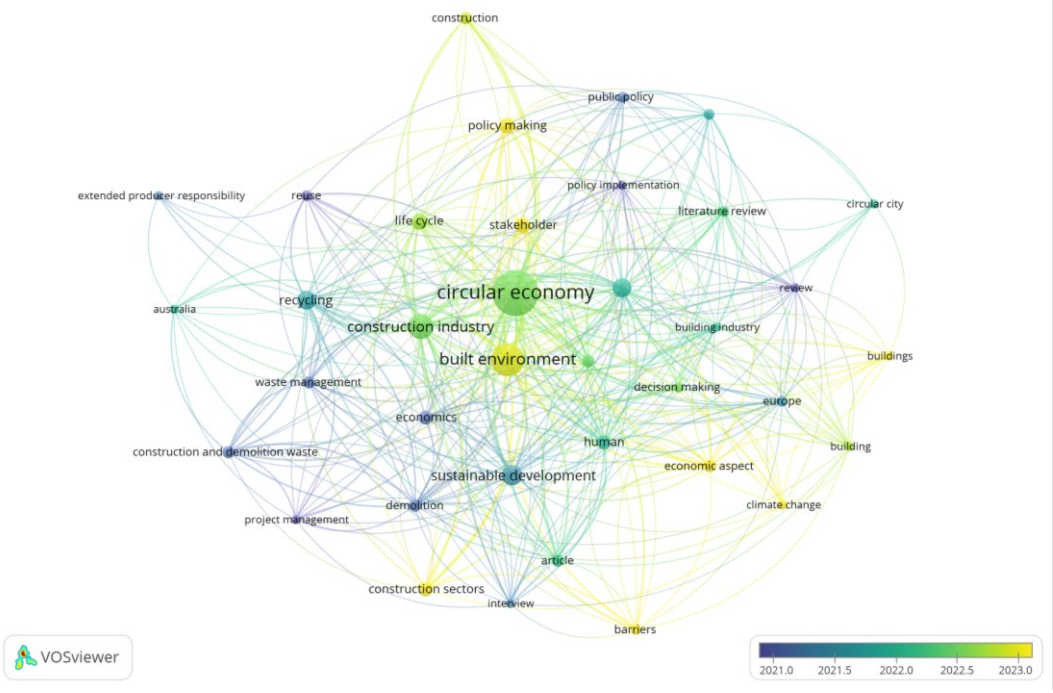


Figure 3: Keyword analysis after applying the PRISMA framework

"Sustainability", "construction industry", and "stakeholders" are closely linked to "circular economy" and "built environment", highlighting the integration of environmental considerations in construction practices. Older keywords (2021-2022) include "recycling", "waste management," and "construction and demolition waste", indicating an initial focus on material recovery and environmental management practices. Keywords like "policy making" and "stakeholder" indicate that research has increasingly focused on regulatory measures and structured approaches for circular economy adoption, yet the presence of "barriers" and "economic aspect" suggests ongoing challenges in policy enforcement, financial incentives, and stakeholder engagement. The built environment and construction sector are closely linked with terms like "demolition," "reuse," and "sustainable development," emphasizing the role of materials circularity, adaptive reuse, and sustainable construction practices. The "decision-making" and "stakeholder" connections highlight the necessity of multi-stakeholder collaboration for circular economy transitions.

3. RESULTS

3.1 IDENTIFICATION OF PARAMETERS

Analysing the selected papers, numerous parameters were identified. These parameters contribute to achieving the circular economy principles at the policy level. The 10 identified parameters are as follows:

Table 2: Identification and mapping of circular economy parameters across the reviewed literature

Design for Disassembly	This strategy ensures that, post-building use, the parts of the structure can be easily modified or removed without harming the rest of the structure. The understanding that "waste does not exist " promotes the design for disassembly. (Banihashemi et al., 2024; Charef et al., 2022; Guerra & Leite, 2021; Karaca et al., 2024)
Resource Efficiency	There is a need for an integrated system to promote circular economy and resource efficiency. Several innovative technologies have emerged in recent times that can be used to monitor resource efficiency and ensure a closed-loop system. (Ababio & Lu, 2023; Adabre et al., 2024; Bos et al., 2022; Bostancı et al., 2025; David et al., 2024; Kazmi & Chakraborty, 2025; Sharma et al., 2022; Shooshtarian et al., 2022; Uddin et al., 2025; Zhang et al., 2024; Zuofa et al., 2023)
Circular Construction	To achieve this principle, the desire and willingness along with the resources to do so need to be combined. Circular construction ensures the building is designed to be disassembled or refurbished. (Andabaka, 2024; Coenen et al., 2023; Guerra & Leite, 2021; Ikiz Kaya et al., 2025; Isoaho & Valkama, 2024)
Waste Reduction	It is essential to decrease the waste generated by the construction industry to move towards a more circular economy. Resource reuse and recycling directly contributes to less waste generation. (Bolivar et al., 2025; Chartier & Pot, 2024; Gomide et al., 2024; Heurkens & Dąbrowski, 2021; Iyer-Raniga et al., 2023; Josa & Borrion, 2025; Kaewunruen et al., 2024; Lecciones et al., 2022; Marzani et al., 2025; Mhatre et al., 2023; Noll et al., 2019; Omwoma et al., 2017; Sharma et al., 2022; Stahel, 2017)
Water Circularity	Water is one such resource that is essential throughout the lifecycle of the building, from its inception to post occupancy. The current system in India does not levy any tax on water which highly impacts the way people utilize it. A more sensitive approach to water utilisation and recycling can result in significant reduction in its demand. (Almulhim & Al-Saidi, 2023; David et al., 2024; Lecciones et al., 2022; Omwoma et al., 2017; Vassi et al., 2022)
Supply Chain Circularity	Integrating circular economy principles in the supply chain ensures material efficiency, waste reduction and resource recovery throughout the lifecycle of the building. Several studies have shown that this model can enable closed-loop systems that minimise raw material extraction. (Ancapi, 2023; Zhang et al., 2024)
Renewable Energy Consumption	Incorporation of renewable energy is crucial to reduce dependency on fossil fuels and, in turn reduce emissions. Technologies like solar, wind and bioenergy promote green energy contributing to a more circular economy. (Dewagoda et al., 2022; Mhatre et al., 2023)

Embodied Carbon Minimisation	Research emphasises the importance of minimising embodied carbon by using low-carbon emitting materials, more efficient logistical planning and other construction techniques. (Bucci Ancapi et al., 2022; Gomide et al., 2024; Josa & Borrion, 2025; Kaewunruen et al., 2024; Ness, 2022; Nußholz et al., 2023)
LCA	LCA is a foundational tool to evaluate the environmental impact buildings have from their construction to their demolition. It enables designers to compare impacts of different materials and construction techniques and make the necessary decisions. (Keles et al., 2025; Rajčić et al., 2025)
Material Reuse and Recycle	Reuse and recycling of materials reduce the demand for virgin materials while also increasing the lifespan of the structure. However, there exists a conflict on whether reuse and recycling of materials is economical, taking into consideration the logistical and regulatory barriers. (Amudjie et al., 2022; Çimen, 2021; Foster & Saleh, 2021; Giorgi & Lavagna, 2024; Ikiz Kaya et al., 2025; Josa & Borrion, 2025; Lecciones et al., 2022; Marzani et al., 2025; Ranta et al., 2018; Zuofa et al., 2023).

This identification of circular economy parameters underlines the multi-dimensionality of circularity within the built environment. Each parameter symbolises a critical intervention point. The diverse literature across these parameters reflects the growing awareness of circular economy principles globally and underscores the gaps in application and integration. Notably, the constant mention of stakeholder engagement and decision-making emphasizes that successful circular economy adoption is as much a technical challenge as it is a governance and collaborative imperative, requiring active engagement across sectors, scale, and phases of development.

Table 3: Categorisation of circular economy parameters with regards to different construction phases

Construction phases	Pre-Construction	During Construction	Post-Construction
Circular Economy Parameters	Design for Disassembly Resource Efficiency	Circular Construction Waste Reduction Water Circularity Supply Chain Circularity Renewable Energy Consumption Embodied Carbon Minimisation	LCA Material Reuse and Recycle

The construction process can be categorised into mainly 3 phases: pre-construction, construction and post-construction. The pre-construction phase involves design and planning, the construction phase involves the actual realisation of the project, and the post-construction phase involves the use and end-of-life process of the structure. The 10 identified parameters can be categorised into these 3 phases. Table 2 highlights this categorisation of circular economy parameters with respect to the construction phases. On mapping literature with reference to the construction phases, as shown in Figure 4, illustrates the temporal evolution of the circular economy parameters applied across the

three construction phases from 2017-2025. In the initial years, there was limited adoption of circular economy parameters, particularly in the construction phase, where efforts were mostly dispersed and restricted to practices such as waste reduction and material reuse and recycle. The distribution highlights a gradual increase in circular economy strategy adoption post 2022 during the construction phase, including a more systematic adoption of strategies. In contrast, the post-construction phase has experienced a steep and accelerated increase in strategies, particularly post 2022. This increase is indicative of a broader understanding of the significance of building performance throughout the different construction phases.

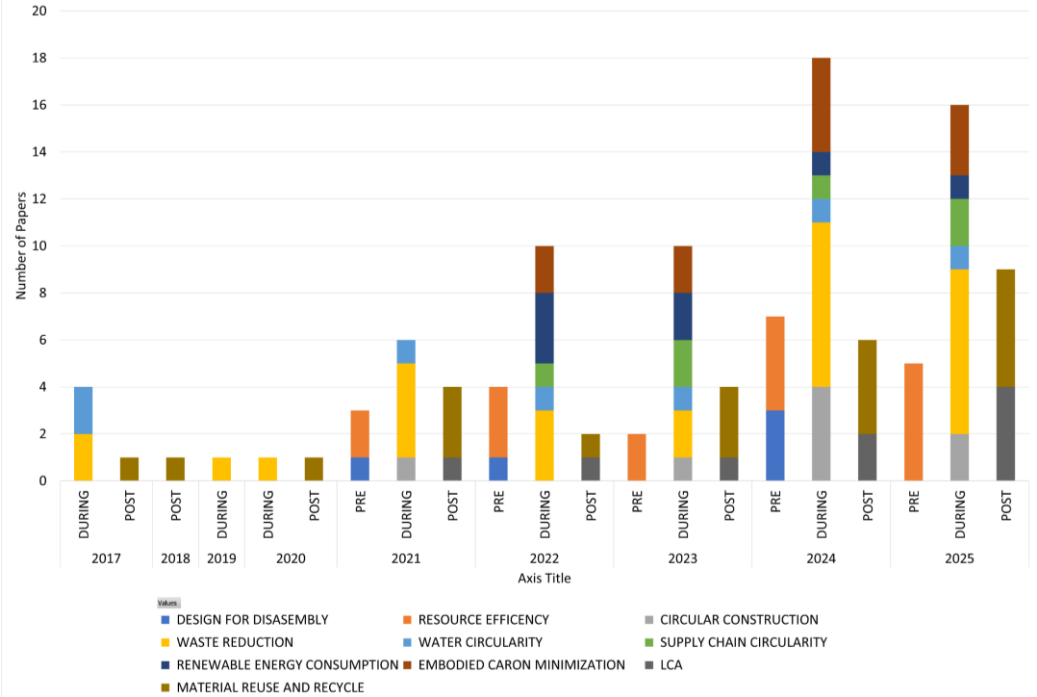


Figure 4: Temporal distribution of circular economy strategies during the different construction phases (2017-2025)

The emphasis is more towards the development of lifecycle thinking, with particular emphasis on post-occupancy evaluation, flexibility, and long-term performance. This can be observed using tools such as Building Information Modelling (BIM) for lifecycle monitoring, post occupancy feedback systems and the incorporation of maintenance plans that are aligned with circular economy principles. The trend points to policy and industry practices increasingly shifting away from traditional linear "design-build-dispose" paradigms towards regenerative, holistic, and feedback-informed design approaches that cover the whole lifecycle of the built environment.

3.2 DISCUSSION

Based on the analysis above, resource efficiency, circular design, waste reduction, material reuse and recycling are the factors that are most frequently addressed, and they represent the fundamental ideas of circular economy in the built environment. Water circularity and renewable energy use are both moderately represented, suggesting that efforts to incorporate sustainable resource management are still underway. Life cycle assessment (LCA), supply chain circularity, and embodied carbon minimisation are less

common, indicating a lack of attention in policy towards long-term environmental effect assessment. There is a need for more research on modular building techniques and adaptive reuse because the design for disassembly and circular construction are the least addressed. Overall, the results indicate that although research and policy initiatives recognise circular economy principles, some elements, especially long-term sustainability strategies— sector is Extended Producer Responsibility (EPR) as suggested by Shooshtarian et al. (2021) need more attention and policy integration. An effective market-based policy strategy that can greatly support circular economy in the building

According to Evertsen and Knotten, (2024), one of the most important methods for developing a closed loop constructed environment is to shut the loop by recycling and reusing materials. Greater London's circular built environment policies have improved construction efficiency but fall short of achieving a fully circular city. While they address resource depletion and waste, they lack focus on building reuse, community involvement, and systemic urban transformation, which are essential for a truly resilient and resource-efficient future (Bucci Ancapi et al., 2024). The policy framework for a circular built environment typically follows a top-down approach, where policymakers set guidelines that practitioners, such as developers and contractors, are expected to implement. Contrary to this In Norway, the national authorities establish overarching regulations while allowing local governments the flexibility to make region-specific decisions (Evertsen & Knotten, 2024).

In case of developing countries like India, integration of the policy framework in circular economy principles through various initiatives is required. While some of the flagship policies by the government, such as SMART city mission encourage green buildings, smart energy, and water efficiency systems to support long-term sustainability, the 2070 net-zero objective of the Indian government marks the turning point in India's climate policy. To achieve this net-zero aim, the integration of circular economy principles at the design phase is highly recommended. Even though they are effective in promoting low-carbon technology to a considerable degree, policies lacking a long-term mitigation aim would not be able to meet India's climate ambitions to meet the objectives of the Paris Agreement (Chaturvedi et al., 2024).

Based on the review findings, circular parameters such as Design for disassembly in the pre-construction phase become the most essential and urgent parameter that must be integrated in the regulatory and assessment frameworks in the built environment, followed by systematic phase wise integration of the other parameters, providing foundation for future targeted studies.

4. CONCLUSIONS

The primary research gap lies in the lack of mandatory enforcement of circular economy principles in the current policies. Existing literature highlights the importance of circular economy principles but does not guarantee their enforcement. There is also insufficient research on policy barriers, incentives, and the role of different stakeholders in ensuring the adoption of circular economy E principles across the construction industry in India. A major setback in the enforcement of these policies includes people's participation which needs to be included in the current policies. The lack of public awareness and involvement, together with the lack of defined financing sources and incentives to encourage companies and developers to embrace circular processes, are significant

obstacles to compliance. Additionally, overlapping jurisdictional regulations and fragmented rules lead to bureaucratic obstacles that slow down implementation and lessen the impact of policies. For the construction industry to close these gaps, a thorough regulatory framework with legally binding requirements, clear enforcement procedures, stakeholder engagement plans, and a planned adoption roadmap for the circular economy is needed. Building further on the identified research gap, this research will extend to analysing multiple national and state level policy frameworks. The 10 identified circular economy parameters would be crucial in analysing the policies and further identifying the gaps in the implementation of the same.

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MOVING FROM LINEAR TO CIRCULAR APPAREL ECONOMY IN SRI LANKA: PRISMA-BASED ANALYSIS OF CIRCULAR ECONOMY AND SUPPLY CHAIN INTERACTIONS

C.H. Kumara[1], Harshini Mallawaarachchi[2] and J.A.D.K.S. Jayakodi[3]

ABSTRACT

The apparel industry is one of the largest and most resource-intensive industries in the world in terms of the resources necessary for the production process, as well as energy consumption, waste and carbon emissions. Circular economy (CE) can be considered as one of the critical success factors for developing the closed-loop supply chain. However, limited research that examines the applicability of CE to the apparel industry, this study aimed to address this gap by exploring the interactions between CE and apparel supply chain through PRISMA-based analysis of key literature. The systematic literature review procedure was adopted in this study, and the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines were followed as the methodological basis. A total of 116 articles were included in the review and Scopus-based tools, VOSviewer, R-studio and Biblioshiny software were used for the bibliometric mapping. The results reveals that the number of journal publications has been increased throughout the past decade, and the "Journal of Cleaner Production" has emerged as the prominent journal in this research domain. Next, the interactions between CE and the apparel supply chain were reviewed as key implication of the research. Accordingly, this paper provides a comprehensive synthesis of existing literature on the interaction of circular economy and apparel supply chain and serves as a basis for future research in this field. Since this research is a primary step of a research project, a closed-loop apparel supply chain model will be developed as a way forward.

Keywords: *Apparel Industry; Circular Economy; Interactions; Supply Chain.*

1. INTRODUCTION

The apparel industry is one of the largest and most resource-intensive industries in the world in terms of the resources necessary for the production process, as well as energy consumption, water pollution and waste production (Gönlügür, 2019). Over the past few years, the industry has undergone significant shifts, which have developed due to the

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forthcoming of technology, globalization and transforming consumer trends (Lund et al., 2019). Due to increased awareness of people across the world on the effects of industrialization on the environment and people, there has been increasing emphasis on sustainability in the Apparel industry (Toprak & Anis, 2017). According to Payne (2015) A closed loop supply chain is therefore a concept whereby a product is taken throughout its life cycle from its manufacture until the materials used in its manufacture are reclaimed or recycled. This aimed at making the waste circulation to be in a closed-loop cycle system, hence reducing the utilization of virgin materials and having a lowered negative impact on the environment. Thus, necessary to note that a closed-loop supply chain in the apparel industry could greatly support the responsibility for minimizing net carbon emissions (Mishra et al., 2020).

According to Moktadir et al. (2020) the CE principles can be considered as one of the critical success factors for developing the closed-loop supply chain in the apparel industry. The circular economy is a concept that is aimed towards the reduction of wastage and more so the endless reuse of resources (Moktadir et al., 2020). In a circular economy, the products are developed for a long life, and the materials are kept in use for as long as possible by processes like recycling, remanufacturing, and refurbishing (Bakker et al., 2021). In the case of the Sri Lankan apparel sector, implementing circular economy within a closed-loop supply chain can be associated with significant environmental advantage. The integration of a closed-loop supply chain model in the Sri Lankan apparel industry offers a chance to contribute towards net-zero carbon emission and improves the sector's sustainability (Lakmali et al., 2020). Although there are issues and problems with the practical application of this model, the advantages of making changes for the better are huge and include improvement in such aspects as environmental preservation, economic efficiency, and customer desire (Gowsiga & Thayaparan, 2020). Apparently, there is a research gap concerning the methodology of managing the apparel supply chain with an aim of enabling the shift towards the circular economy. Current research has examined closed-loop systems mostly from the environmental perspective and some fundamental concepts of the CE (Manage & Dissanayake, 2021). Still, there is limited research that examines the applicability of CE for apparel supply chain. Therefore, this research aimed to address these gaps by exploring how the circular economy can be applied and implemented in apparel supply chain. Thus, as the initial step, the study presented in this paper sets outs to explore the interactions between CE and apparel supply chain through PRISMA-based analysis of key literature. Accordingly, two objectives are formulated as follows: (i) To review the evolution of publications, prominent journals, and authors who have made the most publications on the intersections of CE and apparel supply chain, and (ii) To recognise different interactions between CE and apparel supply chain.

2. LITERATURE REVIEW

2.1 THE CONCEPT OF CIRCULAR ECONOMY

CE is a regenerative system, with the intention of closing material loops by reducing resource use and the generation of waste. It supplants the conventional model 'take-make-dispose' with another model. Geissdoerfer et al. (2017) define the concept of CE as "an economic system that is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times,

distinguishing it from the traditional linear economy". Indeed, CE is intrinsic to reshaping the operational dynamics of industries by incorporating resource recovery and extending product life cycles. Nguyễn et al. (2023) highlighted the role of CE in promoting ideas of Corporate Social Responsibility (CSR) for corporate environmental management and supply chain development. Further to the authors, the conception of CE highlights the ecological and economic aspects of resilient supply chains. The principles of CE focus on creating sustainable systems that align economic activities with environmental conservation. Designing out waste and pollution, keeping products and materials in use and regenerating natural systems are the key circular economy principles according to Abdelmeguid et al. (2022). Designing out waste refers to reducing waste generation by innovating designs that promote reuse and recycling (Islam et al., 2020). Material in use can be considered as maximising resource utility by extending the lifespan of products through repair, refurbishment, and recycling (Wilson, 2022), while Regeneration of natural systems ensures industrial practices contribute to replenishing ecosystems and natural resources (Gazzola et al., 2020). These principles collectively foster a circular framework where industries, including apparel, move towards sustainability. Todeschini et al. (2017) highlighted in their study how these principles pave the way for innovative business models, offering economic opportunities and reducing environmental footprints. However, the application of circular economy in apparel industry still remains limited due to several reasons such as limited stakeholder engagement, policy and regulatory barriers (van Eeden et al., 2019; Fobbe & Hilletofth, 2022; Chhimwal et al., 2021).

2.2 CIRCULAR ECONOMY AND APPAREL SUPPLY CHAIN

Integrating circular economy practices into the apparel supply chain leads to numerous advantages, including cost saving, reducing the dependency on raw materials, maximising resource usage through material recovery processes and reducing environmental impact (Gazzola et al., 2020; Sudusinghe & Seuring, 2020; Dissanayake & Weerasinghe, 2020; Gebhardt et al., 2022). Further, Su et al. (2023), noted that the CE implementation in supply chain meant that there were low greenhouse gas emissions as it aimed at managing material flow much better and also reducing landfill waste. Over the last couple of decades, the Sri Lankan apparel industry being one of the largest export markets around the globe there is a growing trend to implements CE practices in the country (Manage & Dissanayake, 2021). Efforts to recycle, use environmentally friendly products in production processes, and encourage change in consumer practices are pushing manufacturers towards compliance with international benchmark sustainability. Collaborative consumption models, as explored by Chowdhury et al. (2022), emphasise shared usage of resources and align seamlessly with CE principles to reduce the overall carbon footprint in apparel supply chains.

3. RESEARCH METHODOLOGY

The systematic literature review procedure was adopted in this study to explore the prominent literature related to the circular economy, apparel supply chain and their interactions. As claimed by (Denyer & Tranfield, 2009), the systematic review is a structured approach to identifying existing literature, synthesising data and presenting findings on established knowledge and gaps in a particular research domain. Accordingly, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)

guidelines were followed as the methodological basis in this systematic literature review (SLR). Figure 01 illustrates the PRISMA guideline-based SLR procedure graphically.

Initially, a literature search was conducted in the Scopus database to identify the key publications related to the circular economy and apparel supply chain. In this regard, the search was limited to titles, keywords, and abstracts and the used search string was: (TITLE-ABS-KEY ("circular economy" OR "closed-loop economy") AND TITLE-ABS-KEY ("apparel" OR "fashion industry" OR "textile industry" OR "garment sector" OR "clothing industry") AND TITLE-ABS-KEY ("supply chain" OR "value chain")). From the initial search, the Scopus database identified 278 articles. Out of these, 03 articles were excluded due to duplication. Subsequently, article screening was conducted in two phases.

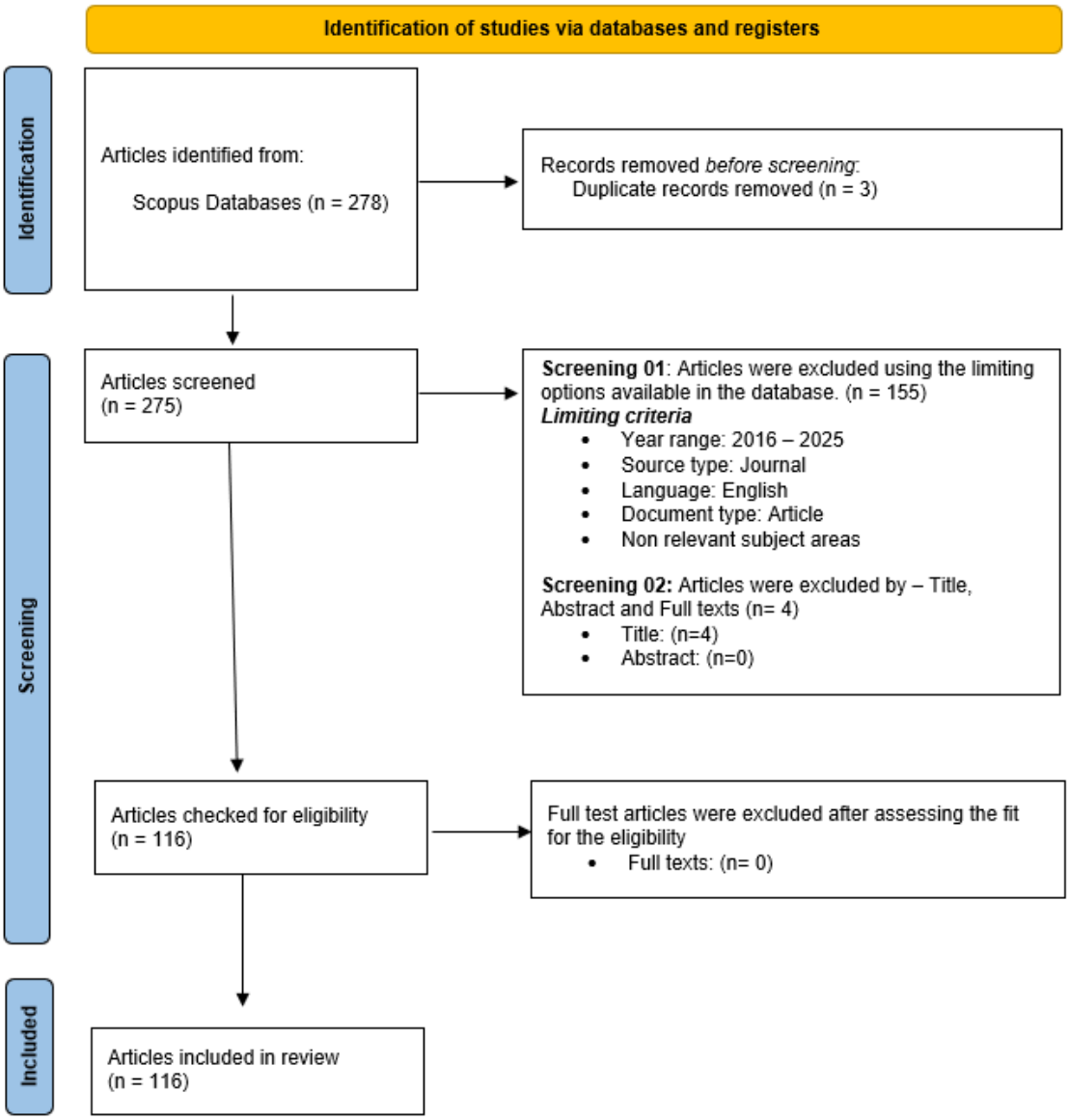


Figure 1: PRISMA guideline-based SLR procedure

In Screening 01, the articles were screened by several restricting criteria in the database as: year range: 2016 – 2025; Source type: Journals; Document type: Articles; Language:

English. Further, excluded subject areas were Earth and Planetary sciences, Computer science, Physics and Astronomy, Agriculture and Biological science, Biochemistry, Genetics and Molecular biology, Medicine, Immunology and Microbiology and Health professions and articles were excluded based on the title and abstract in the second screening phase. Subsequently, 120 articles were selected for assessing the eligibility. Subsequently, articles were further screened by reviewing the title and abstract, and 4 articles were excluded. Accordingly, 116 articles were selected to check the eligibility. Subsequently, the articles were further assessed for eligibility by reviewing the full text and no articles were excluded; a total of 116 articles were included in the review.

As the next step, articles were analysed in terms of the evolution of the number of publications, leading journals, leading countries, leading authors, co-occurrence of keywords and thematic map. In this regard, Scopus-based tools, VOSviewer, R-studio and Biblioshiny software were used for the bibliometric mapping.

4. KEY RESEARCH FINDINGS

This section discusses the key research findings gained through the systematic review under two major areas: (i) Outcomes of bibliometric analysis, and (ii) Circular economy and supply chain interactions in the apparel industry.

4.1 OUTCOMES OF THE BIBLIOMETRIC ANALYSIS

4.1.1 Evolution of the number of Journal Articles Published on Circular Economy and Apparel Supply Chain

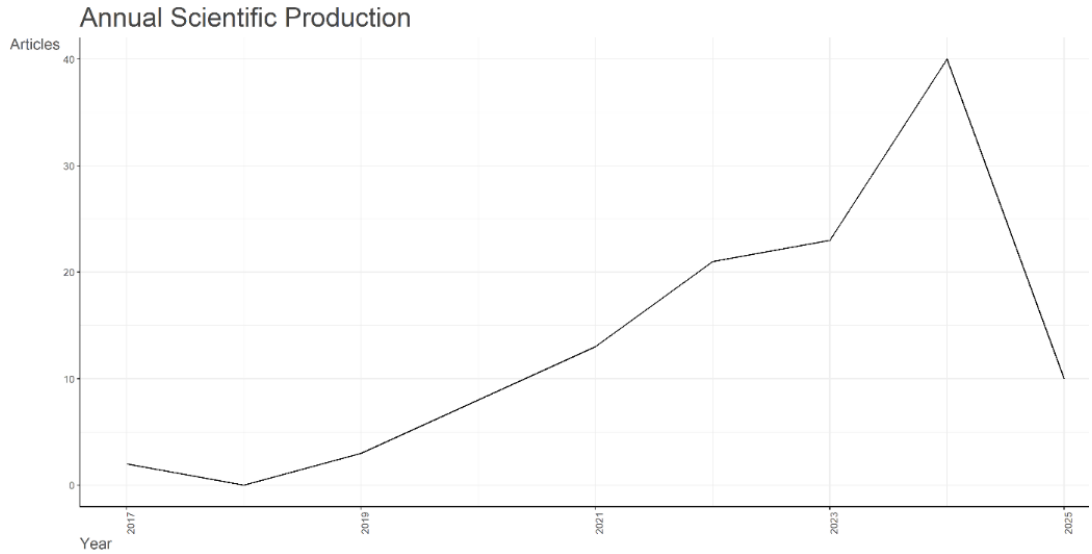


Figure 2: Evolution of the number of journal articles

As per the result of this PRISMA-based systematic literature review, 116 journal articles have been published from 2016 to the first three months of 2025 related to the circular economy and apparel supply chain. Figure 02 graphically represents the evolution of the number of journal articles published on this research domain.

Upon the analysis, no publications related to the circular economy and apparel supply chain existed in 2016. There were only 2 publications in 2017, and again, the number of publications sharply declined to zero in 2018. However, the graph shows an upward

trajectory of the annual scientific production from 2019 onwards. This upward trend may be attributed to the global shift towards and policy enhancements such as the European Union Circular Economy Action Plan 2020. Accordingly, the number of publications has increased to 3, 8, 13, 21, and 23 in 2019, 2020, 2021, 2022, and 2023, respectively. Notably, this ascending trend peaks in 2024, with 40 publications. Further, 10 publications were identified in the first three months of 2025. Overall, the graph portrays positive growth of the scholarly focus on the topic of circular economy and apparel supply chain within the past decade, elaborating the significance of integrating circular economy principles into the apparel supply chain.

4.1.2 Leading Journals Published on Circular Economy and Apparel Supply Chain

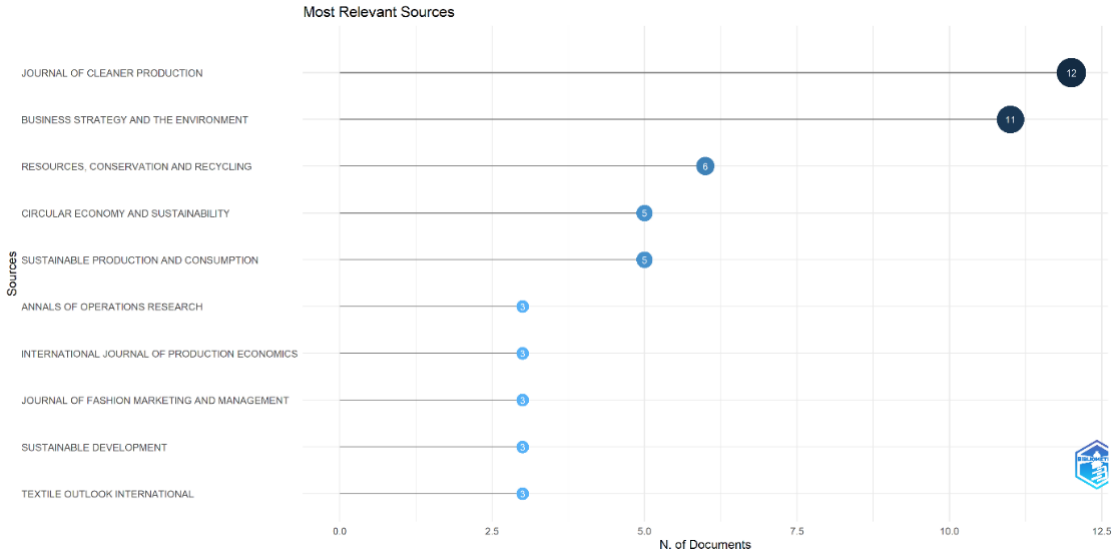


Figure 3: Leading journals published on circular economy and apparel supply chain

Figure 03 illustrates the leading journals published on the intersection of circular economy and apparel supply chain. Here, the x-axis represents the number of publications, while the y-axis lists the names of journals and sources contributing to this research area. Further, the number of publications associated with each journal is presented within a dot, and the dot size is correlated with the number of documents published.

Upon the analysis results, the "Journal of Cleaner Production" was the leading journal in this research domain, contributing the highest number of publications with 12 articles. Further, the "Business Strategy and the Environment" journal has also provided a significant contribution to scholarly publications in the past decade, with 11 journal articles. The "Resources Conservation and Cleaning", "Circular Economy and Sustainability" and "Sustainable Production and Consumption" are some other remarkable journals in this research domain with 6, 5, and 5 publications respectively. Additionally, "Analysis of Operation Research", "International Journal of Production Economics", "Journal of Fashion Marketing and Management", "Sustainable Development", and "Textile Outlook International" have also contributed to this research although there are fewer publications. In conclusion, this distribution of journals illustrates that a wide range of journals has addressed this research area, reflecting the emerging scholarly interest and the significance of this research domain.

4.1.3 Leading Authors Published on Circular Economy and Apparel Supply Chain

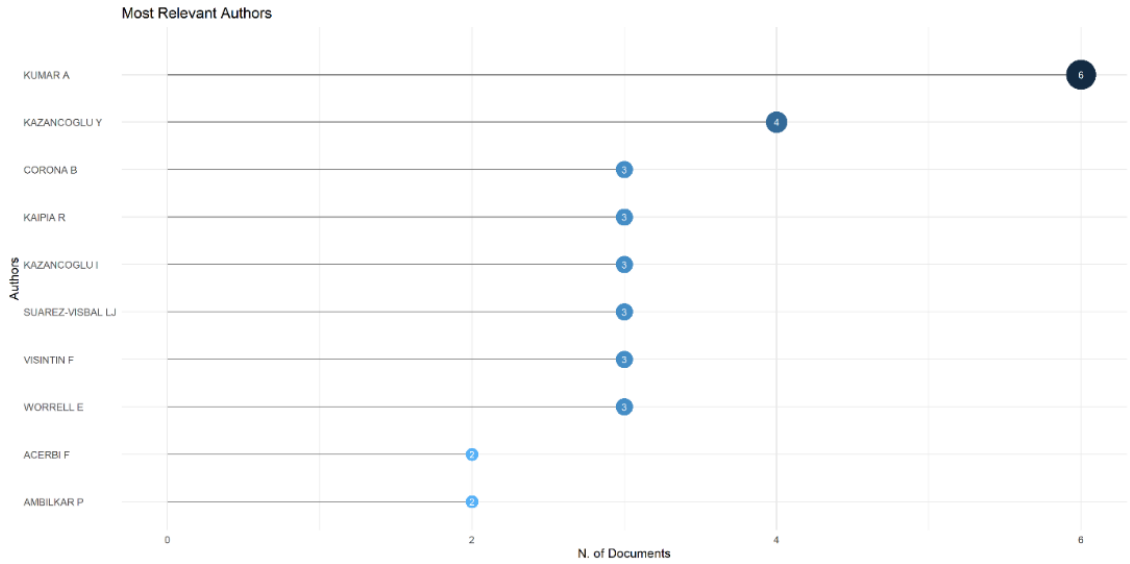


Figure 4: Leading authors published on circular economy and apparel supply chain

Various scholars have contributed to investigating the adoption of the circular economy concept for the apparel supply chain. Accordingly, Figure 04 illustrates the leading authors who have published the highest number of articles in this research area. The vertical axis indicates the authors, while the horizontal axis indicates the number of articles published. Similar to the graph in Figure 03, the number of publications of each author is presented within a dot, and the dot size is correlated with the number of documents published.

Upon the analysis, Kumar A stands out as the leading author in the circular economy and apparel supply chain, who has 6 publications within the past decade. Following closely, Kazancoglu Y has published 4 journal articles reflecting the strong research presence and ongoing contribution to this specific academic discipline. Several notable authors, Corona B, Kaipia R, Kazancoglu I, Suarez-visbal L. J., Visintin F, and Worrell E has published in 3 journals by each demonstrating the consistent involvement in advancing this scholarly field. Further, Acerbi F and Ambilkar P have also contributed to investigate the intersection between circular economy and apparel supply chain within past decade. Additionally, analysis results reveal that there are many authors who have actively been involved in this study area, even though with a smaller number of publications. Overall, the distribution of authorship indicates that there are a number of scholars who are actively contributing to the growth of this evolving academic discipline while a few scholars are taking the leading role.

4.1.4 Co-occurrence of Keywords on Circular Economy and Apparel Supply Chain Publications

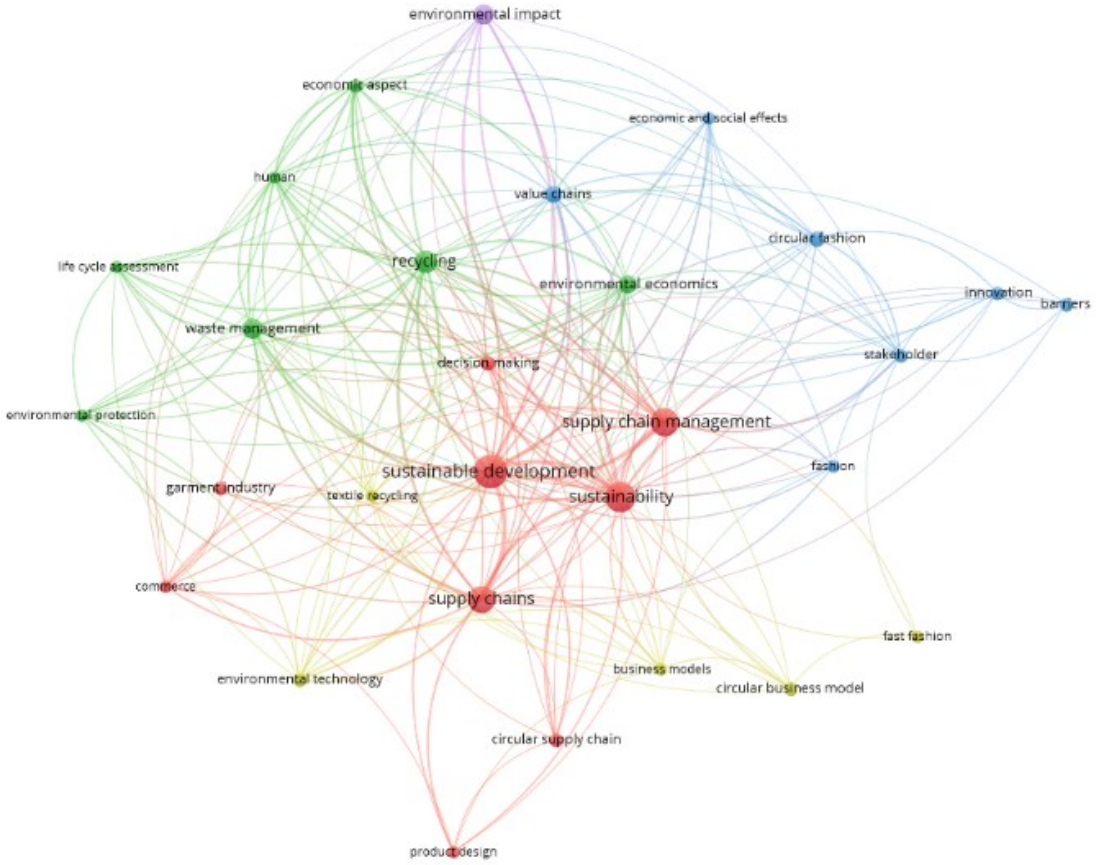


Figure 5: Co-occurrence of keywords on circular economy and apparel supply chain publications

This graph demonstrates the co-occurrence of keywords of publications related to the circular economy and apparel supply chain. The co-occurrence analysis was conducted using VOSviewer software to identify the research trends within this research area. The unit of analysis was selected as the author keywords to identify the frequently co-occurring terms used by authors, and the minimum occurrence threshold level was set at ten (10). Further, the modularity-based clustering algorithm was applied to group keywords. According to the results, the graph illustrates five major thematic research domains, each represented by a different colour, and their interrelationships among key topics.

The red colour cluster indicates the sustainable development and circular concepts, while the green colour cluster includes keywords related to supply chain management and operations. The key aspects related to environmental assessment and tools are represented by the blue colour cluster. Additionally, research domains related to governance and stakeholder engagement are presented in the yellow colour cluster while resource management aspects are indicated in the purple colour cluster. While this thematic clustering reveals the interrelationship in current literature in the intersection of apparel supply chain and circular economy, it also uncovers some critical research gaps. For instance, although governance and stakeholder engagement aspects were discussed in literature, it lacks the interrelationship with supply chain management and operations

clusters, which represents a literature gap in studies of combining policy frameworks with supply chain practices. Further, the disconnection between waste management and stakeholder aspects underscores the necessity of exploring stakeholder engagement strategies for waste management within circular apparel industry.

4.2 CIRCULAR ECONOMY AND APPAREL SUPPLY CHAIN INTERACTIONS TOWARDS CIRCULAR APPAREL ECONOMY

The following literature synthesis elaborates the key aspects related to the research problem on "how the circular economy can be applied and implemented in the apparel supply chain. It discussed several subtopics: benefits of adopting CE, approaches for CE implementation, barriers, and future research directions in the intersection of circular economy and apparel supply chain. Benefits of integrating the circular economy with apparel supply chain

The apparel industry can be considered one of the most ecologically harmful industries in the world due to the intensive consumption of natural resources and the complexity inherent in its supply chain (Boström & Micheletti, 2016; Denizel & Schumm, 2024). According to Niinimäki et al. (2020), the apparel industry contributes to 8% – 10% of global carbon emissions, which equals 4 – 5 billion tonnes per year, while 20% of global wastewater. Further, the apparel industry accounts for 20% of global waste, even though only 20% of waste is collected for circular use (Papamichael et al., 2023). Accordingly, the concept of "Circular Economy" (CE) has emerged as a promising solution for mitigating these adverse environmental impacts of the industry (Wiegand & Wynn, 2024). Accordingly, many research scholars have drawn their attention to incorporating CE in the apparel industry, owing to its numerous advantages. CE promotes an economic paradigm that continuously regenerates itself while minimising reliance on finite natural resources and mitigating ecological degradation (Hvass & Pedersen, 2019). Further from the environmental perspective, CE helps to reduce waste generation, minimise the extraction of virgin natural resources, maximise the production from resources, optimise the usage of natural resources, minimise waste generation and enhance the product life cycles (Lenka et al., 2010; Kayikci et al., 2022; Salmi & Kaipia, 2022).

4.2.1 Approaches for Adopting Circular Economy into Apparel Supply Chain

Saha et al., (2022) claimed that CE offers diverse business opportunities across various domains, including improving sustainability, enhancing brand reputation, increasing long-term shareholder value and profitability. However, the implementation of the circular apparel economy requires considerable attention due to the presence of various challenges and scholars have explored different methods for implementing CE in the apparel supply chain (Zaidi & Chandra, 2024). Accordingly, Agent-Based Models (AGM), Entrepreneurial Business Models, Lifecycle Assessment and Plan-Do-Act-Check (PDCA) framework are some examples of those methods (Todeschini et al., 2017; Hazen et al., 2021; Rivera et al., 2021; Wilson, 2022). Among these methods, PDCA can be considered a robust framework for the systematic incorporation of CE into the apparel supply chain because its iterative nature assures continuous improvement (Hazen et al., 2021). Here, the "Plan" phase provides a clear objective in terms of setting achievable aims for CE implementation; the "Do" phase involves the implementation of planned activities including buying recycling machinery, training employees and developing consumer engagement; the "Check" phase incorporates the impact assessments of the implemented CE practices and the "Act" provides feedbacks and enhancements for the

identified gaps in the check phase (Mendoza et al., 2017; Hazen et al., 2021; Walzberg et al., 2021).

4.2.2 Barriers to Implementing Circular Economy in Apparel Supply Chain

Nevertheless, the practical implementation of CE principles in the apparel supply chain remains limited due to the presence of numerous barriers despite the existence of certain enablers. (Saha et al., 2022; Salmi & Kaipia, 2022) identified limited government support, managerial reluctance, company culture and obtaining necessary technologies are some barriers that against the CE implementation in the apparel supply chain. Further, Lewandowski (2016) and Freund et al. (2019) claimed that consumer demand and the market for circular apparel products remain underdeveloped. However, digitalisation, supportive regulatory frameworks and increased customer awareness of environmental considerations serve as the key enablers that motivate the transition towards a circular apparel economy (Wójcik-Karpacz et al., 2023).

4.2.3 Future Research Directions in the Interaction of Circular Economy and Apparel Supply Chain

In recent years, scholarly studies related to the circular economy and the apparel supply chain have broadened to diverse research domains. Accordingly, researchers attempt to integrate the circular apparel supply chain into novel digital technologies, including blockchain technology, robotics, artificial intelligence, Internet of Things and digital fabrication (Wiegand & Wynn, 2024). Correspondingly, blockchain technology ensures reliable, decentralised data transmission through the partners in the supply chain; robotics allows autonomous operation in apparel production and logistics processes; the Internet of Things supports real-time monitoring throughout the apparel life cycle, and digital fabrication allows for computer-controlled modelling and manufacturing (Agrawal et al., 2022; Bressanelli et al., 2022; Alves et al., 2023; Rusch et al., 2023; Hassan et al., 2024).

5. CONCLUSIONS AND A WAY FORWARD

The circular economy concept is a transformative model that fosters sustainability in various industries, including the apparel industry. Incorporating the circular economy in the apparel industry leads to waste minimisation, increases resource efficiency, reduces carbon footprint, and enhances product lifecycle. Hence, this study focused on investigating the intersection of the concept of circular economy and apparel supply chain through a systematic review as a basis for future research. A bibliometric analysis was conducted to identify key literature publications in the Scopus database between 2015 to 2024. Accordingly, this study provides a unique contribution to the existing knowledge by providing a consolidated overview of research trends in the intersection between circular economy and apparel supply chain. The bibliometric analysis outcomes significantly contribute to identifying the number of published journals, leading journal authors, countries active in this field, and the co-occurrence of keywords on circular economy and apparel supply chain publications. The analysis results are evident that this field of study is an evolving research domain over the past decade and continues to exhibit growth, reflecting its contribution to achieving global sustainability goals within the apparel industry. Notably, analysis reveals that the concept of CE is transferring to the concept of digital circular economy with the current technological advancements. Accordingly, the apparel industry is progressing towards more sustainability and efficiency by striving to balance all environmental, social, and economic dimensions. As

future research directions, "A closed-loop apparel supply chain model for achieving net zero goals of the apparel industry" will be developed considering the intersection of CE and apparel supply chain as a way forward for this research.

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OPTIMISING MATERIAL SELECTION FOR DESIGN FOR DECONSTRUCTION: A KANO MODEL-BASED EVALUATION OF DOORS AND WINDOWS

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ABSTRACT

The construction industry faces a major challenge due to its waste generation and resource depletion leading to environmental impacts. To mitigate these the circular economy (CE) offers a solution by repurposing construction waste as raw materials. This approach can be further enhanced by integrating eco-design strategies, particularly Design for Deconstruction (DfD). Material selection is a crucial aspect of successful deconstruction. However, current research lacks specific focus on material selection for deconstruction feasibility within a CE framework, especially for joinery components. This study addresses this gap by identifying crucial criteria for material selection in DfD, specifically targeting doors and windows to promote circularity. The study uses a mixed-method approach, involving preliminary interviews with 5 interviewees followed by a questionnaire survey with 50 respondents based on the Kano Model where the content analysis and the Kano Model were used to analyse the collected data. Purposive sampling was used to select samples for the preliminary interview and questionnaire survey. Finding reveals that the "avoid toxic and hazardous materials" as the most critical criteria for material selection in DfD for doors and windows, while "maintain updated as-built drawings and material inventories with disassembly instructions" remain the least concern criteria among the identified seven crucial criteria. Ultimately, this research contributes to improving decision-making when selecting materials during the construction design phase to foster circularity and reduce the environmental impact of the construction industry. Additionally, the results of the study can be recommended to policymakers to incorporate in the standards such as GreenSL rating system and further research promotes other eco-design methods and policy formulation.

Keywords: *Circular Economy; Construction; Design for Deconstruction; Kano Model; Material Selection.*

1. INTRODUCTION

The construction industry generates a significant amount of waste, contributing to a high percentage of landfill waste (Ajayi et al., 2015). Statistics indicate that this waste volume

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accounts for 30% to 40% of the total solid waste generated in the global context (Li et al., 2024). Akanbi et al. (2019) suggested that the activities executed at the end of the building's useful life, particularly during building demolition, produce 50% of the solid waste generated from total construction demolition waste (CDW) globally. Conversely, the construction industry consumes a substantial quantity of raw materials, accounting for 40% of natural resources used (Valentini, 2023). This leads to resource depletion where the natural resources are consumed faster than they can be replenished (Baldassarre, 2025). Thus, the CDW and resource depletion are substantial challenges to the construction industry due to the associated environmental impacts (Ruiz et al., 2020).

To mitigate the environmental impacts of the construction industry, waste generated from this sector can be repurposed to reduce the need for raw material extraction and to decrease landfill waste (Akhtar & Sarmah, 2018). This can be achieved through waste management processes such as 3R (Reducing, Reusing, and Recycling), which assist in recovering materials (Cruz-Rios & Grau, 2020). Nevertheless, the main obstacles to adopting these technologies are the costs and time associated with operations, along with the low demand for reused materials (Akhtar & Sarmah, 2018). However, Ruiz et al. (2020) argued that the CE model is better suited to address inefficiencies compared to the traditional reduce, reuse, and recycle model. According to Rahla et al. (2021) the CE is characterised as "an economic system that replaces the 'end-of-life' concept with efforts to reduce, alternatively reuse, recycle, and recover materials throughout production, distribution, and consumption processes" (p. 2). This CE model aims to minimise waste generation and material consumption by keeping resources in circulation and maximising their value (Benachio et al., 2020). Moreover, adopting a CE approach can lead to significant economic and environmental benefits, such as the upcycling of outdated buildings (Akinade et al., 2019). The application of CE practices can be enhanced through the use of eco-design methodologies, such as DfD (Munaro et al., 2022).

DfD is an approach that considers the deconstruction of a building during the early design phase (Crowther, 2018). This strategy challenges the traditional view that demolition is the inevitable endpoint for a building. Instead, it emphasises the potential to recover building materials from end-of-life (EOL) (Arisya & Suryantini, 2021). DfD approach influenced by factors such as material selection, construction connections, disassembly procedures, assembly hierarchy, health and safety considerations, and deconstruction planning (Machado et al., 2018). A thorough understanding of material properties and careful selection are necessary for evaluating the life cycle impact of materials, which ultimately enhances environmental performance by improving material recovery and reducing waste generation supporting CE (Benachio et al., 2020; Rahla et al., 2021).

Conversely, many studies have been conducted on DfD, primarily focusing on its adaptation (Ostapska et al., 2024), its connection to CE practices (Akanbi et al., 2019; Akinade et al., 2019; Bertino et al., 2021), and the development of frameworks and guidelines that outline DfD criteria (Akinade et al., 2019; Machado et al., 2018). However, the application of these principles has not been extensively studied (Machado et al., 2018). Although research has addressed material selection in relation to CE (Bertino et al., 2021; Rahla et al., 2021), there has been limited exploration of material selection specifically for deconstruction feasibility supporting CE. In this context, Zoghi et al. (2021) developed a hybrid multi-criteria decision-making model for material selection in DfD, considering all building components. However, the availability of studies to address the deconstruction feasibility for joinery components is not examined despite its potential

to hinder the deconstruction due to adhesive connections and the use of composite materials (Joustra et al., 2021; Krišťák & Réh, 2021). Moreover, Rahla et al. (2021) and Zoghi et al. (2021) indicated that current material selection methods do not adequately prioritise deconstruction feasibility. According to Akanbi et al. (2019), incorporating DfD criteria into material selection during the design stage necessitates a more technical and practical understanding of the various characteristics of materials. Despite the considerable research available on DfD, including various multi-criteria decision-making models for material selection relating to all components, a significant gap persists in prioritising DfD principles for joinery components, particularly doors and windows (Joustra et al., 2021; Machado et al., 2018; Zoghi et al., 2021).

This study addresses the identified gap by investigating the crucial criteria for material selection in DfD, for doors and windows, ensuring the circularity. To achieve this aim, the research will pursue three objectives: first, to identify the general criteria from existing literature; second, to pinpoint the criteria specifically related to doors and windows in material selection for DfD; and third, to identify and rank the crucial criteria for material selection in DfD for doors and windows. Hereinafter, the paper comprises a literature review (2), methodology (3), findings (4), discussion (5), and conclusions (6.0).

2. LITERATURE REVIEW

2.1 CONCEPT OF CIRCULAR ECONOMY (CE)

The CE is an economic system designed to eliminate waste and pollution, keep materials in the loop and regenerate the natural system (Ellen Macarthur Foundation, 2015). The definition of CE is advancing beyond the traditional 3R principles (Rahla et al., 2021). Additionally, the implementation of the CE in the construction industry represents an ideal opportunity due to its potential to reduce waste, conserve resources, and enhance productivity (Varsha et al., 2025).

2.2 APPLICATION OF CE IN THE CONSTRUCTION INDUSTRY

In the construction industry, CE principles can be applied through Value Retention Processes (VRPs) and end-of-life (EOL) scenarios (Ellen Macarthur Foundation, 2015). VRPs, which include reuse, repair, remanufacturing, and refurbishment, contribute directly to the CE by extending the lifespan of materials and products (Tolio et al., 2017). Moreover, recycling or recovery becomes crucial at EOL, particularly when value retention processes are not feasible (Eberhardt et al., 2020). As noted by Eberhardt et al. (2020), selecting the right materials is a key strategy for implementing CE principles in the construction industry. Additionally, many studies underscore the importance of integrating CE principles in material selection to address the environmental challenges posed by the construction sector (Ruiz et al., 2020). As discussed, CE practices in the construction industry can be effectively facilitated through VRPs, EOL scenarios, and efficient material selection during the design phase (Rahla et al., 2021). To combine these strategies, eco-design methodologies can serve as a vital enabler (Benachio et al., 2020).

2.3 ECO-DESIGN METHODOLOGIES IN THE CONSTRUCTION INDUSTRY

Eco-design approaches aim to integrate sustainable practices into construction activities, thereby improving the environmental performance throughout the lifespan of buildings, minimising environmental impacts, and fostering economic and social aspects (Munaro

et al., 2022). Despite the challenges in the construction industry, such as the complexity of the building process, diverse stakeholders, and the duration of construction projects, applying eco-design practices in this field is both feasible and suitable (Kuo et al., 2018). Furthermore, numerous eco-design concepts have been embraced in the literature to ensure their adaptability to the construction industry (Munaro & Tavares, 2023). The idea of "Design for" has become a common method, with "X" representing the specific design goal related to the EOL situation of a building. This approach encompasses strategies like Design for Disassembly, Design for Recycling, and DfD (Arisya & Suryantini, 2021; Munaro et al., 2022). Furthermore, concepts such as Design for Reuse and Design for Adaptability help maintain value before the building reaches the end of its life cycle (Tolio et al., 2017). These strategies highlight how eco-design practices can support CE principles by prolonging the service life of buildings and maintaining the flow of materials in continuous circulation (Munaro & Tavares, 2023).

2.4 DESIGN FOR DECONSTRUCTION

DfD is the planned separation of building elements to recover and reuse the materials at the EOL (Zoghi et al., 2021). This concept is primarily applied considering building design, material selection, and connection methods to enable efficient deconstruction and material recovery (Machado et al., 2018). DfD is a critical concept when comparing with other eco-design methodologies because it optimises the recovery and reuse of high-value secondary materials (Ostapska et al., 2024) and reduces the overall environmental footprint through the repurposing of high-energy embodied building materials (Kanters, 2018). Further, this supports the transition toward CE. Additionally, the factors supporting DfD have been widely documented in the literature as general criteria as illustrated in Table 1.

Table 1: General criteria that enable DfD

Category	Sub-Categories and Criteria	References
1. Building Materials and Components	1.1 Material Selection and Use: Use reusable, recycled, recyclable materials, Avoid toxic and hazardous materials, Minimise variation in materials, parts, and components, Avoid composite materials and inseparable subassemblies, Use durable materials, Avoid secondary finishes that reduce reusability, Provide permanent identification for material types. 1.2 Modular and Prefabricated Components: Use prefabricated, mass-produced standardized building components, Design for modularity to enhance flexibility, Use framing techniques, Consider handling logistics for materials and components	[1], [2], [3], [4], [5], [7], [8], [9], [10]
2. Structural Systems and Interface Coordination	2.1 Layer Separation, Standardisation, and Modularity: Facilitate the separation of building layers (structure, services, cladding), Provide access to all building parts and components, Use simple and standardised building forms, Minimise inter-system interactions. 2.2 Handling, Logistics, and Flexibility: Ensure components are sized for easy transport and assembly, Use simple tools for assembly/disassembly, Provide realistic tolerances for manoeuvring during disassembly, Dedicate specific volumes for each system, Ensure spaces are adaptable to changing needs, Use	[1], [2], [3], [4], [8], [10]

Category	Sub-Categories and Criteria	References
	lighter components suitable for manual disassembly, Use larger parts to reduce total components for mechanical disassembly	
3. Joint Systems, Assembly, and Disassembly Processes	3.1 Mechanical Connections and Accessibility: Use mechanical fasteners rather than adhesives or chemical bonds, Avoid joints or screws that hinder reuse, Minimize the number of fastener types, Ensure joints are durable and reusable, Design connectors to withstand repeated usage, Make joints accessible for easy disassembly. 3.2 Assembly Sequencing and BIM Integration: Use open building systems for flexibility, Enable parallel rather than sequential disassembly, Organize components based on lifespan, Systematize assembly for easy maintenance and replacement, Maintain updated as-built drawings and material inventories, Identify disassembly points permanently, Use BIM to simulate disassembly processes, Provide adequate assembly/disassembly instructions	[1], [2], [3], [4], [5], [6], [9], [10]
4. Life Cycle Coordination and Human Collaboration	4.1 Planning for Reuse and End-of-Life: Plan deconstruction/demolition from the design stage, Design retractable foundations to reduce demolition impact, Use eco-labelled, natural, or minimally packaged materials. 4.2 Circular Economy and Environmental Impact: Support research on the benefits of salvageability, Provide training on environmental, social, and economic benefits of DfD, Ensure safety in all deconstruction activities. 4.3 Safety and Team Coordination: Promote collaboration among team members, Engage contractors early in the design process, Provide training on DfD practices. 4.4 Knowledge Sharing and Training: Involve stakeholders in disassembly planning, Share knowledge on material inventories and design updates	[3], [4], [5], [8], [10]

[1] - (Machado et al., 2018), [2] - (Zoghi et al., 2021), [3] - (Ostapska et al., 2024), [4] - (Akinade et al., 2019), [5] - (Bertino et al., 2021), [6] - (Kanters, 2018), [7] - (Cruz-Rios & Grau, 2020), [8] - (Akanbi et al., 2019), [9] - (Munaro & Tavares, 2023), [10] - (Sadafi et al., 2014)

The general criteria can be categorised ranked according to direct influence (durability, toxicity, reusability and recoverability, security measures, as-built drawings) influence on the ease of the process (modularity, connections, material identification system) and influence on prolonging the life (Machado et al., 2018). The application of DfD criteria is crucial for material selection at the microscale, with implications for the macroscale building, indicating the interdependency of these factors (Munaro & Tavares, 2023).

2.5 MATERIAL SELECTION IN DESIGN FOR DECONSTRUCTION

DfD enables planned deconstruction at the end of a building's life (Crowther, 2018). Consequently, the incorporation of material selection during the design phase for DfD is essential, as it will directly affect the viability of resource recovery at the EOL, thereby supporting CE practices (Akinadé et al., 2018). Additionally, to assist in material selection at the design stage, literature has identified factors such as ease of disassembly, non-toxicity, modularity, and compatibility (Akanbi et al., 2019). For example, durability

and recyclability are crucial for maintaining the integrity and value of resources throughout multiple usage cycles (Akinade et al., 2019). The concepts of the CE can be integrated with DfD, which ultimately reduces waste and conserves resources by keeping materials in circulation within the construction sector (Eberhardt et al., 2020).

2.6 KANO MODEL

The Kano model, created by Noriaki Kano in the 1980s, classifies customer requirements into three categories: basic, performance, and excitement attributes, depending on how they influence satisfaction (Cho & Kim, 2022). Moreover, the main aim of the Kano model is to pinpoint and rank features that offer the greatest value to customers, thus directing resource allocation and design efforts (Slevitch, 2024).

The Kano model classifies customer needs into six primary categories. **Must-be qualities (M)** are fundamental expectations that, if not met, result in dissatisfaction; however, exceeding these does not greatly increase satisfaction (Cho & Kim, 2022). **One-dimensional qualities (O)** have a direct linear relationship with satisfaction, indicating that improved performance leads to greater satisfaction. **Attractive qualities (A)** are surprising features that boost satisfaction but do not lead to dissatisfaction if they are absent (Zoghi et al., 2021). **Indifferent qualities (I)** have no effect on customer satisfaction, independent of their presence (Cho & Kim, 2022). **Reverse qualities (R)** lead to dissatisfaction when they are present (Zoghi et al., 2021). Furthermore, a **Questionable category (Q)** consists of responses that can be ambiguous due to differing individual tastes (Slevitch, 2024). The Kano model assist to eliminate and prioritize key criteria, offering a clear framework for decision-making for subsequent works and its data-driven nature enhances objectivity (Cho & Kim, 2022) Thus, it is identified as the preferred quantitative analysis method in this study over other methods such as MoSCoW or RICE which rely on estimates and subjective judgment (Slevitch, 2024).

3. METHODOLOGY

This study utilises a mixed-methods approach to determine and rank the crucial criteria for material selection in DfD for doors and windows. As suggested by Creswell (2014), mixed methods utilised strengths of both quantitative and qualitative research, and this combination will provide an expanded understanding of the research question. Thus, the research employs a mixed-method approach to address the research question.

3.1 DATA COLLECTION METHODS

In the first phase (Qualitative), preliminary interviews were conducted with interviewees who have knowledge of DfD and CE principles. This is to fulfil the second objective, which is to identify the material selection criteria in DfD for doors and windows based on the criteria outlined in Table 1, which was completed upon achieving the first objective. To facilitate this process, an interview guideline was prepared that incorporated all the criteria from Table 1, as well as those specifically related to material selection for doors and windows identified by the researcher. By analysing these two documents, the interviewees provided their opinions and made relevant changes to the shortlisted criteria. The study employed semi-structured interviews for preliminary interviews due to their appropriateness for addressing exploratory research questions (George, 2023). This facilitates an in-depth exploration of new concepts such as DfD. For this phase, the "purposive sampling" method was used, which is categorised under nonprobability

sampling methods, because this approach can align the research sample with the research aim, ensuring the reliability of data (Campbell et al., 2020). This can be further justified because the data collection targets specific group the experts who have knowledge of DfD and CE. According to Creswell (2014), smaller sample sizes are often used for preliminary interviews to gain insights before the full-scale study. As a result, the sample size was considered as 5 interviewees for the preliminary interviews.

In the second phase (Quantitative), the purpose was to achieve the third objective which is to identify and rank the crucial criteria for material selection in DfD for doors and windows. For this purpose, a questionnaire was prepared using the results of the first phase and distributed among professionals within the construction industry who were engaged in the design process, including architects, engineers, quantity surveyors and academic researchers who are aware of the DfD and CE. The structure of the questionnaire included functional (FQ) and dysfunctional (DFQ) questions for each criterion, and responses were collected on a five-point scale (Like, must be, Neutral, Live with, Dislike) based on the Kano model questionnaire (Zoghi et al., 2021). In addition, the data collected from this questionnaire were subsequently analysed utilising the Kano model. Similarly, for the second phase "purposive sampling" was used, and according to Zoghi et al (2021) a sample size of 50 responses was considered adequate to acquire meaningful results in Kano model. In addition, the sample size of 50 professionals, provides a balance between feasibility and the need for reliable results (Cho & Kim, 2022). Thus, the sample size was considered as 50 for the second phase.

3.2 DATA ANALYSIS METHOD

Content analysis is a method where researchers systematically code and interpret data to identify patterns, themes, and meanings (Krippendorff, 2019). Thus, the preliminary interview data were analysed using content analysis. Consequently, in the second phase, Shapiro-Wilk normality test and Kruskal-Wallis test was utilised to signify the independence of the responses from their different professions. Then, each response will be evaluated based on the Kano evaluation table (Table 2) and categorised into distinct categories to identify the crucial material selection criteria in DfD for doors and windows.

Table 2 : Kano evaluation table

Criteria		**Dysfunctional question (-)**				
		Like	**Must be**	**Neutral**	**Live with**	**Dislike**
Functional question (+)	Like	Q	A	A	A	O
	Must be	R	I(Q)	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I(Q)	M
	Dislike	R	R	R	R	Q

According to Table 2 each response was evaluated, and based on the frequency of the responses, the criteria will be divided into different groups. For instance, if a responder answers, "live with" for a functional question and "dislike" for a dysfunctional question, the category was determined as "M - must be." After completing these steps, the criteria identified as "M-must-be" and "R-reverse" were selected as crucial criteria and ranked accordingly for material selection in DfD for doors and windows, as the criteria identified

as “M-must-be” are essential requirements, while “R-reverse” could adversely impact material selection in DfD for doors and windows. Then the ranking was done based on the frequency of the responses towards the selected category prioritising “M” over “R”.

4. ANALYSIS

This section analyses the data collected in the first and second phases.

4.1 PHASE 01

Initially, preliminary interviews were conducted to shortlist criteria related to material selection in DfD for doors and windows based on the identified broader criteria associated with DfD. Five interviewees who have knowledge of the DfD and CE, along with significant experience within the construction industry, were interviewed. The profiles of these respondents are detailed in Table 3.

Table 3 : Preliminary interview respondents' details

ID	Current Designation	Experience related to the research area
PIR1	Researcher/Lecturer	Having experience in the construction industry (10+ years) and experience in the research area
PIR2	Researcher	Having research related to CE and experience in the research area
PIR3	Researcher/Lecturer	Having research related to CE and DfD
PIR4	Researcher	Having research related to CE and experience in the research area
PIR5	Lecturer/ Industry	Having experience in the construction industry (30+ years)

As a result, 14 criteria were identified as crucial criteria for material selection in DfD for doors and windows. A summary of the preliminary interview findings is illustrated in Figure 1. In addition, for the analysis each criterion was coded (A1, B1...etc.) as illustrated in Figure 1.

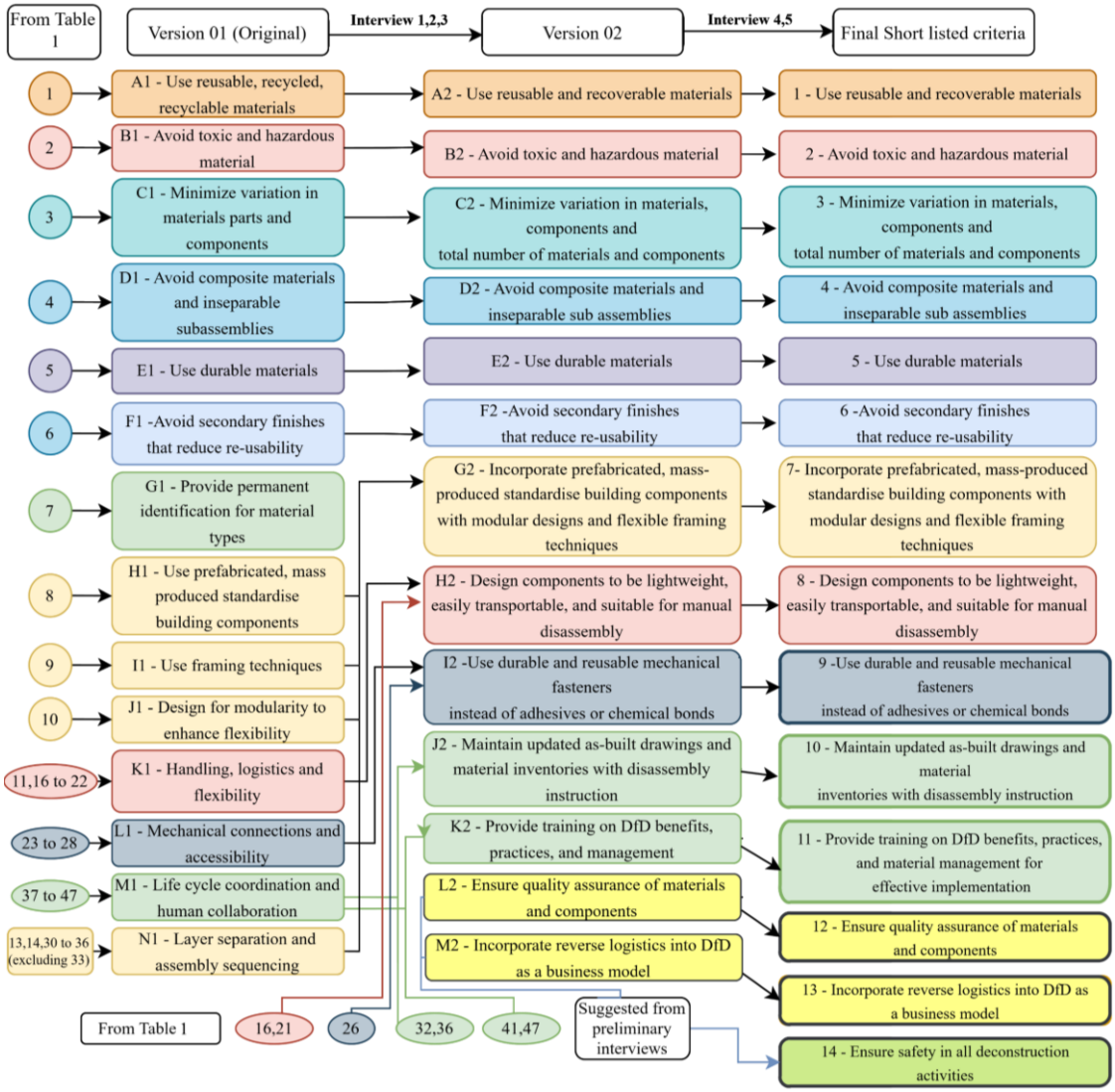


Figure 1 : Summarised findings of preliminary interviews

In the interview with **PIR 1**, all the criteria were deemed significant. In the case of PIR 2, A1 changed to use reusable and recoverable material since recoverable material covers a broader aspect. Furthermore, both **PIR 2** and **PIR 3** proposed to integrate H1, I1, and J1. **PIR 2** mentioned, *"We have to think about the construction before deconstruction, modularity facilitates that aspect, and it is better to merge all criteria related to modularity",* and **PIR 3** verified that in a subsequent interview. Additionally, **PIR 2** emphasised the importance of quality assurance in DfD as *"Quality assurance is also important because otherwise people will not buy it for reuse, and it also helps to have better market values for components"*. Similarly, the importance of reverse logistics was highlighted as *"Reverse logistics will add more value to the DfD concept since it transfers the material and component to the starting point"*. Additionally. **PIR 3** indicated that 32 and 36 should be included as J2, highlighting that *"Documentation is critical in DfD as the demolition contractor needs to have adequate information when demolishing and dismantling the components"*. Regarding criterion K2, **PIR 4** specified, *"For careful deconstruction, this is a requirement because we do not just throw them to the landfills"*. However, **PIR 5** argued that *"Training is not mandatory to all people but people who are*

involved in the process." Thus, the criterion was rephrased, adding effective implementation to indicate the success of the process utilising training. Additionally, **PIR 4** suggested including safety stating, *"Safety as a crucial criterion in the deconstruction aspects"*.

4.2 PHASE 02

A questionnaire survey was conducted based on insights from preliminary interviews to identify the crucial criteria related to material selection in DfD for doors and windows. The survey yielded a response rate of 77%, after sending it to 66 local industry professionals and academic researchers with familiarity regarding DfD, successfully achieving the required sample size for the study.

4.2.1 Statistical Analysis of the Data Set

The Shapiro-Wilk test was conducted on both functional and dysfunctional questions using SPSS software, with the null hypothesis stating that *"The data sample (FQs or DFQs) follows a normal distribution"*. According to the results, the $p \leq 0.05$ for all FQs and DFQs, rejecting the null hypothesis. 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 whether there are any differences among the three professional groups. Then, the Kruskal-Wallis test was performed on every functional and dysfunctional question, utilising SPSS software. For this test, the null hypothesis is stated as *"The distribution of sample (FQs or DFQs) is the same across the categories of the designation"*. As per the test result, the $p > 0.05$, retaining the null hypothesis for all FQs and DFQs. This suggests that the respondents' answers are not influenced by their professions. This further implies that the sample size does not have to be uniform across each profession.

4.2.2 Kano Model

The responses from the participants for each question (FQ and DFQ) for each criterion were evaluated using the Kano evaluation table (Table 2), and the category was assigned subjectively to each respondent as displayed in Table 4.

Table 4 : Results of the Kano model evaluation

Criteria	A	M	O	I	R	Q	Total	Category
Criteria 1	11	18	10	10	2	0	51	Must be
Criteria 2	4	29	8	8	2	0	51	Must be
Criteria 3	16	5	13	15	2	0	51	Attractive
Criteria 4	11	9	6	19	3	3	51	Indifference
Criteria 5	8	20	13	8	1	1	51	Must be
Criteria 6	11	2	8	26	2	2	51	Indifference
Criteria 7	26	3	7	11	3	1	51	Attractive
Criteria 8	15	8	19	8	0	1	51	One-dimensional
Criteria 9	14	11	12	11	2	1	51	Attractive
Criteria 10	12	15	10	13	0	1	51	Must be
Criteria 11	12	16	10	13	0	0	51	Must be
Criteria 12	6	19	16	10	0	0	51	Must be

Criteria	A	M	O	I	R	Q	Total	Category
Criteria 13	15	5	12	18	0	1	51	Indifference
Criteria 14	1	28	13	8	0	1	51	Must be

M – Must be, O – One dimensional, A – Attractive, R – Reverse, I -Indifference, Q - Questionable

According to Table 4, the category with the highest frequency from this assessment was used to assign a general category to the criterion. The findings revealed that seven criteria (1, 2, 5, 10, 11, 12, and 14) were classified under the "Must-be" category, indicating they are critical baseline requirements. In addition, no criteria were primarily categorised as "reverse." Based on this evaluation crucial criteria can be ranked as 01 - Avoid toxic and hazardous materials, 02 - Ensure safety in all deconstruction activities, 03 - Use durable materials, 04 - Ensure quality assurance of materials and components, 05 - Use reusable and recoverable materials, 06 – Provide training on DfD benefits, practices, and material management for effective implementation, 07 - Maintain updated as-built drawings and material inventories with disassembly instruction based on the number of responses.

5. DISCUSSION

The materials selection during the design stage for DfD is crucial, as it will have a direct impact on the feasibility of resource recovery at the end of their life cycle, thus supporting CE initiatives (Akinadé et al., 2018). According to Machado et al. (2018), although there are principles related to DfD, the applications have not been extensively explored in the literature, and there is a notable gap of research addressing the deconstructability of joinery components (Joustra et al., 2021). Consequently, this study seeks to bridge that gap by specifically examining material selection within the framework of DfD.

5.1 RELATIONSHIP OF THE FINDINGS WITH THE EXITING LITERATURE

Akanbi et al. (2019) stated that non-toxicity is an essential requirement for selecting materials in DfD, and this was further validated by the study ranking it as the top criterion. Additionally, Akinade (2019) indicated that durability and recyclability are vital for preserving the integrity and value of materials across multiple usage cycles. This was ascertained by the identified crucial criteria, including the use of durable materials and the use of reusable and recoverable materials. Eberhardt et al. (2020) proposed that thoughtful selection of materials in building construction can further improve VRPs and EOL scenarios within CE practices. This was substantiated indicating ensuring the quality of materials and components as a crucial requirement. This criterion not only facilitates deconstruction at the EOL but also enhances the VRP. This was confirmed by PIR2, mentioning that *"quality assurance is also important because otherwise people will not buy it for reuse, and it also helps to have better market values for components"*. According to Kuo et al. (2018), the complex nature of the construction process, varied stakeholders, and the duration of building projects pose obstacles in the construction sector. Nonetheless, the implementation of eco-design methods remains viable and appropriate. This can be explored with the key criteria identified, including safety, providing training, and maintaining documentation in DfD, which directly address the noted challenges. PIR 3 reiterated this by stating, *"documentation is critical in DfD as the demolition contractor needs to have adequate information when demolishing and dismantling the components"* Furthermore, PIR 4 indicated that *"safety is a crucial criterion in the deconstruction*

aspects" supporting how these criteria can indirectly aid in overcoming challenges in construction, thereby making the use of eco-design concepts beneficial.

5.2 UNDERLYING DRIVERS AND PATTERNS IN FINDINGS

The adhesive connections and the use of composite materials potentially hinder the deconstructability of doors and windows, as suggested by existing global literature (Joustra et al., 2021; Krišťák & Réh, 2021). However, this study does not identify these factors as crucial criteria within the context of the Sri Lankan sector. Furthermore, the established criteria can effectively address the identified issues related to reuse and recycling, such as low demand, as noted in the global literature (Akhtar & Sarmah, 2018). For instance, the implementation of quality assurance measures can significantly enhance the demand for reused materials. In addition, the general criteria for DfD can be categorized into three groups based on their significance: direct influence, influence on the ease of the process, and influence on the ease of the process (Machado et al., 2018). The study ranks these criteria according to these patterns, further identifying their relationship to existing global literature and validating them.

6. CONCLUSIONS

The research aimed to identify key criteria for material selection in DfD specifically for doors and windows. This was achieved through a literature survey, preliminary interviews, and a questionnaire based on the Kano model. Initially, 47 criteria were found in the literature, which were then narrowed down to 14 criteria during the preliminary interviews. After the Kano evaluation, 07 criteria were identified as crucial criteria and ranked based on the frequency of response. According to the results, avoid toxic and hazardous materials was identified as the most crucial criterion, while maintaining updated as-built drawings and material inventories with disassembly instructions was recognised as the least important criterion among the identified seven criteria.

This study significantly contributes to making an informed decision for the designers at the design phase when selecting materials for doors and windows to facilitate deconstruction. Consequently, material circularity can be promoted in line with CE within the construction sector, supported by DfD, in order to reduce the environmental effects associated with the construction industry from a wider environmental and social viewpoint. The findings of the study hold significant practical implications that can inform the development of sustainability-oriented policies, including the GreenSL rating system. Furthermore, from a theoretical standpoint, there is an opportunity for further research to investigate the market acceptability of reused and recycled components, as well as the potential for eco-design methodologies to enhance policy formulation in waste management within the context of Sri Lanka. As limitations of the study, the research does not consider a specific type of construction project type, as the existing literature only outlines criteria applicable to all construction projects in general. Furthermore, the research specifically addresses doors and windows, which may limit the applicability of the findings to other building components. Additionally, it is important to recognise that the data collection was conducted within the context of Sri Lanka.

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OPTIMIZING QUALITY MANAGEMENT IN THE CONSTRUCTION INDUSTRY: A COQ-BASED PREDICTIVE ANALYSIS

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ABSTRACT

The construction industry faces persistent challenges due to the absence of a standardized financial classification system for quality-related costs, resulting in inefficiencies and project delays. The Cost of Quality (COQ) framework, widely utilized in manufacturing, remains underutilized in construction due to its static assumptions that fail to account for complex interdependencies among quality costs. This study refines COQ classifications and examines the relationship between visible factors (VF) and hidden factors (HF) by using a predictive approach. To fill this gap, a questionnaire survey of 142 construction quality professionals in India was analyzed using SmartPLS 4.0, leading to the development of a predictive COQ model. The Partial Least Squares Structural Equation Modelling (PLS-SEM) results reveal that prevention costs significantly reduce external failure costs ($\beta = 0.465$, $p < 0.05$), while other hypothesized paths, including internal to external failure, were not statistically significant. The model explains 13.2%–22.0% of the variance across COQ components. These findings suggest that prioritizing preventive measures, particularly strategic planning and quality data analysis, is crucial for cost optimization in construction. The study contributes a validated predictive framework and highlights avenues for future research, including regional COQ indexes and AI-enhanced quality monitoring.

Keywords: *Complexity Theory; Construction Industry; Cost of Quality; Predictive Model; SmartPLS.*

1. INTRODUCTION

Quality issues in construction projects are a major concern, frequently leading to disputes between clients and contractors due to defects and inconsistent quality standards (Jha & Chockalingam, 2009). Studies indicate that poor quality in construction results in significant project delays, costly rework, and reduced overall efficiency (Kazaz & Birgonul, 2005). One of the key factors contributing to these challenges is the lack of uniformity in defining and measuring quality. In construction, quality is often defined as "fitness for use," while in other industries, it is characterized as "meeting customer expectations." This inconsistency in definitions can lead to subjective assessments and financial inefficiencies.

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The emergence of Quality 4.0, which integrates digital tools and smart technologies to improve quality management, presents a new opportunity to enhance quality frameworks in construction. Traditional Quality Management (QM) approaches, such as Total Quality Management (TQM), International Organization for Standardization (ISO) standards, and Six Sigma, have been widely used to improve quality performance (Sharma & Laishram, 2024). These approaches have led to better communication, reduced material wastage, and fewer instances of rework. However, despite their benefits, the construction industry continues to struggle with accuracy in quality standards, leading to non-transparent decision-making and cost inefficiencies (Hall & Tomkins, 2001). Many construction firms also underestimate the actual expenses linked to poor quality, affecting their overall profitability. The manufacturing sector, in contrast, has successfully demonstrated how effective quality management can drive profitability and establish consistent quality standards through the Cost of Quality (COQ) framework (Pursglove, 1995). COQ analysis enables organizations to set quality objectives, evaluate system efficiency, and develop strategic decisions. While COQ has proven effective in quantifying and improving quality management in manufacturing, its application in construction remains limited. A significant reason for this underutilization is the reliance on traditional accounting systems, which often fail to align with COQ measurement needs. As a result, many construction firms overlook the financial benefits of proactive quality management, leading to higher failure costs and reactive quality control measures (Garg & Misra, 2021). A key limitation of the traditional COQ framework is its static nature, which assumes fixed relationships between cost components (Kazaz et al., 2005). In reality, quality-related costs interact dynamically as organizations enhance their quality processes; the costs associated with prevention and appraisal fluctuate, influencing failure costs over time. The traditional COQ model does not account for these adaptive changes, leading to gaps in decision-making. To address these issues, there is a need for a more dynamic COQ framework that incorporates complex interactions and feedback mechanisms within quality management systems. This study introduces a new perspective on COQ, modelling dynamic interactions between cost components and incorporating Visible Factors (VF) and Hidden Factors (HF). By leveraging complexity theory, this research proposes a more adaptable COQ model that reflects real-world quality cost variations in construction. To bridge the theoretical and practical gaps in COQ applications within the construction industry, this study sets out to achieve three key objectives: (i) to investigate the dynamic interrelationships among the four COQ categories such as prevention, appraisal, internal failure, and external failure costs; (ii) to evaluate the influence of visible and hidden factors on quality cost performance; and (iii) to construct and validate a predictive model using Partial Least Squares Structural Equation Modelling (PLS-SEM). By contextualizing these objectives within construction project environments and applying complexity theory, the study provides new insights into how strategic quality investments can lead to improved cost efficiency and decision-making.

2. LITERATURE REVIEW

2.1 CONCEPT OF COST OF QUALITY

The COQ framework was first introduced by Juran and Godfrey (1951) in their book Quality Control Handbook. They defined COQ as the total cost incurred due to quality-related issues, emphasizing that these costs could be eliminated if no quality problems

existed. Similarly, Crosby (1979) described COQ as a key performance indicator, stating that reducing quality-related costs leads to improved overall performance. This perspective highlights COQ as a critical tool for translating quality efforts into financial metrics, making it more accessible to decision-makers and project managers in construction.

The COQ framework is classified into four key categories, based on BS 6143: Part 2 (1990):

1. Prevention costs – Investments made to ensure consistent quality performance through employee training, system improvements, and defect prevention (Hall & Tomkins, 2001).
2. Appraisal costs – Expenses allocated to inspections, audits, and monitoring to maintain quality compliance (Hall & Tomkins, 2001; Heravi & Jafari, 2014).
3. Internal failure costs – Costs associated with errors detected before project completion, such as rework, redesigns, and defective material replacements (Hall & Tomkins, 2001; Heravi & Jafari, 2014).
4. External failure costs – Expenses incurred after project delivery, including legal disputes, warranty claims, and reputational damage (Hall & Tomkins, 2001).

Most research on COQ in construction has focused on examining relationships between these cost categories. Some studies suggest that failure costs tend to be lower in well-managed projects, where prevention and appraisal investments play a crucial role in minimizing quality issues. However, other studies challenge this assumption, arguing that COQ relationships are complex and influenced by various internal and external factors.

2.2 RESEARCH GAP

Despite the growing interest in applying COQ frameworks across industries, existing research has largely focused on manufacturing, leaving a gap in understanding its relevance to construction. Unlike manufacturing, construction projects are highly dynamic, involve multiple stakeholders, and suffer from inconsistent quality standards and documentation (Hall & Tomkins, 2001; Kazaz & Birgonul, 2005). Traditional COQ models are ill-equipped to account for these complexities. Moreover, few studies have explicitly explored how HF interact with measurable quality costs (Khadim et al., 2023). By integrating complexity theory and PLS-SEM, this study hypothesizes that prevention investments and professional roles are not only drivers of COQ efficiency but also act through dynamic relationships that differ by project context. This theoretical framing strengthens the model's relevance to construction and provides a foundation for its predictive hypotheses. By developing a predictive COQ model, this research aims to enhance decision-making in construction quality management and provide practical recommendations for industry professionals. A strategic roadmap has been developed to address the limitations of the traditional COQ model and facilitate the adoption of a predictive quality cost framework in the construction industry. This approach explores the interrelationships among COQ components through a structured hypothesis-driven analysis:

- H1: There is a significant relationship between prevention costs and internal failure costs, where increased appraisal efforts contribute to reducing internal failure costs.

- H2: Internal failure costs are positively correlated with external failure costs, meaning that higher internal failure costs are associated with greater external failure costs.
- H3: There is a significant positive relationship between prevention costs and external failure costs, indicating that increased prevention efforts lead to a reduction in external failure costs.
- H4: Stakeholder involvement plays a critical role in optimizing COQ, suggesting that effective engagement and collaboration contribute to achieving cost efficiency and quality improvements.

3. METHODOLOGY

This study adopted a comprehensive four-stage research strategy to explore the influence of VF and HF on the COQ in construction projects. The methodology was designed to ensure a systematic and structured approach to addressing the research objectives through literature review, expert validation, data collection, statistical analysis, and model development. The first stage involved an extensive literature review to identify key factors influencing COQ in construction. A desktop search using Scopus, Web of Science (WOS), and EBSCOhost was conducted, employing the building blocks approach for keyword identification (Araújo et al., 2017). The search included keywords such as "cost of quality," "quality costs," "construction industry," "quality models," "rework," and "PAF" to filter relevant studies. The snowballing and trial-and-error techniques further refined the selection process, leading to the identification of 22 critical factors, which were subsequently grouped into visible and hidden categories. The second stage involved the administration of a self-administered questionnaire to examine the impact of VF and HF on COQ components. This approach, widely recognized in construction management research, enabled the collection of responses from a diverse and geographically dispersed sample (Raouf & Ghamdi, 2020). A pilot study with five participants was initially conducted to assess the clarity and reliability of the questionnaire, leading to refinements before full-scale distribution. The final survey, developed using Google Forms, consisted of two sections: one covering demographic information and the other assessing 22 COQ-related factors on a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The sample size was determined using Cochran's formula, establishing a minimum requirement of 97 respondents for a 95% confidence level (Heravi & Jafari, 2014). The study successfully collected 142 valid responses, ensuring statistical robustness. A purposive sampling strategy was employed to target professionals actively involved in construction quality management, allowing for a focused examination of COQ practices (Palinkas et al., 2015). The third stage comprised data analysis, conducted using Statistical Package for Social Sciences (SPSS) version 29. Various statistical techniques were employed to validate the data and identify key relationships:

- Reliability Analysis: Cronbach's alpha was used to assess internal consistency, yielding a coefficient of 0.847, exceeding the recommended threshold of 0.7 (Hoque & Hasan, 2022).
- Normality Testing: The Kolmogorov-Smirnov (K-S) test and z-scores for skewness and kurtosis confirmed a non-normal distribution, justifying the use of non-parametric methods.

- Non-Parametric Tests: The Kruskal-Wallis test and Post-hoc analysis identified statistically significant differences among COQ categories, aligning with the ordinal nature of the data (Chan & Tam, 2000).

The fourth stage involved the construction and evaluation of a hypothetical predictive model. The proposed model comprises five latent constructs: prevention cost, appraisal cost, internal failure cost, and external failure cost. Additionally, a fifth construct, quality professional role, was incorporated to evaluate moderating effects. An initial conceptual framework was formulated on the basis of theoretical relationships (H1–H4). This model was tested using PLS-SEM via SmartPLS 4.0. PLS-SEM was selected due to its ability to handle complex models with latent variables, making it ideal for this exploratory study (Hair et al., 2014). Figure 1 and Table 5 presents the refined model, which reflects the removal of statistically insignificant paths and highlights significant influences along with the model's explanatory power. The model's reliability was assessed through Composite Reliability (CR), Cronbach's Alpha (α), and Average Variance Extracted (AVE). The results showed that all AVE values exceeded 0.5, confirming strong construct validity (Fornell & Larcker, 1981). Additionally, bootstrapping with 5000 resamples was performed to establish confidence intervals for path coefficients, ensuring statistical robustness (Ghani et al., 2017). This four-stage methodology provides a comprehensive framework for analyzing COQ in construction projects, integrating expert insights, advanced statistical techniques, and robust modelling approaches. The combination of qualitative expert validation, quantitative data analysis, and PLS-SEM modelling enhances the practical application of COQ strategies and contributes to the ongoing discourse on quality management in the construction industry.

4. DATA ANALYSIS

The collected data was analyzed using SPSS version 29 and SmartPLS 4.0 to assess the relationships between COQ components and the influence of VF and HF.

4.1 RELIABILITY AND VALIDITY ANALYSIS

To ensure internal consistency, Cronbach's Alpha (α) was used, achieving a reliability score of 0.847, surpassing the minimum threshold of 0.7. Moreover, CR further confirmed the robustness of the measurement model, while AVE ensured that each construct effectively captured the intended variance.

4.2 NORMALITY TESTING AND NON-PARAMETRIC ANALYSIS

Data normality was assessed using the Kolmogorov-Smirnov (K-S) test, which indicated deviations from normal distribution. Consequently, non-parametric tests were applied. The Kruskal-Wallis test examined differences across respondent groups, while Post-hoc analysis identified specific variations among COQ categories.

4.3 PARTIAL LEAST SQUARE-STRUCTURAL EQUATION MODELLING (PLS-SEM)

4.3.1 Model Development

A predictive model was formulated based on insights drawn from the literature review and findings from non-parametric tests. Through an iterative refinement process, factors with low path coefficients were systematically removed to enhance model consistency.

The finalized PLS-SEM model was assessed using reliability and validity tests, ensuring its robustness, as depicted in Figure 1. To verify construct reliability, key statistical measures including Cronbach's Alpha, CR, and AVE, were derived from SmartPLS 4.0. The results confirmed acceptable convergent validity across all constructs, as summarized in Table 1. Additionally, discriminant validity was evaluated using the Fornell-Larcker criterion and cross-loading assessments. The Fornell-Larcker criterion requires that the square root of AVE for each construct be greater than its correlation with other latent variables, a condition met in this study, as detailed in Table 2. Furthermore, cross-loading assessments confirmed that each indicator exhibited higher loadings with its own construct than with unrelated variables, meeting the validity requirements outlined in Table 3.

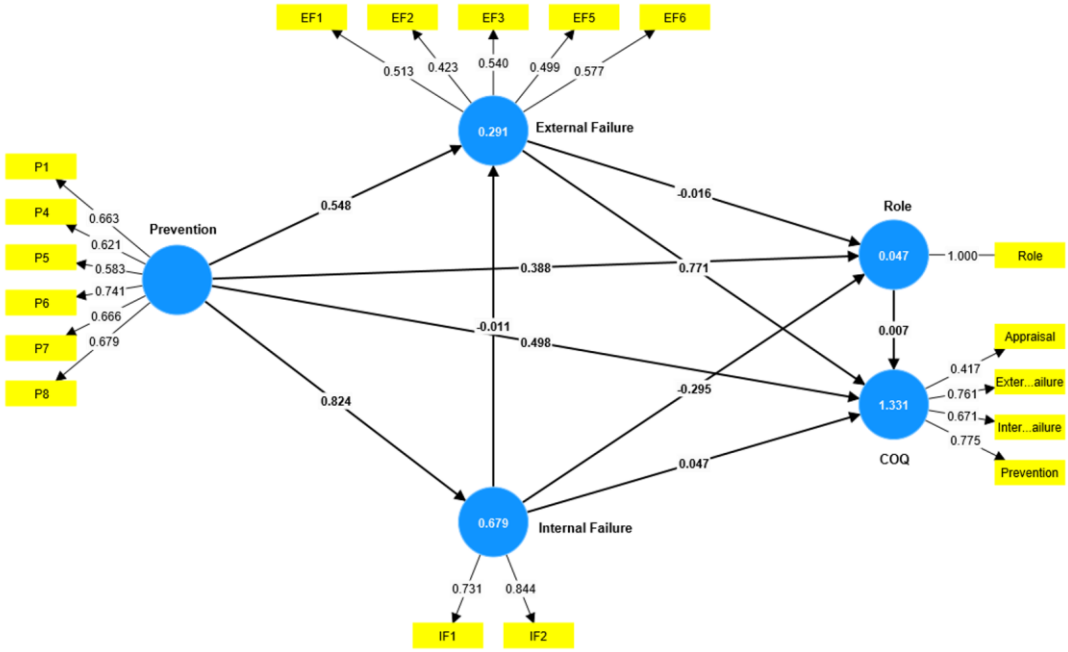


Figure 1: Final model

Table 1: Results of reliability tests

Constructs	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
COQ	0.765	0.788	0.758	0.451
External Failure	0.637	0.644	0.639	0.263
Internal Failure	0.763	0.774	0.767	0.623
Prevention	0.819	0.825	0.822	0.436

Table 2: Results of Fornell-Larcker criterion

Constructs	COQ	External failure	Internal failure	Prevention	Role
COQ	0.672				
External Failure	1.061	0.513			
Internal Failure	0.797	0.441	0.789		

Constructs	COQ	External failure	Internal failure	Prevention	Role
Prevention	0.953	0.539	0.824	0.660	

4.3.2 Model Evaluation

Following the verification of reliability and validity, the model's explanatory power and path coefficients were assessed. The R-squared (R^2) values indicated the proportion of variance explained by the model, with values of 22.0% for Prevention, 21.0% for Internal Failure, and 13.2% for External Failure, demonstrating a substantial explanatory capacity for these categories. The significance of the path coefficients (denoted as ß1 to ß2) was tested using bootstrapping with 5000 resamples in SmartPLS 4.0. The bootstrapping method involves resampling the dataset multiple times and rerunning the PLS model to ensure result consistency. The statistical reliability of the dataset, alongside observed path coefficients (p-values and outer weights at the 95% confidence interval), was verified using this methodology. The analysis revealed that two hypotheses attained statistical significance, whereas three hypotheses did not, as summarized in Table 4. However, all hypothesized relationships exhibited a positive directional influence, reinforcing the interconnectivity of COQ components in construction quality management.

Table 3: Results of cross-loading of PLS model

Items	COQ	External failure	Internal failure	Prevention	Role
EF1 (Complaints)	0.480	0.550	0.190	0.256	0.065
EF2 (Liability claims)	0.394	0.538	0.183	0.226	-0.073
EF3 (Penalties for poor quality)	0.515	0.691	0.165	0.254	0.091
EF5 (Costs of repair during warranty period)	0.478	0.716	0.190	0.232	0.009
EF6 (Delay of Project)	0.537	0.692	0.262	0.285	0.048
IF1 (Rejected item)	0.525	0.315	0.883	0.513	0.044
IF2 (Repair, rework, or replacement)	0.591	0.250	0.914	0.662	-0.012
P1 (Strategic planning for COQ)	0.566	0.216	0.522	0.766	0.064
P4 (Maintenance & Calibration of test and measuring equipment)	0.530	0.318	0.400	0.630	0.171
P5 (Assuring contractor/supplier/sub-contractor quality)	0.477	0.183	0.478	0.631	0.112
P6 (Staff training)	0.639	0.320	0.541	0.794	0.009
P7 (Acquisition, analysis & reporting of quality data)	0.556	0.327	0.466	0.751	0.100
P8 (Quality improvement programs)	0.575	0.340	0.462	0.775	0.104

5. RESULTS

The findings of this study provide insights into the influence of professional roles, VF and HF factors, and COQ categories on quality cost dynamics in the construction industry. The analysis highlights key relationships that impact COQ optimization and cost management strategies. The Kruskal-Wallis test results indicate that a respondent's profession does not significantly impact their expertise in COQ components, including prevention, appraisal, internal failure, and external failure costs. Post-hoc analysis further supports this, with p-values above 0.05 across all categories. Despite the lack of significant variance in expertise levels, the role of quality professionals in construction remains vital for minimizing quality-related costs by ensuring the effective implementation of standards and processes. Their expertise helps mitigate defects, reduce rework, and improve cost efficiency. However, studies suggest that top management commitment is a critical determinant of COQ success (Aoieong et al., 2002). Organizations that prioritize structured quality investments through training, process optimization, and advanced quality management (QM) systems achieve greater cost reductions in the long term (Mashwama et al., 2017). Conversely, when management focuses solely on cost-cutting rather than quality improvements, higher failure costs arise due to rework, client dissatisfaction, legal disputes, and warranty claims (Omar & Murgan, 2014). A collaborative approach between top management and quality professionals is therefore essential for enhancing COQ efficiency and cost savings.

The study also highlights the significance of VF and HF in COQ performance. Among HF, the most critical factors include strategic planning for COQ (P1) and quality data analysis (P7), both of which play a major role in long-term cost efficiency. Organizations investing in staff training and quality improvement programs experience immediate improvements in defect reduction and cost control. Research suggests that at least 30 hours of quality training significantly improves workforce performance, while extending training to 100 hours correlates with increased labour productivity (Shafiei et al., 2020). Furthermore, repair and rework (IF2) costs contribute significantly to internal failure expenses, with studies showing that 6% to 15% of total construction costs result from defective materials and rework expenses (Yarnold et al., 2021). Quality improvement programs (P8), using methodologies such as Six Sigma, Lean, and PDCA cycles, are particularly effective in preventive cost optimization.

While VF are often prioritized in quality management strategies, HF such as strategic planning (P1) and data analysis (P7) are frequently overlooked, despite their crucial role in cost reduction and process efficiency. Strategic planning enables organizations to align quality initiatives with business objectives, mitigating cost overruns and inefficiencies (Tawfek et al., 2012). Additionally, effective quality data management (P7) allows firms to track and predict quality-related costs, minimizing delays and preventing rework expenses. Without a systematic approach to data-driven decision-making, organizations risk misallocating resources, leading to higher failure costs and inefficient cost structures. This underscores the need for an integrated approach combining VF and HF to enhance COQ performance and ensure long-term cost optimization.

The PLS-SEM model findings further reveal insights into COQ cost interactions. The study found that H1 (Prevention → Internal Failure), H2 (Internal Failure → External Failure), and H4 (Quality Professionals' Role in COQ Optimization) were not statistically significant. While these hypotheses suggested potentially positive relationships, they did

not yield statistical validation ($\beta = 0.186$, $p = 0.081$; $\beta = 0.180$, $p = 0.179$; $\beta = 0.107$, $p > 0.05$, respectively). This aligns with previous research, indicating that higher appraisal costs do not always translate into immediate reductions in internal failure costs due to time lags in quality improvement processes. Similarly, the absence of a direct relationship between internal and external failure costs suggests that poor internal failure monitoring may not necessarily lead to external failure cost reductions (Quinn & Bhatty, 1989), the impact of quality professionals in COQ optimization varies across organizations, depending on company policies, project scope, and available resources (Schiffauerova & Thomson, 2006). Conversely, H3 (Prevention → External Failure) was statistically significant. The findings confirm that prevention costs have a strong positive influence on external failure costs ($\beta = 0.465$, $p < 0.05$). This reinforces the argument that investment in preventive quality measures significantly reduces overall failure rates (Kiani et al., 2009). Organizations prioritizing ISO 9001-based quality frameworks demonstrate higher COQ efficiency, as structured quality management systems streamline defect prevention (Glogovac & Filipovic, 2018). Further examination suggests that higher prevention investments lead to lower failure costs, as increased spending on staff training, process improvements, and technological advancements mitigates defects and rework-related expenses. However, organizations must maintain a balance between prevention and appraisal investments to avoid over-allocation of resources (Hall & Tomkins, 2001). Achieving an optimal COQ strategy involves ensuring equilibrium between prevention, appraisal, and failure costs, where quality objectives are met while controlling total expenditure. Overall, the study underscores the critical role of VF, HF, and proactive quality investment in optimizing COQ in construction projects. The findings reinforce the need for strong managerial commitment, data-driven quality management, and strategic investments in preventive measures to achieve long-term cost efficiency and enhanced quality performance.

Table 4: Path coefficients and significance values

Hypothesis	Path coefficient	T statistics (|O/STDEV|)	P values	Statistical support
H1: Prevention -> Internal Failure	0.186	4.610	0.081	Not Supported
H2: Internal Failure -> External Failure	0.180	1.345	0.179	Not Supported
H3: Prevention -> External Failure	0.465	1.828	0.000	Supported
H4: Role -> COQ	0.107	1.591	0.112	Not Supported

6. CONCLUSION

The integration of COQ techniques into the construction industry signifies a pivotal advancement toward more strategic and data-driven quality management. This transition supports a broader shift from reactive defect control to preventive, system-oriented quality assurance frameworks aligned with sustainability, lifecycle performance, and long-term value creation. However, the full potential of COQ remains underleveraged due to limited awareness of HF such as strategic planning, organizational alignment, and quality data utilization elements that profoundly shape quality outcomes but often remain obscured in conventional models. This study systematically identified and validated 22

influencing factors, categorized into VF and HF, and organized them into four thematic dimensions. This structured taxonomy enhances stakeholders' ability to diagnose inefficiencies and design targeted interventions within quality management systems. Notably, VF such as staff training and process standardization serve as immediate levers for reducing defects and rework, while HF such as strategic quality planning and digital data monitoring are shown to drive long-term cost efficiencies and organizational learning. The model, evaluated using PLS-SEM, demonstrated that prevention costs have a statistically significant inverse relationship with external failure costs ($\beta = 0.465$, $p < 0.05$), supporting the strategic value of preventive investments. Conversely, the hypothesized links between internal and external failure costs, and between prevention and internal failure, did not attain statistical significance, suggesting potential moderating variables or context-dependent dynamics that merit further investigation.

From a theoretical perspective, the study contributes to the refinement of COQ theory by incorporating complexity-informed constructs and validating their operational interdependencies. Practically, it offers a diagnostic framework for construction firms to benchmark COQ performance and prioritize quality investments that yield measurable cost benefits. Nonetheless, certain limitations warrant consideration. The study's geographic scope was restricted to Indian construction professionals, and data were collected cross-sectionally, which may limit temporal and contextual generalizability. Moreover, reliance on self-reported perceptions introduces potential biases. Future research should focus on developing a standardized, region-sensitive COQ index to enable cross-context comparisons and enhance model applicability. Furthermore, longitudinal investigations leveraging real-time project data and AI-driven quality analytics are also recommended to capture dynamic quality-cost trade-offs over time. This study offers a foundational yet adaptable model for understanding and operationalizing COQ in construction. By integrating quantitative rigor with industry-specific insights, it paves the way for more efficient, transparent, and sustainable quality management practices across diverse construction environments.

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8. ANNEXURE: Model development

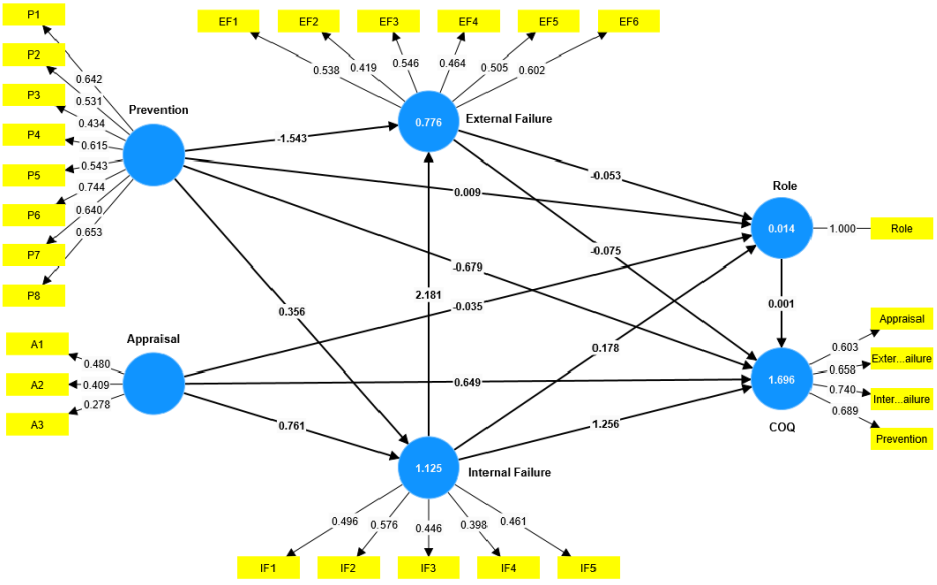


Figure A: Development of model – Phase 1

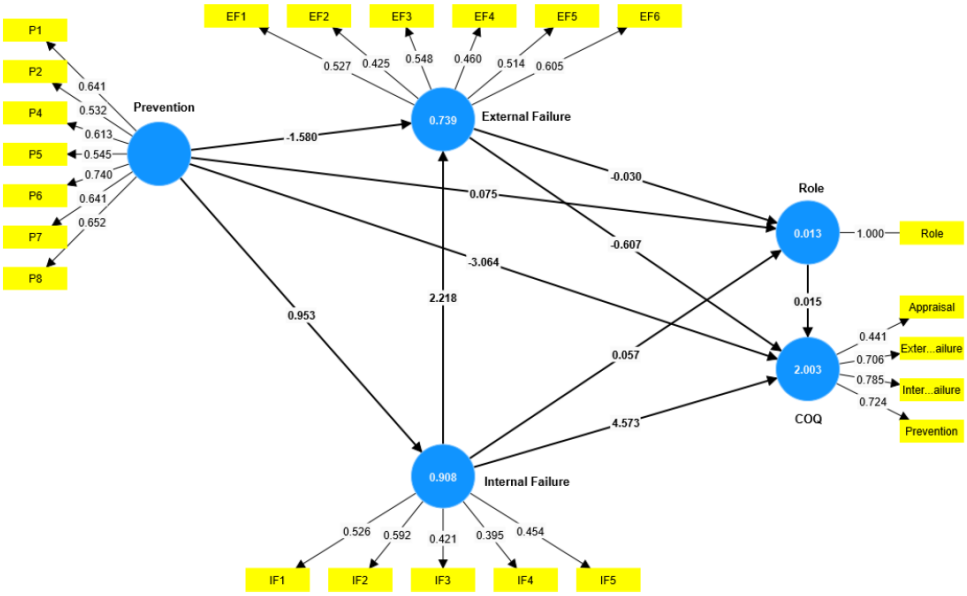


Figure B: Development of model – Phase 2

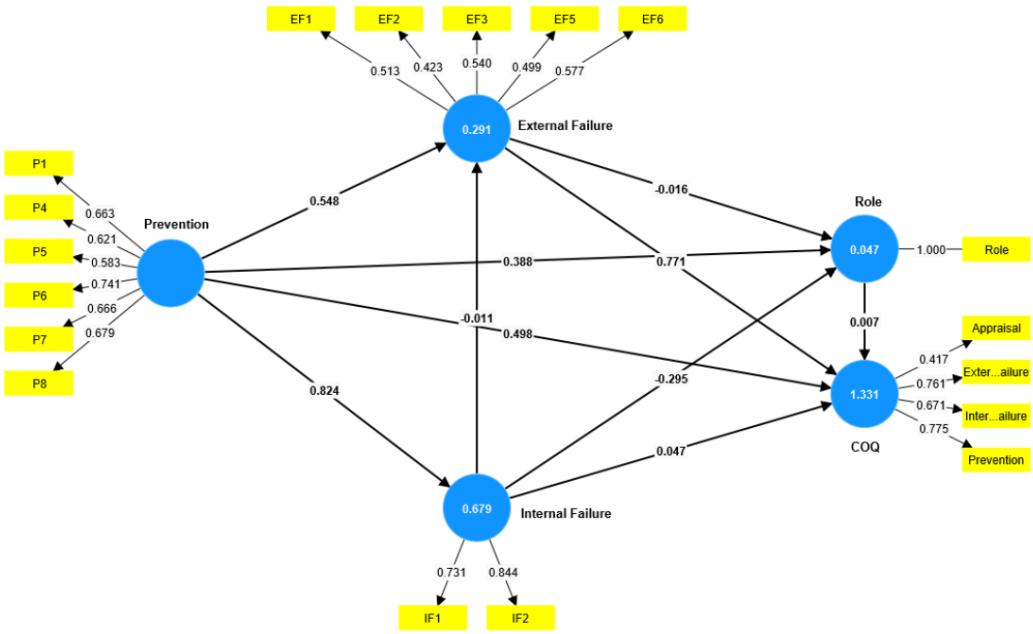


Figure C: Development of model – Phase 3 (Final Version)

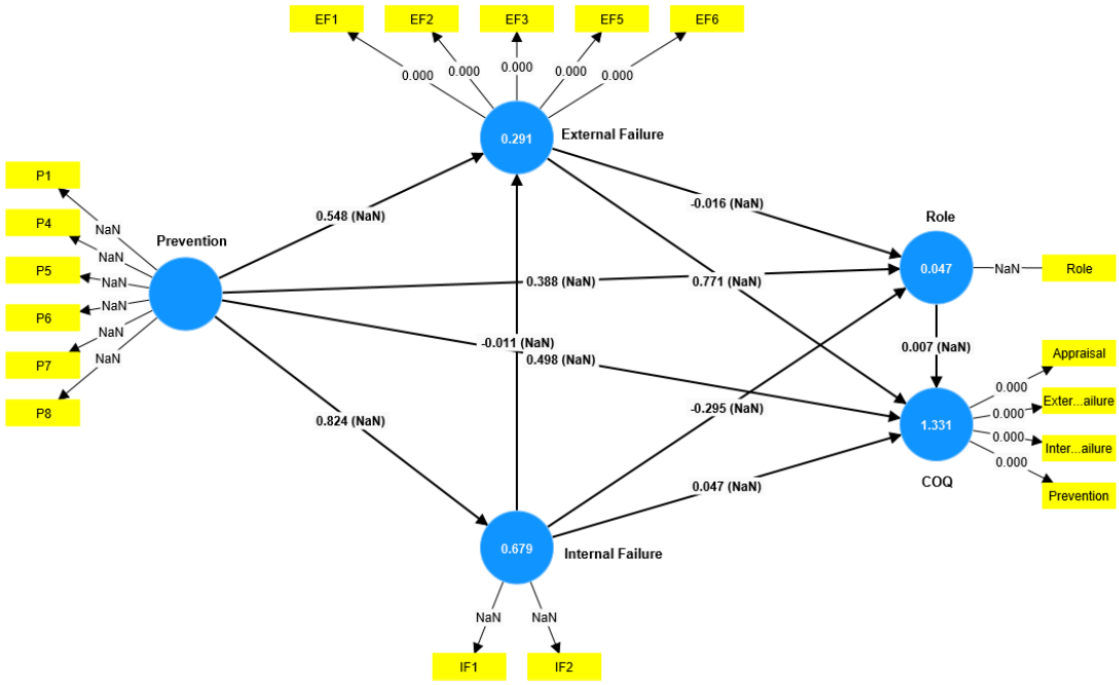


Figure D: Bootstrapping of the final model

Logendran, J., Sivanraj, S., Ligasabesan, V., Jayasena, H.S. and Eranga, B.A.I., 2025. Perceived and expected cost optimisation affordances of building information modelling in Sri Lankan construction projects. 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. 1070-1082. DOI: https://doi.org/10.31705/WCS.2025.80. Available from: https://ciobwcs.com/papers/

PERCEIVED AND EXPECTED COST OPTIMISATION AFFORDANCES OF BUILDING INFORMATION MODELLING IN SRI LANKAN CONSTRUCTION PROJECTS

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ABSTRACT

Building information modelling (BIM) has been widely recognised for its potential within the construction sector to optimise the construction process. This study aims to investigate the cost optimisation affordances of BIM and analyse the perceived and expected affordances within the Sri Lankan construction sector. The study adopted a mixed-method research approach where semi-structured interviews with industry experts were conducted to identify and validate key affordances, followed by a questionnaire survey to assess their significance. Content analysis and the Relative Importance Index (RII) technique were used for data analysis. The findings reveal that cost estimation accuracy, improved project coordination and reduction of variation and claims are the most significant cost optimisation affordances of BIM. Furthermore, strategies for enhancing the realization of BIM's potential were identified, emphasising stakeholder training and policy development. This study contributes to theory by addressing the knowledge gap in affordances related to cost optimisation and provides practical insights for practitioners in the Sri Lankan construction industry to maximise the benefit of BIM for cost optimisation.

Keywords: *Affordances; Building Information Modelling; Cost Optimisation; Strategies.*

1. INTRODUCTION

The construction sector faces several difficulties, such as schedule and cost overruns, labour shortages, productivity problems, and health and safety concerns (Abioye et al., 2021). One of the primary issues faced by Sri Lankan construction projects is cost overrun (Fernando & Gunarathna, 2023). Kamaruddeen et al. (2020) identified that the most influential factors for cost overruns include insufficient material supply, resource shortages, modifications to the scope of work or material specifications, client requests for acceleration, errors made during construction, cost variations, a lack of qualified

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personnel, ineffective project management, an inability to control costs, and the award of the project to the bidder with the lowest price. In addition to that, delays in project completion can lead to substantial financial burdens (Kumar Karn & Raj Dahal, 2021).

Cost optimisation is the standard operating procedure in the majority of developing and undeveloped country construction companies (Zhang et al., 2020). Building Information Modelling (BIM) represents a comprehensive suite of information technologies widely employed within the architectural, engineering, and construction (AEC) sectors. BIM positively influences the collaboration of stakeholders by integrating information and technology within the construction projects (Zhang et al., 2020). Through this integration, various software tools are consolidated into a digital platform to improve communication among all stakeholders involved in a project, as emphasised by Kumar et al. (2017). A key aspect of BIM is the creation of virtual project models with both physical and functional data, enabling detailed analysis of project scope and enhancing project control. Jayasena et al. (2019) identified three different sets of affordances, including real, perceived, and expected affordances, for examining innovations.

The concept of expected affordances was introduced by Jayasena et al. (2019), however, none have comprehensively investigated cost optimisation affordances for BIM within the Sri Lankan context. In recent years, technological advancements in the Sri Lankan construction sector have led to increased adoption of various technologies (Epasinghe et al., 2018), including BIM. Despite this progress, there remains a lack of research on how BIM affordances contribute specifically to cost optimisation within this context. Thus, this study aims to bridge this knowledge gap by investigating the cost optimisation affordances of BIM in Sri Lanka. The objectives of this study are:

1. To identify the building cost optimisation affordances of BIM
2. To analyse the perceived and expected affordances of BIM
3. To identify strategies to bridge the gap between the expected and perceived affordances of BIM for cost optimisation

This research includes a comprehensive literature review, a detailed description of the research methodology, an in-depth analysis of the findings, and a conclusion including the key outcomes, providing valuable insights for both academia and industry stakeholders.

2. LITERATURE REVIEW

2.1 SIGNIFICANCE OF BIM IN CONSTRUCTION PROJECTS

Ibrahim et al. (2019) identified that BIM offers benefits in all phases of the construction process. The advantages of the BIM are discover and reduce errors or conflicts, automatically insert and adjust modifications in all dimensions of 3D, 4D (time), and 5D (cost) models (Ebada et al., 2021), assess time and cost during the construction phase, monitor and track progress during construction, increase productivity and project efficiency, reduce and identify clashes (Al-Ashmori et al., 2020). In addition to that, reduction in construction cost and project duration, speed up the process, improve safety performance, and provide life cycle data (Chan et al., 2019).

Wang and Chen (2023) mentioned that BIM has been widely used as a digital tool for construction and as a management technique and it is anticipated that BIM will be crucial to project management. In comparison to traditional procedures, this technological

approach allows for greater and more efficient communication among project participants by encapsulating all project aspects into a single 3-dimensional model (Mahamadu et al., 2019). It is considered imperative that stakeholders representing different specialities in construction work together to create novel procedures and techniques that complement the integrated character of BIM (Onungwa et al., 2017).

2.2 COST OPTIMISATION AFFORDANCE OF BIM

BIM is appropriate for the entire cost management process in construction projects. It can be applied to efficiently reduce cost and enhance cost management effectively (Tang & Liu, 2022). The two main advantages of BIM technology are cost reduction and high documentation quality (Mesároš & Mandičák, 2017). BIM affordances mean comprehension of the decision-making process used by a specific adopter when choosing BIM tools and functions in the context of subjectivity (Jayasena et al., 2023). The real affordance is based on what BIM can provide to each user. Expected affordances and perceived affordances are concepts from design and technology that describe how users relate to a tool, system, or interface, based on what they think it can do versus what it does for them. According to Jayasena et al. (2019), perceived affordances of BIM mean what the adapter believes is achieved with the chosen BIM technology, whereas expected affordance is what the user expects to achieve. Table 1 provides the cost optimisation affordances of BIM highlighted by various studies.

Table 1: Affordances of BIM in cost optimisation

Cost optimisation affordances for BIM	Citations
Utilise the parametric functions and components.	[2], [5]
Prepare accurate cost estimation	[5], [19]
Decrease repetitive work.	[2], [3], [4], [5], [8]
Reduce paperwork.	[5], [9], [13]
Reduce the errors in the drawing.	[3], [10], [15], [18], [19]
Assess the planned and actual status of the work.	[6], [18]
Provide effective communication between stakeholders	[3], [5], [6], [12], [17], [19], [21]
Ensure data security.	[7], [16]
Forecast the risk of construction.	[1]
Expect to receive a rate of investment.	[14], [20]
Clash Detection.	[3], [10], [15], [18], [19]
Improve company reputation.	[15]
Satisfy the client.	[11], [22]

[1] - Abanda et al. (2020); [2] - Afshari (2022); [3] - Bagcal et al. (2019); [4] - Bilov et al. (2023); [5] - Park et al. (2022); [6] - Dakhil and Underwood (2016); [7] - Das et al. (2021); [8] - Gao et al. (2016); [9] – Okoye and Obi (2013); [10] - Halttula et al., (2015); [11] - Hafeez et al. (2016); [12] - Jung and Häkkinen (2018); [13] - Khatib and Alzoubi (2022); [14] - Kocakaya et al. (2019); [15] - Lahiani (2020); [16] - Maksudovna et al. (2023); [17] - Okereke et al. (2021); [18] - Smith (2014); [19] - Thurairajah and Goucher (2013); [20] - Ullah et al. (2019); [21] - Wang and Chen (2023); [22] - Zima and Mitera-Kiełbasa (2021)

2.3 STRATEGIES TO IMPLEMENT BIM FOR COST OPTIMISATION

Various studies have identified several strategies for successful BIM implementation. Liu et al. (2015) emphasised that the government and BIM education institutions should establish strategic implementation plans and promote BIM education to overcome barriers to BIM adoption. Furthermore, financial support from funding agencies and government organisations is crucial for investment in BIM (Zima & Mitera-Kiełbasa, 2021). Developing BIM standards at both local and global levels, establishing protocols for stakeholder liabilities and data security, providing BIM training and certification, fostering teamwork for BIM execution with top management support, ensuring sufficient technological facilities, and clearly defining roles and responsibilities in BIM operations are essential strategies (Asma et al., 2016; Darwish et al., 2020; Ma et al., 2023; Smith, 2014)

Famadico (2023) highlighted the need to establish feasible pathways for transitioning from traditional practices to BIM, increasing BIM-related research, making BIM widely accessible, and developing guidelines to facilitate BIM implementation. Educational support is significant in addressing knowledge-related barriers, as Ma et al. (2023) noted, which suggested that proper BIM training enhances practitioners' knowledge. Rafindadi et al. (2023) further advocated providing free trial access to BIM software, continuous workshops, and seminars, while Aka et al. (2021) emphasised the efficiency of offering BIM training to fresh graduates. Increasing public awareness about BIM can spread knowledge of its key benefits, enhance client trust through improved working environments, and reduce miscommunication among stakeholders (Farouk et al., 2023; Zaini et al., 2020). Finally, government policies and guidelines are indispensable, providing the necessary procedures for BIM implementation, mandating its use in government-funded projects, reducing tax policies for BIM software acquisition, and organising platforms for BIM education and awareness (Olugboyega et al., 2019; Rani et al., 2023).

3. METHODOLOGY

The study analysed the perceived and expected cost optimisation affordances of BIM in Sri Lankan construction projects. It is significant to obtain expert perspectives and experience to interpret the cost optimisation affordances of BIM and to gain a more comprehensive understanding of the two major types of affordances in this study. In-depth discussion based on the professionals' experience in the field is necessary to obtain a more comprehensive understanding of the subject matter (Saunders et al., 2023).

In research, a mixed-methods approach combines several research methods, which is useful for overcoming the limitations of mono-methods (Kothari, 2021). The mixed-method approach allowed for the collection of relevant data from various sources through a combination of qualitative and quantitative paradigms. The research methodology was structured as follows: an initial literature review was conducted to understand the background of cost optimisation real affordances of BIM. Subsequently, the mixed method approach enabled the validation of data obtained from the literature, distinguished between perceived and expected affordances, and identified suitable strategies to bridge the gap between perceived and expected affordances of BIM in cost optimisation. Data collection was conducted in two stages: interviews in the first phase, which allowed for validation of the findings of the literature and identification of new cost optimisation

affordances of BIM and questionnaires in the second phase to quantitatively assess the cost optimisation affordances and to categorise them as expected and perceived affordances. Experts for interviews were selected using purposive sampling, and their profiles are presented in Table 2.

Table 2: Profile of interview experts

Expert	Designation	Experience in the construction industry (at least 15 years)	Experience in BIM (more than 5 years)	Bachelor's/ Postgraduate Degree
E1	Contract Manager	✓	✓	✓
E2	Senior Quantity Surveyor	✓	✓	✓
E3	Senior Quantity Surveyor	✓	✓	✓
E4	Senior Quantity Surveyor	✓	✓	✓
E5	Senior MEP Quantity Surveyor	✓	✓	✓
E6	Contract Manager	✓	✓	✓
E7	Contract Manager	✓	✓	✓
E8	Senior MEP Quantity Surveyor	✓	✓	✓
E9	Senior Quantity Surveyor	✓	✓	✓
E10	Senior Quantity Surveyor	✓	✓	✓
E11	Contract Manager	✓	✓	✓
E12	Senior Quantity Surveyor	✓	✓	✓
E13	Senior Quantity Surveyor	✓	✓	✓

In-person recorded interviews were conducted, which lasted around thirty minutes. The findings from the interview were analysed using a three-phase manual content analysis. In qualitative research, this tool allowed us to find selective codes (Williams & Moser, 2019). Firstly, the interview outcomes were transcribed, followed by a critical review to identify the affordances of cost optimisation. Finally, affordances were standardised and classified according to deductive and inductive codes.

The results from the previous stages were used to conduct a questionnaire survey. Data was collected from 40 professionals, including quantity surveyors from various organisations within Sri Lanka. These professionals were selected based on their years of experience within the construction industry (minimum of 5 years) and their knowledge on cost optimisation affordances of BIM. This phase identified the level of perception and expectation for each cost optimisation affordance. Participants were asked to rank each affordance based on their level of perception and expectation.

4. RESULTS AND DISCUSSION

4.1 COST OPTIMISATION AFFORDANCES OF BIM IN THE SRI LANKAN CONSTRUCTION INDUSTRY

The first step involved validating the cost optimisation affordances of BIM identified in the literature review and identifying any additional affordances. Table 3 presents the cost

optimization affordances of BIM based on responses from industry experts. As indicated in the table, all affordances were acknowledged by the majority of experts. Additionally, experts identified nine (9) new cost optimisation affordances of BIM, including the ability to create multiple design scenarios, accurate quantity take-offs, improved collaboration, minimised variations and claims, automated lifecycle cost analysis, enhanced asset management, reduced visualisation time, accelerated processes, and decreased reliance on human resources.

Among the identified affordances, a few were unanimously recognised by all experts, including BIM's ability to generate accurate cost estimates, perform precise quantity take-offs, reduce visualisation time, and accelerate processes. Meanwhile, some affordances were less commonly acknowledged. These include BIM's capability to decrease reliance on human resources and utilise parametric functions and components for enhanced efficiency and automation.

4.2 ANALYSIS OF PERCEIVED AND EXPECTED AFFORDANCES OF COST OPTIMISATION USING BIM

A questionnaire survey was used to evaluate the significance of the real affordances of BIM for Cost optimisation and to identify the extent to which those affordances are expected and perceived. Table 4 provides the outcomes of the survey, starting with the most significant affordance at the top of the table. From the data obtained using the Questionnaire, cost-related and quality-oriented cost optimisation affordances of BIM emerged as the highest-ranked in terms of significance. Specifically, the ability of BIM to prepare accurate cost estimation (A2) recorded the highest RII (0.955), followed closely by the ability to assess the planned and actual status of the work (A6), accurate Quantity Take-off (A15), and minimize variation and claims (A17) all with the same RII of 0.950. These findings underscore those participants prioritise BIM's capacity to streamline budgeting, cost control, and project scope management in cost optimisation affordances.

Despite the strong significance ratings for many cost optimisation affordances of BIM, a notable portion remained largely expected rather than perceived in practice. In this survey, participants were asked to classify each affordance as either perceived (if they had experienced it) or expected (if they believed in its potential but had not yet observed it). According to the responses, even for highly significant affordances, the majority of respondents indicated they were still expected rather than perceived. This discrepancy can be due to a variety of factors, including the maturity level of BIM implementation (Martin et al., 2019), the duration of projects (Mahamadu et al., 2019), or limited training and awareness among team members. Additionally, certain affordances, such as Asset Management (A19), which gained an RII of 0.875, had a perceived rate of 0. This suggested that although it is recognised as a significant affordance, its benefit had not been encountered. This may be perceived only under specific project circumstances (for large-scale infrastructure development). Hence, while the industry values these BIM capabilities, the full realisation of many benefits may require extended exposure, proper skill-building, and organisational readiness to utilise them effectively.

Table 3: Cost optimisation affordances of BIM in SL construction industry as per interview outcomes

	Code	Affordances of BIM in Cost Optimisation	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	Total
Affordances as per Literature	A1	Utilise the parametric functions and components.	✓			✓	✓			✓			✓	✓	✓	7
	A2	Prepare accurate cost estimation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	13
	A3	Decrease repetitive work.	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓		10
	A4	Reduce paperwork.	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	10
	A5	Reduce the errors in the drawing.	✓	✓				✓	✓	✓	✓	✓			✓	8
	A6	Assess the planned and actual status of the work.	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	11
	A7	Provide effective communication	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	12
	A8	Ensure data security.	✓	✓		✓	✓	✓	✓		✓	✓		✓		9
	A9	Forecast the risk of construction.		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	12
	A10	Expect to receive a rate of investment.	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓	10
	A11	Clash Detection.	✓	✓	✓			✓		✓	✓	✓	✓		✓	9
	A12	Improve company reputation.		✓					✓	✓	✓	✓	✓	✓	✓	8
	A13	Satisfy the client.	✓	✓		✓		✓	✓		✓	✓		✓	✓	9
Additional Affordances after interviews	A14	Create multiple design scenarios	✓	✓		✓		✓	✓		✓			✓	✓	8
	A15	Accurate Quantity Take-off	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	13
	A16	Improve Collaboration	✓	✓	✓			✓		✓	✓	✓	✓		✓	9
	A17	Minimise variation and claims	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	11
	A18	Automated lifecycle cost analysis	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	11
	A19	Asset management	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	11
	A20	Reduce time for visualisation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	13
	A21	Speed up processes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	13
	A22	Decrease dependency on human resources	✓	✓				✓		✓	✓	✓			✓	7

Table 4: Perceived and Expected affordances of cost optimisation using BIM

Code	Affordances of BIM in Cost Optimisation	Significance of the affordances	Affordances	
			Expected	Perceived
A2	Prepare accurate cost estimation	0.955	68%	32%
A6	Assess the planned and actual status of the work.	0.950	55%	45%
A15	Accurate Quantity Take-off	0.950	13%	87%
A17	Minimise variation and claims	0.950	60%	40%
A5	Reduce the errors in the drawing.	0.940	40%	60%
A14	Create multiple design scenarios	0.930	68%	32%
A11	Clash Detection.	0.925	65%	35%
A13	Satisfy the client.	0.900	58%	42%
A19	Asset management	0.875	100%	0%
A9	Forecast the risk of construction.	0.865	13%	87%
A12	Improve company reputation.	0.865	0%	100%
A7	Provide effective communication between stakeholders	0.855	68%	32%
A16	Improve Collaboration	0.855	33%	67%
A18	Automated lifecycle cost analysis	0.840	48%	52%
A8	Ensure data security.	0.800	43%	57%
A20	Reduce time for visualisation	0.800	40%	60%
A21	Speed up processes	0.775	43%	57%
A10	Expect to receive a rate of investment.	0.755	65%	35%
A1	Utilise the parametric functions and components.	0.740	43%	57%
A3	Decrease repetitive work.	0.740	58%	42%
A4	Reduce paperwork.	0.690	13%	87%
A22	Decrease dependency on human resources	0.625	68%	32%

4.3 STRATEGIES TO BRIDGE THE GAP BETWEEN EXPECTED AFFORDANCES AND PERCEIVED AFFORDANCE

The expert interviews were used to identify and evaluate strategies to help stakeholders experience the cost optimisation affordances of BIM. The identified measures were quantitatively assessed through the questionnaire survey in the second phase. The outcomes have been summarised in Table 5. Analysis of the RII results revealed that comprehensive training and upskilling (S1) scored the highest RII with 0.895, highlighting that training and skill development are essential for leveraging BIM tools effectively, particularly for cost estimation and budget management. This was followed by government policies (S9) with RII of 0.885. This supports the findings of Albtoush et al. (2020), Abusafiya and Suliman (2017) and Amri and Marey-Pérez (2020) indicating

that regulatory and standards-based strategies are critical for motivating consistent, high-quality adoption of BIM across the sector. Standardising the workflows & protocols (S5) and technology integration and updates (S7) also emerged as highly effective strategies to bridge the gap between the expected and perceived affordances. These findings suggest that focusing on workforce competence, standardised processes, and supportive policies can significantly improve how stakeholders perceive and experience the cost optimisation affordance of BIM.

Table 5: Strategies to bridge the gap between expected and perceived affordances

Code	Strategies to Bridge the Gap	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	RII
S1	Comprehensive Training and Upskilling	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	0.895
S9	Strengthen Government Policies	✓	✓		✓	✓		✓	✓	✓		✓	✓	✓	0.885
S5	Standardised Workflows and Protocols	✓		✓	✓	✓	✓		✓	✓		✓	✓	✓	0.865
S7	Technology Integration and Updates	✓	✓	✓		✓		✓	✓	✓	✓		✓	✓	0.860
S8	Frequent workshops		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	0.840
S6	Management and Leadership Support	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	0.830
S3	Clear Implementation Roadmaps					✓	✓					✓	✓	✓	0.755
S4	Cross-Functional Collaboration	✓		✓							✓	✓			0.660
S2	Pilot Projects and Incremental Adoption	✓				✓	✓	✓	✓	✓					0.640

5. CONCLUSION

This study has explored the cost optimisation affordances of BIM in Sri Lankan construction projects. The findings revealed that BIM significantly contributes to preparing accurate cost estimation, improving project coordination, minimising rework, reducing errors in drawings and facilitating decision-making by creating multiple design scenarios. Moreover, the differentiation between perceived and expected affordances highlighted the potential for optimising BIM's implementation strategies to bridge existing gaps and maximise its benefits. The study also emphasises the necessity for strategic initiatives, including governmental support, industry-wide standardisation, enhanced training programs, and financial incentives, to facilitate BIM adoption. Implementing these strategies can help to overcome barriers such as insufficient technical expertise, high initial investment costs, and resistance to change within the industry.

This research contributes to the existing theory and literature by addressing a significant gap in the study of affordances within the Sri Lankan context. While numerous studies

have explored the three types of affordances, such as real, perceived and expected, there has been a lack of investigation into how these affordances are experienced in the Sri Lankan construction industry. By examining these affordances in the Sri Lankan context, this study identified the major affordances that remain in the expected stage and have yet to be actualized. This contribution is crucial for developing targeted strategies to facilitate the full realization of BIM's potential in terms of cost optimisation. However, this study has some limitations. Firstly, this study was conducted for construction projects in the Sri Lankan context, so the results can differ for other countries depending on the social and economic structure. This research was carried out for a generic view of all types of construction projects in Sri Lanka. Hence for further studies, this investigation can be repeated for specific types of construction projects.

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POST OCCUPANCY EVALUATION (POE) IN GOVERNMENT OFFICE BUILDINGS: A LITERATURE REVIEW

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ABSTRACT

The construction industry is a vital sector in the global economy, with governments acting as one of its primary clients. Despite this significance, many public office buildings have recurring issues in operation and environment, which affect satisfaction, comfort, and productivity for users. Therefore, research aims to develop a framework for the adoption of post occupancy evaluation (POE) in government office buildings. A comprehensive literature review was conducted to recognize pertinent issues with government buildings and their effect on occupants. The research evaluates POE as a tool capable of addressing such issues by providing a systematic assessment of building performance from the user's perspective. A framework is built to explain the linkages between the identified issues, impact on the user, and the intervention function of the POE. Further, the framework presents how POEs act as an intervention device that leads to many advantages, such as improving building operation, evidence-based decision-making, and additional occupant satisfaction; however, the use of a POE in the public sector is hampered by many obstacles, such as institutional inertia, lack of awareness, and resource constraints. The framework also offered strategies to clear these barriers and enhance the use of POE as a building management staple where continuous improvement is prioritized for government office environments.

Keywords: *Office Buildings; Post Occupancy Evaluation; User Satisfaction.*

1. INTRODUCTION

Construction, as a key branch of the economy, remains a significant contributor to the overall Gross Domestic Product, with rates varying from 5% to 10% for several countries (United Nations, 2024, as cited in Lopes & Banaitienė, 2024). Accordingly, Cooray et al. (2018) emphasized that the government is one of the primary clients for construction projects, particularly in areas such as infrastructure development, public facilities, and housing. Despite the construction industry being a major driver for economic development, frequent construction project failures are a potent issue noted in the global context (El-sokhn & Othman, 2014). Construction project failures extend beyond building collapse, further including the failure to achieve intended quality requirements (Shahhossein et al., 2017). Particularly, the government buildings are confronted with

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several failures relating to inadequate interior design, suboptimal facility management, and deficient maintenance (Awasho & Alemu, 2023; Dissanayake et al., 2020). These issues are worsened by the lack of standardization, weak management support, and the absence of quality management systems (Ali et al., 2016; Rahaman et al., 2025). This has led to Sick Building Syndrome (SBS) which has been identified as a common concern in office buildings (Wijerathne et al., 2012).

According to Akinshipe et al. (2022), building defects possess a direct impact on the psychological attitudes of the occupants within an establishment. Workplace productivity is directly proportional to the well-being of employees, and where the psychological well-being has improved by a significant amount, business productivity has been seen to improve by about 10% on average (Krekel et al., 2019). Thus, the investments in improving the building quality requirement will, in return enhance the workplace productivity (van der Voordt & Jensen, 2021). Thus, when a structure does not fulfil specific criteria of user satisfaction, it is classified as unsatisfactory and requires some form of intervention, whether it be maintenance or an upgrade, to restore comfort and convenience to the users (Mughairi et al., 2023).

User satisfaction in buildings is the degree to which a space meets the physical and psychological requirements of users, enabling comfort, functionality and safety in daily operations (Aksoy & Uzunoglu, 2020). Assessment of user satisfaction plays an important role in monitoring building performance as well. The feedback provided by the end users of a building is a crucial source of information on occupant satisfaction, which enables the technical and structural functions to be tailored to the well-being of end users (Croome, 2013 as cited in Lolli et al., 2022). The construction industry benefits from multiple feedback mechanisms such as construction company feedback forms, CRM software, BIM software and inspection and reporting software (Cusumano et al., 2024; Ford & Gosling, 2024; Lin et al., 2016; Venturini & Benito, 2015). Among these mechanisms, post occupancy evaluation (POE) stands out to be a prominent feedback technique with the ability to gather effective and comprehensive feedback from end users (Hadjri & Crozier, 2009).

W. Preiser (2001) defined post-occupancy evaluation (POE) as “the process of evaluating buildings in a systematic and rigorous manner after they have been built and occupied for some time.” The importance of conducting a complete post occupancy evaluation has emerged out of necessity due to the increasing efforts put in the construction industry towards establishing efficient and sustainable building practices (Nugradi, 2022). In the global context, POE has gained significant awareness as an assessment tool for building performance, thus, the recent research were focused on different aspects of POE, including its application in several areas (Ukpong & Ackley, 2019). With regard to the several building types, frameworks have been developed through the application of POE in housing and apartment building projects (Ozoh et al., 2022; Tannor et al., 2023), in high-rise hotel building projects (Anunobi & Zubairu, 2015) and in office building projects (Choi et al., 2012; Hamid & Othman, 2014; Hamida & Hassanain, 2020; Kim et al., 2022) including green building projects (Kim & Kim, 2020) to enhance the building performance.

However, existing literature reveals a noticeable gap in research concerning government office buildings. A study examining POE research from 2010 to 2017 found that residential buildings were the most frequently studied, followed by office buildings,

educational institutions, and university buildings (Li et al., 2018). Hence, pertaining to government office buildings, an evident lack of research can be observed in the global Context. Therefore, a proper analysis of the current condition of the government office buildings has not yet been carried out in terms of post occupancy evaluation to identify the potential issues that are faced by the occupants and the users of the building. The lack of a proper analysis has resulted in the continuity of these mistakes and issues in future government office buildings.

To address this gap, the present research aims to develop a comprehensive framework that promotes the adoption of POE in government office buildings. Four key objectives are developed to achieve the aim: identifying the unique benefits of post occupancy evaluation to government office buildings, identifying the barriers to post occupancy implementation, identifying suitable strategies to adopt POE, and developing a framework for adoption of post occupancy evaluation in government office buildings in government office buildings. Hereinafter, the paper comprises a methodology, findings, conclusions and recommendations.

2. RESEARCH METHODOLOGY

Research methodology is referred to as the scientific technique employed in the pursuit of conducting research (Croom, 2010; Patel & Patel, 2019). In this research, the methodology is formulated by first establishing a solid foundation through a comprehensive background study. Afterwards, a rigorous literature review is conducted, and the collected literature is analysed to address the identified literature gap. A literature review has several purposes, one of which is to show the researcher's understanding of the discipline, including its concepts, vocabulary, theories, critical variables and phenomena, methods of study, and its history (Qutoshi, 2013). The process involves more than summarizing existing literature, as it necessitates a comprehensive understanding of the topic and its importance (Sajeevanie, 2021). Hence, the research methodology adopted in this research is illustrated in Figure 1.

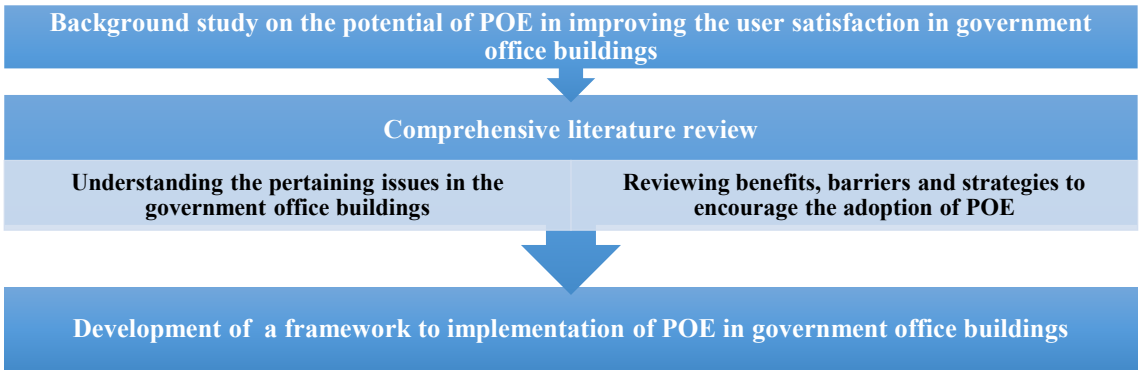


Figure 1: Research methodology

As depicted in Figure 1, an extensive background study was conducted to assess the potential of POE in improving the user satisfaction in government office buildings. The background study revealed the important role POE plays in the construction industry in improving user satisfaction despite its minimal use. A comprehensive literature review was then followed, examining several sources, such as books, reports, theses, journals, magazines, and conference proceedings. The goal was to identify the problems

encountered in the government office buildings, define POE, identify benefits and barriers in implementation of POE and identify strategies to encourage the adoption of POE. To enable a cohesive analysis, search terms such as 'Post Occupancy Evaluation', 'Government Office Buildings' and 'User Satisfaction' were filtered using the search engines 'Google Scholar', 'Science Direct' and 'Emerald Insight'. Then the collected data was analysed using content analysis as it allows the researchers to examine large volumes of data organize them into structured formats to draw conclusions (Zavyalova, 2010). Subsequently, a framework was developed incorporating the findings from the literature review, since it serves as a foundation for advancing knowledge and guiding the research process (Guntur, 2019).

3. RESULTS AND FINDINGS

3.1 PROBLEMS IN GOVERNMENT OFFICE BUILDINGS

Public buildings are vital to a healthy and vibrant society, contributing to the economic and social wellbeing of communities, with a renewed emphasis on their importance recognized by government policies and actions (Ziegelbauer et al., 2005). However, these buildings encounter a multitude of challenges, with maintenance and management issues being a key challenge (Leaman & Bordass, 1999). According to Ali et al. (2016), these maintenance issues include unclear plans, unsystematic approaches, and concerns with human resources and technical aspects, which affect service performance and user productivity. Moreover, as reported by Kim (2022), there are security concerns involved with the government office buildings ranging from inadequate crime prevention designs to need for improved sound insulation to mitigate noise impacts.

Apart from these issues, the SBS has emerged to become a more potent challenge in the government buildings (Adiningsih & Hairuddin, 2021; Thirumalaikolundusubramanian et al., 1991; Wijerathne et al., 2012). In the view of Rostron (2008), the SBS is becoming more prevalent in public buildings, presenting a significant obstacle to the overall efficiency and health of employees. The profound damages experienced in government buildings are often attributed to lack of proper maintenance, as these buildings serve as the focal point of administrative and bureaucratic activities (Wijaya et al., 2020).

3.2 IMPACT OF OFFICE BUILDING ISSUES ON USER SATISFACTION

These building issues within the office buildings significantly affect the user satisfaction of the occupants by diminishing the occupant comfort and minimizing the workplace productivity (Altomonte et al., 2020). User satisfaction with government office buildings stems from environmental, personal, and design elements. Frontczak and Wargocki (2011) emphasize that satisfaction and overall building performance is shaped by the building's thermal comfort, visual and acoustic comfort, indoor air quality, user factor, architecture, and externally, weather conditions. Moreover, accessibility is crucial, especially in public office contexts (Norazman et al., 2023). Out of these factors, thermal comfort is of great importance in offices and significantly influences satisfaction (Park et al., 2018). Other contributory factors are air temperature, size of thermal zone, windows, temperature regulation, radiant temperature asymmetry, cleanliness, and heating, which shape user perceptions of comfort and performance (Artan et al., 2022; Bengi & Topraklı, 2020; Pestana et al., 2021). Also, spatial comfort, privacy, ergonomics, office lighting, and building aesthetics are essential design and functionalities that influence user

experience, as highlighted by W. Preiser (2002). These parameters ensure the comfort, performance and health of the occupants are not compromised (Haroon et al., 2024).

3.3 POST-OCCUPANCY EVALUATION: CONCEPT

The negative impacts experienced by building users underscore the need to address these identified issues, ensuring maximum user satisfaction and workplace productivity for employees. Traditionally, responding to these issues has been conducted in a reactive way, which only repairs when problems arise, thereby increasing costs and causing operational disruptions (Breesam & Jawad, 2021). In fact, it could bring about escalated expenditure in cases where minor issues have been allowed to grow into major problems (Suffian, 2013). According to Breesam and Jawad (2021) proactive maintenance strategies which focus on preventing building issues before they occur serve as a solution for the underlying issues as it involves periodic inspections, predictive analytics, and programmed system replacements. These strategies will prolong the lifespan of building components and enable the uninterrupted availability of the necessary services (Horner et al., 1997). It allows building managers to not only prioritize repairs but also address concerns through active feedback from the end-user, thereby maintaining the building in conformity with the occupants' needs (Breesam & Jawad, 2021). In the opinion of Aliyu et al. (2016), a proper facility assessment should involve all types of occupants irrespective of their knowledge, role in the building, and mother tongue. Typically, assessment systems are primarily used in the design phase, while there is a requirement for certification in the operation phase (Li et al., 2018). Further, Li et al. (2018) reported that only a few ratings systems address the aspects of measurement of actual performance.

POE can be suggested as an appropriate technique since it is an examination of the degree to which occupied design environments meet client satisfaction and functional needs, with criteria on which testing of occupancy performance is usually based on the fulfilment of the functional programme of occupants' requirements (Zimmerman & Martin, 2001). Post occupancy evaluation originated from the UK where the British Ministry of Education in conjunction with local governments first undertook evaluations of buildings in the post-World War II period (Preiser et al., 1988 as cited in Aliyu et al., 2016). Ukpong and Ackley (2019) described indicative POEs as the short assessments that include walkthroughs, document reviews and interviews to explore key strengths and weaknesses while investigative POEs perform more comprehensive interviews and often surveys buildings which are the same to discover deeper understandings. Further, the researchers stated that diagnostic POE is the most in-depth and includes research which may be months or even years long, including technical factors and human behaviour, on a systemic level.

Several governments across the globe have adopted POE as a tool for evaluating the performance of public buildings (Albuainain et al., 2021; Daish et al., 1983; Khalil & Nawawi, 2008; Olagunju et al., 2013). A study in Malaysia has also pinpointed the significance of POE in the sustainability of government buildings in terms of functionality, pointing to evaluation after occupancy as a way of catering for continually recurring maintenance and performance concerns (Nawawi & Khalil, 2008). Similarly, in Nigeria, the POE has also helped in the identification of major maintenance problems, including plumbing failures and roof leakage which has been compounded by inadequate funding (Olagunju et al., 2013) whereas in New Zealand, the government has adopted a formal POE program to evaluate the efficiency of government buildings as well as the

procedure followed in the management process (Daish et al., 1983). Moreover, the new studies in Bahrain are concerned with the evaluation of occupant satisfaction with IEQ in government buildings, exploring the possible relationship between occupants' demographic characteristics, building characteristics and occupant satisfaction levels (Albuainain et al., 2021). Likewise, the United Kingdom and Brazil have put into practice the POE in relation to public buildings to improve the performance of the construction industry, mainly with regards to maintenance and efficiency (Woon et al., 2015). Altogether, these examples show that the use of POE as a planning tool is typical for the modern world and helps governments to achieve the goal of providing the population with comfortable working conditions and, at the same time, maintaining the quality of public services provided in buildings.

Nevertheless, below study depicted in Figure 2, conducted by Li et al. (2018) revealed that among the examined building types with regards to POE from 2010 to 2017, the government buildings are the lowest examined type compared to other building types. Expanding on these results, a detailed review of papers from 2006 to 2022 also provides evidence that the most discussed types of buildings were office, commercial, and public buildings, with a combined percentage of 31% (Lolli et al., 2022), which depicts a slight improvement towards studies of POE in government buildings, yet still inadequate.

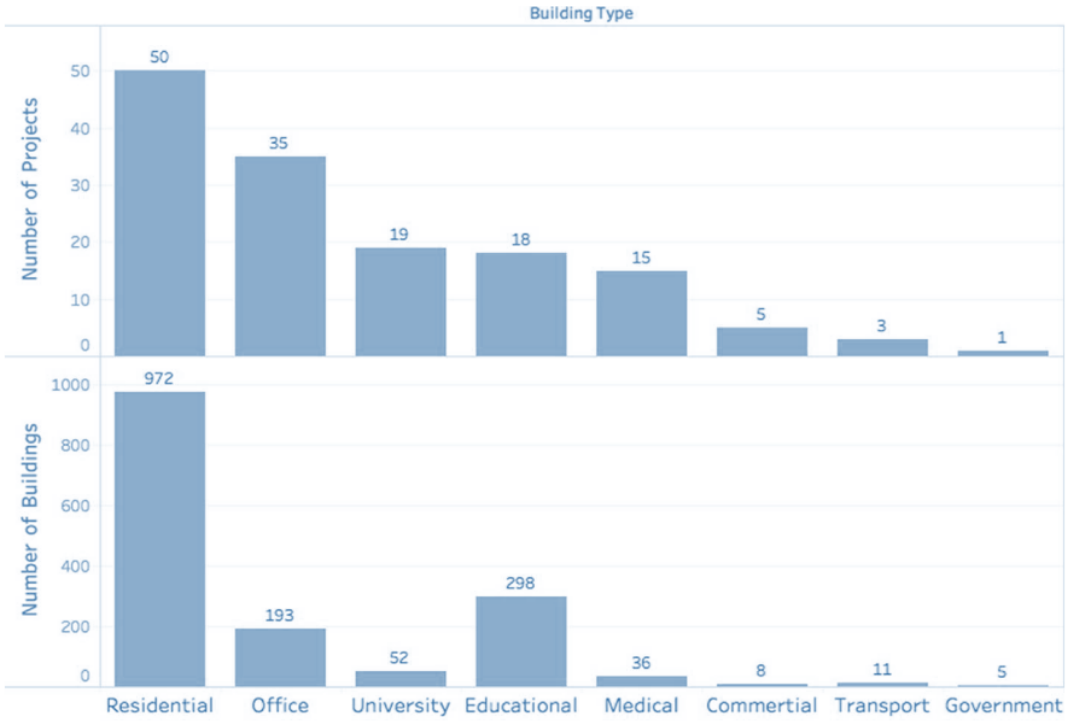


Figure 2: Number of projects and number of buildings per type of building from 2010 to 2017

3.4 BENEFITS OF POE

Post occupancy evaluation is a multifaceted tool that can significantly improve building performance and provide valuable insights for future design (W. F. E. Preiser, 1995). Table 1 discusses the different types of benefits served by POE.

Table 1: Benefits of POE

Item No.	Benefit	Source
1	Provides valuable data to support ongoing improvement and behavioural adjustments in building performance.	[1], [2], [3], [4], [6], [7], [8]
2	Identifies emerging needs or functions to enhance future project design.	[1], [3], [6]
3	Assists in making informed pre-design decisions for new projects, minimizing repeated design errors.	[1], [3], [6], [10]
4	Helps in identifying specific owner/developer requirements, aiding effective space utilization and performance measurement.	[1], [3], [8]
5	Assists developing performance measures for built space	[2], [3], [4], [5], [6]
6	Improves the fit and building performance throughout the life cycle	[1], [3], [4], [5], [6], [7]
7	Acts as a feedback mechanism to design	[1], [3], [4], [5], [6], [8], [10]
8	Reduces long-term owning and operating costs	[1], [4], [6], [7], [8], [10]
9	Uses comparisons with best practices to improve competitive edge, especially in commercial property	[1], [7]
10	Facilitates the replacement or redesign of dysfunctional or rarely used building features, encouraging innovation.	[1], [3], [4], [6], [7], [8], [9], [10]

[1] (Zimmerman & Martin, 2001), [2] (Hadjri & Crozier, 2009), [3] (W. Preiser, 2002), [4] (Bengi & Topraklı, 2020), [5] (Li et al., 2018), [6] (Aliyu et al., 2016), [7] (Eke et al., 2013), [8] (Darkwa et al., 2006), [9] (Forbes, 2002), [10] (Roberts & Edwards, 2022)

As per Table 1, POE provides a variety of benefits, and it can be observed that design improvements are the most potent advantage. Apart from those, POE acts as a learning tool and a source of information on building performance, which in turn benefits the stakeholders involved in the process and the organisations.

3.5 BARRIERS FOR THE IMPLEMENTATION OF POE

Even though POE provides invaluable insights into the building performance, there are several challenges in implementing POE in buildings, and Table 2 presents these challenges according to the conducted studies.

Table 2: Barriers of POE

Item No	Barrier	Source
1	Lack of standard practice as the facility delivery process does not recognize the concept of continual improvement.	[1], [3], [4], [5]
2	Designers are seldom compensated for reviewing the outcomes of their design, discouraging POE involvement.	[1], [3], [4]
3	Lack of investment in Research and Development	[1], [5]
4	Lack of awareness and training is not taught as a part of traditional design education.	[1], [2], [4], [6]
5	Sheer number of stakeholders involved with a conflict of interest.	[1], [2]
6	Lack of funding	[1], [2], [3], [4], [5], [6]
7	Lack of timing	[1], [2], [3], [4], [5], [6]
8	Lack of indicators and accompanying benchmarks	[1], [3]
9	Institutionalized pressure in the industry to continue with standard practice and not to innovate	[1], [6]
10	Owners, especially those with fully leased buildings, may hesitate to initiate POEs that might reveal performance issues.	[1], [3], [4]

[1] (Zimmerman & Martin, 2001), [2] (Hadjri & Crozier, 2009), [3] (Li et al., 2018), [4] (Aliyu et al., 2016), [5] (Darkwa et al., 2006), [6] (Roberts & Edwards, 2022)

As identified by Table 2, lack of funding and lack of timing accounted for limited implementation POE. In addition, false conceptions and lack of awareness within the stakeholders of the industry are another major factor which limits the adoption of POE buildings.

3.6 STRATEGIES TO ENCOURAGE THE ADOPTION OF POE

To promote the wider acceptance of POE and overcome the barriers of implementation, several strategies can be utilised, ranging from focusing on communicating its benefits, streamlining the process, and integrating it into standard practice (Zimmerman & Martin, 2001). Zhao et al. (2024) emphasized that the key strategy for encouraging the adoption of POE is demonstrating its tangible benefits, which include showcasing empirical evidence and case studies that clearly communicate successful outcomes. They further elaborated this stating that presenting specific metrics data rather than vague claims could motivate the stakeholders to adopt it practically. As identified by Ahmed et al. (2021), stimulating POE adoption through policies and regulation implementation is another strategy. In addition, Bughio et al. (2020) reinforced this opinion, stating that governments are able to promote the adoption of POE by mandating its implementation in public buildings and providing financial incentives to the private sector initiatives. Moreover, developing comprehensive and standardized POE toolkits or frameworks to evaluate the current condition of the buildings is another strategy that will improve POE adoption and also facilitate knowledge dissemination between the stakeholders while addressing the knowledge and awareness gap on POE (Joseph et al., 2014).

3.7 FRAMEWORK

Government office buildings require a specialized framework to cater for the adoption of POE owing to their peculiar challenges of insufficient funds and very limited awareness, while the existing frameworks display their own pitfalls including uncertainty of performance assessment and implementing assessment findings (Dam-Krogh et al., 2024; Jayoda et al., 2024). Figure 3 demonstrates the framework developed using the findings of the study to encourage the adoption of POE in government office buildings.

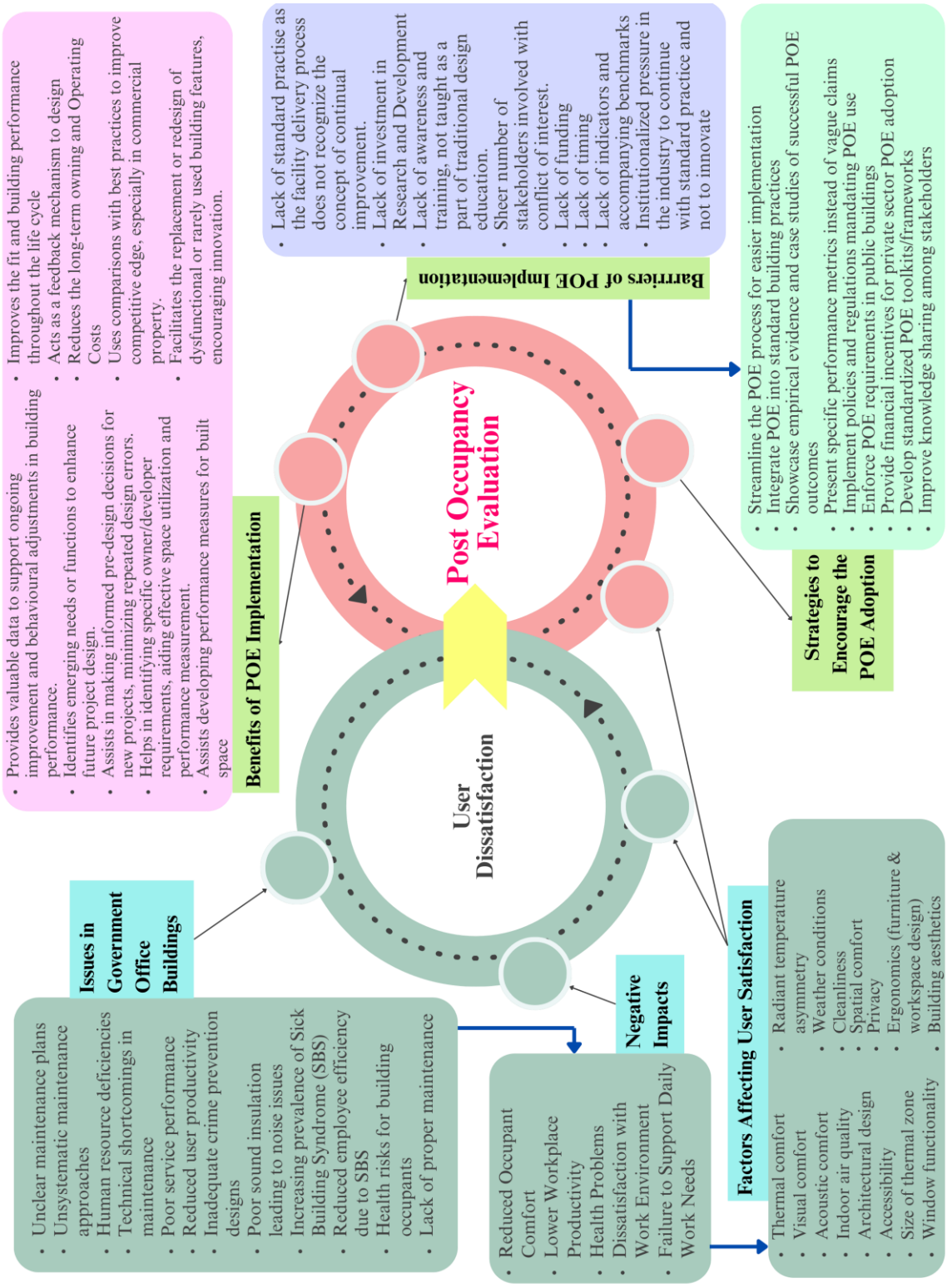


Figure 3: Framework for the adoption of POE in government office buildings

4. CONCLUSIONS AND RECOMMENDATIONS

This study has exposed the inherent problems that have been passed down to government office buildings. These entail issues such as poor maintenance, substandard user comfort, and operational inefficiencies. Mostly, these problems arise due to the absence of systematic feedback mechanisms after a building has been occupied. POE can address these challenges by structuring a building performance assessment from the perspective of its users. Despite POE's merits, including increasing user satisfaction, feeding into the design of future buildings, and enhancing performance over an actual life cycle, the practice is still seldom applied because of building managers being unaware of it, the absence of standard procedures, and scarce resources.

Therefore, the study developed a framework to demonstrate the potential adoption of POE in government office buildings. Important recommendations include integrating POE into policies and procurement standards, setting up standards for the toolkits, providing a budget for POE in the building lifecycle, and enhancing stakeholder awareness of POE through training. By deploying these interventions, public sector agencies can take steps in transforming into a more proactive versus reactive, user-driven, and performance-targeted approach.

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POTENTIAL USE OF PLASTIC WASTE AS A SUSTAINABLE CONSTRUCTION MATERIAL IN SRI LANKA

S. Geerthanan[1] and S. Sivanraj[2]

ABSTRACT

Global demand for sustainable development places a tremendous force on the construction industry to promote sustainable construction. In Sri Lanka, while there is a gradual shift towards sustainable construction, the number of projects implementing such practices remains limited, highlighting a significant gap in the industry's contribution to sustainability goals. Currently, around 90% of construction materials are obtained from natural resources, raising concerns about long-term environmental impact and resource depletion. Simultaneously, the country faces the growing issue of plastic pollution, driven by the extensive use and non-biodegradable nature of plastics. Addressing both challenges, the integration of recycled plastic waste into construction materials presents a promising and sustainable alternative. Recycled plastics can be utilised in various applications such as concrete mixtures, paving blocks, roofing sheets, interior partitions, and prefabricated components. This research explores the barriers and benefits of using plastic waste as a sustainable construction material through a quantitative approach using questionnaires, aiming to support environmental preservation and resource efficiency in Sri Lanka's construction sector.

Keywords: *Construction; Plastic; Recycle; Sri Lanka; Sustainability.*

1. INTRODUCTION

Plastic production and use began in 1950, with unmanaged plastic garbage reaching 851,493 tons worldwide by 2010 (Geyer et al., 2017). The production of plastic worldwide is increasing at an exponential rate, with waste generation expected to rise by 70% by 2050. Plastic waste is inextricably linked to key social processes such as urbanisation, development, urban planning, land management, greenhouse gas emissions, labour, social equity, public health, rural-to-urban migration, population growth, increased consumption, and climate change (Conlon, 2021). The exponential growth in plastic manufacturing and the resulting spike in plastic trash have prompted researchers and scientists to seek new and sustainable ways to reuse/recycle plastic garbage to lessen its negative impact on the environment (Lamba et al., 2022).

The construction sector is a major global consumer of both biological and physical natural resources, contributing considerably to the global economy's unsustainable growth and drawing criticism for wasteful resource usage (Muhammed et al., 2023).

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According to World Bank studies, municipal solid waste management is one of the most important services that a city can provide. This is true regardless of a country's economic situation, since it is equally important in low- and high-income metropolitan areas. Effective waste management is seen as a critical component in ensuring public health, environmental sustainability, and overall urban livability (Hoornweg & Bhada-Tata, 2012). The bulk of plastics are discarded after a single use (Suaryana et al., 2018). Most countries in the Global South often face significant challenges in handling plastic waste after it has been discarded, primarily due to limited infrastructure, insufficient financial resources, and a lack of effective waste management systems. As a result, much of the plastic ends up in open dumps, waterways, or the environment, leading to serious environmental and public health issues (Hoornweg & Bhada-Tata, 2012).

Sri Lanka has become a major hotspot for the buildup of floating plastic trash in the Indian Ocean as a result of poor plastic waste management methods and a heavily populated coastal region. The country is presently rated fifth out of the top eleven countries with the greatest amounts of mismanaged plastic trash, demonstrating the gravity of the problem and its contribution to marine pollution (Jambeck et al., 2015). The issues associated with plastic waste management have mainly gone unresolved in nations such as Sri Lanka due to a lack of trustworthy technical data required for informed decision-making and efficient planning. Understanding existing waste management systems is critical for developing countries, particularly in circumstances where environmental restrictions are generally less rigorous. Implementing scientifically based policy solutions can have a transformative impact by boosting environmental protection, increasing economic resilience, and encouraging resource efficiency (Millette et al., 2019).

Developing countries, such as Sri Lanka, confront challenges with inappropriate building materials and complex supply networks, leading to increased environmental impact (Bon & Crosthwaite, 2001). To address these critical issues, this research project will investigate the possible use of plastic trash as a sustainable construction material in Sri Lanka. The project aims to contribute to efficient waste management solutions by investigating novel ways to recycle wasted plastics in the construction industry, while also encouraging environmentally friendly building practices and increasing sustainability in the local construction sector.

2. LITERATURE REVIEW

2.1 CONSTRUCTION INDUSTRY IN SRI LANKA

The construction sector is a crucial driver of a country's economic development. Productivity is a critical component in determining its influence. Increasing productivity in the construction sector not only improves the efficiency and performance of construction operations but it also contributes significantly to a country's GDP. As a result, increasing productivity in this sector is usually seen as a critical step toward overall economic development (Durdyev et al., 2013). Sri Lanka has experienced a rise in construction activity in the postwar period, owing to increased interest and significant expenditures in large-scale capital development projects from both the government and the private sector. Research show that the construction subsector has grown significantly throughout this time period (Lamba et al., 2022). While this fast expansion offers various benefits, such as job creation, infrastructure development, and economic stimulus, it also

poses considerable obstacles, such as resource restrictions, environmental concerns, and the need for better planning and regulation (Manoharan et al., 2023).

2.2 SUSTAINABLE DEVELOPMENT IN THE SRI LANKAN CONSTRUCTION INDUSTRY

As Sri Lanka faces demographic and epidemiological transitions, as well as severe budgetary restrictions, policymakers must assess the successes and challenges of achieving universal health coverage (UHC) and the Sustainable Development Goal (SDG) for health (De Silva et al., 2016). Sustainable building aims to achieve long-term development by considering environmental, social, economic, and cultural factors. It has become a focal point for nations. Population growth and economic expansion are putting significant strain on the world's resources (Ametepey et al., 2015). Sustainable construction responds effectively to current environmental and socioeconomic challenges by incorporating sustainable development principles into the entire construction cycle, from raw material extraction to planning, design, construction, deconstruction, and waste management, while focusing on minimising environmental and social impacts (Athapaththu & Karunasena, 2018). Waste plastic is being recognised as a useful resource in a variety of industries, including construction materials, fuel conversion, and the creation of home items, textiles, and apparel. Among these possibilities, using plastic waste to generate construction materials has received a lot of interest. This is mostly due to its capacity to solve both environmental issues and material shortages, providing a sustainable alternative that upholds circular economy principles while improving the performance and longevity of construction goods (Lamba et al., 2022).

2.3 WASTE MANAGEMENT IN SRI LANKA

Municipal Solid Waste Management (MSWM) is a major global challenge, especially for the quality and sustainability of urban ecosystems. It has far-reaching consequences for environmental health, public well-being, and socioeconomic development (Subasinghe, 2024). Municipal solid waste is often classified into numerous unique components based on its origin and type, as demonstrated in Figure 1, which depicts the major solid waste categories.

Due to the rapid urbanisation and population, limited infrastructure has resulted in significant waste management challenges (Dharmasiri, 2019). The key issues include inadequate waste segregation, insufficient collection and disposal mechanisms and lack of awareness regarding the impacts of this waste (Saja et al., 2021). In Sri Lanka, most of the waste is managed by disposing it into open areas and landfills and burning it (Kumara & Pallegedara, 2020). There have been efforts made by government programs and international collaborations to improve waste management within Sri Lanka. However, the implementations of these have been impacted by resource constraints and a lack of political support.

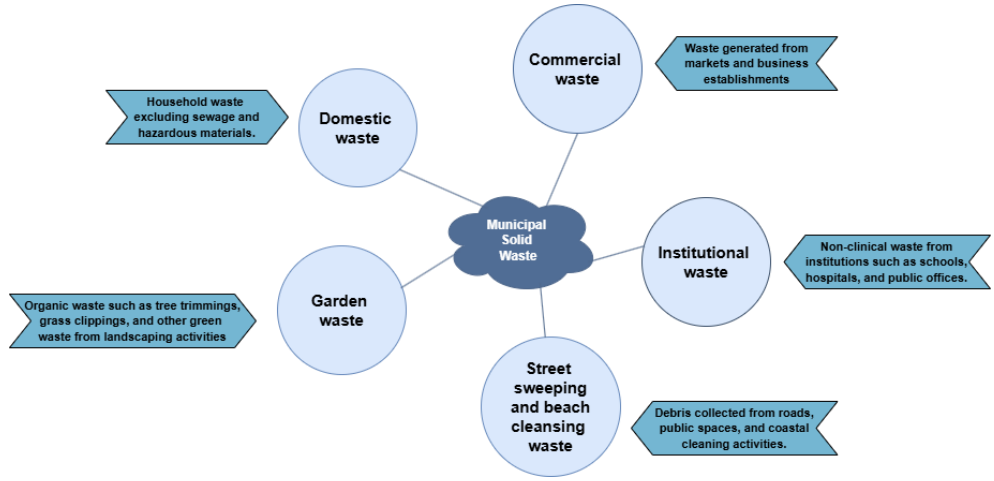


Figure 1: Major municipal solid waste

2.4 PLASTIC WASTE IN SRI LANKA

Wealthy nations often have modern and efficient waste management systems in place to ensure proper waste collection, recycling, and disposal. In sharp contrast, many low- and middle-income nations face inadequate waste management infrastructure, resulting in widespread inappropriate trash disposal. In some of these countries, 80 to 90 percent of plastic garbage is not properly handled, greatly contributing to environmental contamination and posing serious hazards to rivers, seas, and marine ecosystems. Plastic waste in the seas harms the environment, economy, and aesthetics (Jambeck et al., 2018).

Sri Lanka now has approximately 400 plastic processing enterprises, with a total investment of Rs. 15 billion in reprocessing across the nation (Samarasinghe et al., 2021). According to the Manoharan et al. (2023) report, In Sri Lanka, the plastic material flow is divided into many important stages. It starts with the plastic product manufacturing business, which employs virgin and recycled plastic pellets to make items, some of which are exported and the remainder consumed locally (Jambeck et al., 2015). These goods are subsequently distributed to intermediate users, who use them to manufacture end-use items, and eventually to end consumers, who consume both locally manufactured and imported plastic products. After usage, plastic garbage is collected and sent to recycling facilities, landfills, or exported. Some of this trash is used in cement factories as an alternative fuel, while others are recycled into plastic pellets (Hama & Hilal, 2017). Another technique is to convert plastic to oil using technologies such as pyrolysis. However, a large quantity of plastic garbage gets disposed of in landfills, and some ends up in the open environment, either dumped or burned, with some ultimately making its way into the ocean.

The construction sector creates a substantial amount of solid waste; therefore, there is a growing emphasis on proper construction and demolition waste management (Banihashemi et al., 2018). Construction and destruction waste types include ceramics, cement, conduit, blocks, floor finishes, lumber, tar and bituminous items, glass, hazardous components, plastic, asphalt, metals, soil, dredged soil, building and demolition debris, insulation and gypsum-based materials (Ghosh et al., 2016).

2.5 USE OF PLASTIC WASTE IN THE CONSTRUCTION INDUSTRY

Polyethene Terephthalate (PET), High-Density Polyethene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethene (LDPE), Polypropylene (PP), and Polystyrene (PS) are the five most frequent plastic waste components found in municipal solid waste. Each of these plastic varieties has a different chemical structure, use, and amount of recyclability. They are commonly used in construction applications because of their durability and availability in huge quantities as waste (Ismail & AL-Hashmi, 2008). Studies show that adding plastic waste in small proportions (typically 10–20%) can improve certain properties like ductility, water resistance, and insulation, though excessive amounts may compromise strength and durability (Athithan & Natarajan, 2023; Lamba et al., 2022). Plastics are also valued for their lightweight, chemical resistance, and low cost, making them suitable for insulation, waterproofing, and other specialised building applications (Cui, 2025).

Plastics have been successfully used in a wide range of construction materials, including concrete, mortar, building plaster, blocks, pavement surfaces, base and subbase layers of pavements, and Hot Mix Asphalt. Integrating plastic waste into these applications not only enhances particular mechanical features (such as durability, flexibility, and wear resistance) but also provides a sustainable manner of plastic waste disposal (Rahat et al., 2022). Table 1 presents the construction applications, associated barriers, and potential benefits of utilising plastic waste in the construction sector.

3. RESEARCH METHODOLOGY

This study, using a quantitative questionnaire survey, investigated the problems associated with the prospective inclusion of plastic trash as a construction material in the Sri Lankan construction sector. This commonly used technique of study provides important insights into people's attitudes, opinions, and preferences. It is especially useful for measuring the incidence of specific behaviours or occurrences and spotting developing patterns or trends (Borrego et al., 2009). This research study enrolled 42 participants and used 5-point Likert scales to assess the applications, associated barriers, and potential benefits of utilising plastic waste in the Sri Lanka Construction Sector. To evaluate the data, the Relative Importance Index (RII) approach was used, which computes the relative significance of each element based on weighted replies. The RII readings were then classified into four significance categories (High, High-Medium, Medium, and Low) based on prescribed ranges. Data was interpreted using RII, and the results were visually portrayed with charts and diagrams. The following equation (Equation 1) is used to determine the RII:

$$RII = \frac{\sum w}{A\ x\ N} \qquad Equation\ (1)$$

Where:

- ∑w = Sum of the weights assigned to each factor by the respondents
- A = Highest possible weight (e.g., 4 or 5 depending on the scale used)
- N = Total number of respondents

Table 1: Summary of construction applications, associated barriers, and potential benefits of utilising plastic waste in the construction sector

Material	Construction Application							Barrier						Benefit			Source
	Concrete	Pavements	Plaster	Block	Mortar	Asphalt	Hot mix asphalt	Functionality	Collection	Recycling	Separation	Processing	Performance	Improve performance	Environment quality	Reduce cost	
PET	√		√	√		√		●	●	●	●	●		x	x	x	(Abu Abdo & Khater, 2018; Batayneh et al., 2007; Hama & Hilal, 2017; Ismail & AL-Hashmi, 2008; Khalid et al., 2018; Salim et al., 2019)
HDPE		√				√	√	●				●		x	x	x	(Angelone et al., 2016; Arabani & Pedram, 2016; Gibreil & Feng, 2017)
LDPE				√		√	√	●				●		x	x	x	(Angelone et al., 2016; Kumi-Larbi et al., 2018; Suaryana et al., 2018)
PP						√	√	●				●		x	x	x	(Angelone et al., 2016; Wang et al., 2022)
PVC	√				√			●		●		●		x	x	x	(Aciu et al., 2018; Puri et al., 2013)
PS	√	√	√					●				●	●	x	x	x	(Hama & Hilal, 2017; Ismail & AL-Hashmi, 2008; Salim et al., 2019)

4. RESEARCH FINDINGS AND ANALYSIS

This study's data was mostly acquired via a structured questionnaire survey, which included closed-ended questions meant to generate measurable replies. These questions used a five-point Likert scale, which allowed participants to express varied levels of agreement or significance in a consistent style. The collected replies were systematically examined using the RII approach, which allowed for the prioritising and comparison of crucial elements based on the respondents' collective judgments. This analytical method allowed for a clear interpretation of the data, facilitating relevant discoveries and conversations within the study environment.

The questionnaire was distributed to 42 professionals, including civil engineers, lecturers, quantity surveyors, construction managers, project managers, structural engineers, quality assurance managers, architects, and materials engineers, to gain diverse perspectives on the applications, challenges, and potential benefits of using plastic waste in Sri Lanka's construction industry. Among the chosen respondents, 92% were aware of the usage of plastic waste in building applications, and 55% had directly engaged in a project that included plastic waste in construction.

4.1 SUITABILITY OF DIFFERENT TYPES OF PLASTIC WASTE FOR SUSTAINABLE CONSTRUCTION PRACTICES

According to the responses of 42 participants, the majority of construction experts believe various forms of plastic waste are viable for construction uses. Figure 2 presents the details of the respondents.

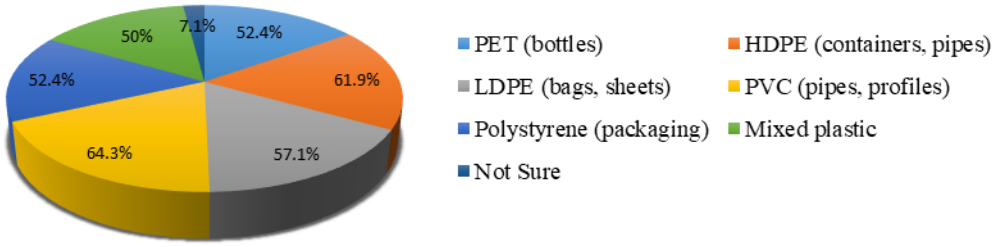


Figure 2: The suitability of different types of plastic waste for sustainable construction practices

PVC (pipes and profiles) was the most popular material, chosen by 64.3% of respondents, followed by HDPE (containers and pipes) at 61.9% and LDPE (bags and sheets) at 57.1%. PET (bottles) and polystyrene (packing) were both recognised by 52.4% of respondents, whereas 50% felt mixed plastic could be used successfully in building. Only a small portion, 7.1%, indicated they were unsure about which types of plastic waste are suitable. These findings demonstrate a high level of awareness and acceptance among experts about the possibilities of various plastic waste in building procedures.

4.2 CONSTRUCTION APPLICATIONS OF INCORPORATING PLASTIC WASTE

Table 2 gives the RII and accompanying rankings for various construction applications that use plastic waste.

Table 2: Construction applications of plastic waste

Construction Applications	RII	Rank
Plastic-infused bricks/ blocks	0.705	3
Asphalt roads with plastic	0.681	6
Plastic fibre-reinforced concrete	0.719	2
Wall panels and formwork	0.695	4
Insulation materials	0.690	5
Furniture and fittings	0.757	1
Roofing tiles	0.671	7

According to the findings, furniture and fittings scored the highest with an RII of 0.757, suggesting that it is the most appropriate application. This is followed by plastic fibre-reinforced concrete (RII = 0.719) and plastic-infused bricks/blocks (RII = 0.705), which rank second and third, respectively. Wall panels, formwork, and insulation materials had intermediate rankings, with RIIs of 0.695 and 0.690. Meanwhile, asphalt roads with plastic and roofing tiles were deemed the least acceptable uses, with RIIs of 0.681 and 0.671, placing sixth and seventh, respectively. These rankings indicate the professional preference for using plastic waste mostly in non-structural or secondary building components.

4.3 KEY BARRIERS TO USING PLASTIC WASTE IN CONSTRUCTION

Table 3 highlights the main barriers to employing plastic trash in building based on their relative importance (RII).

Table 3: Key barriers to using plastic waste in construction

Key Barriers	RII	Rank
Lack of standards and regulations	0.686	11
Concerns about structural strength	0.695	7
Long-term durability issues	0.724	1
Lack of awareness or expertise	0.719	2
High processing costs	0.705	4
Environmental concerns about microplastics	0.710	3
Difficulty in sourcing and sorting plastic waste	0.681	12
Resistance from clients or stakeholders	0.690	8
Lack of technical knowledge	0.690	8
Cost and availability of technology	0.705	4
Absence of regulatory support	0.690	8
Negative perception of plastic materials	0.705	4

The most important hurdle is long-term durability (RII 0.724, Rank 1), followed by a lack of information or experience (RII 0.719, Rank 2) and environmental concerns regarding microplastics. High processing costs and a bad image of plastic materials share fourth place (RII 0.705). Other notable barriers include concerns about structural strength, resistance from clients or stakeholders, a lack of technical knowledge, the cost and availability of technology, a lack of regulatory support, and, finally, a lack of standards

and regulations, as well as difficulty sourcing and sorting plastic waste, which are ranked as the least significant barriers.

4.4 POTENTIAL BENEFITS OF USING PLASTIC WASTE IN CONSTRUCTION

Table 4 presents potential benefits of using plastic waste in construction, graded by the Relative Importance Index (RII).

Table 4: Potential benefits of using plastic waste in construction

Potential Benefits	RII	Rank
Utilising plastic waste can reduce construction costs.	0.652	12
It helps in effective waste management and reduces landfill usage	0.700	4
It contributes to environmental sustainability	0.724	1
It improves the thermal or acoustic performance of buildings	0.690	7
Plastic-based materials are lightweight and suitable for construction.	0.667	10
It fosters innovation in construction techniques and materials	0.705	3
It creates employment opportunities in the recycling sector	0.714	2
Lightweight, durable, and eco-friendly alternative to traditional	0.690	7
Increased flexibility and crack resistance	0.657	11
Recyclable	0.676	9
Corrosion-resistant	0.700	4
Reduces landfill waste, maintenance-friendly	0.700	4

Contributing to environmental sustainability is seen as the most important advantage (RII 0.724, Rank 1), followed by generating job opportunities in the recycling industry (RII 0.714, Rank 2) and encouraging innovation in building processes and materials (RII 0.705, Rank 3). Helping with effective waste management and decreasing landfill usage, as well as being corrosion-resistant, lowering landfill trash, and maintenance-friendly, all rank fourth (RII 0.700). Additional benefits include the use of lightweight, durable, and ecologically responsible alternatives to traditional materials, as well as improved thermal and acoustic performance in buildings (both with a RII of 0.690, ranking seventh). Other noted benefits include recyclability (RII 0.676, Rank 9), the suitability of lightweight plastic-based materials for construction (RII 0.667, Rank 10), improved flexibility and cracking resistance (RII 0.657, Rank 11), and, finally, the potential cost reduction in construction through the use of plastic waste, which was identified as the least significant benefit in this ranking (RII 0.652, Rank 12).

5. DISCUSSIONS

Sri Lanka's increased emphasis on environmental sustainability and green construction provides an ideal opportunity to incorporate plastic waste as a sustainable material in construction. The findings of this study reveal that the professionals in Sri Lanka recognise the capabilities of using plastic waste for non-structural applications within construction. This aligns with the research conducted by Abdo and Khater (2018), which demonstrated that plastic materials can be utilised in various applications. One of the key findings of this study is the preference for using plastic waste in the secondary construction components rather than structural elements. This aligns with several studies conducted in India and Kenya, where plastic-infused bricks and plastic-reinforced

concrete have been used in low-cost housing and infrastructure projects, yielding positive results (Lamba et al., 2022). In construction projects, incorporating plastic in asphalt has led to improved road durability and water resistance (Angelone et al., 2016), while Kenya has utilised recycled plastic bricks to address housing shortages, demonstrating that technical feasibility can lead to socioeconomic benefits. The top-ranked barrier in this study was concern over long-term durability, which is consistent with global literature highlighting uncertainty about the mechanical and structural integrity of plastic-based construction materials (Rahat et al., 2022; Aciu et al., 2018). Similarly, the lack of awareness and technical expertise identified in the Sri Lankan context reflects challenges faced in other developing nations, where insufficient training and regulatory frameworks hinder the adoption of innovative materials (Gibreil & Feng, 2017).

Despite barriers, promoting environmental sustainability, creating employment and supporting waste management lays a solid platform for using recycled plastic in building. These were in line with the studies conducted by researchers emphasising the circular economy in the construction industry (Samarasinghe et al., 2021; Millette et al., 2019). This method not only eliminates plastic waste, but it also encourages economic growth, so it integrates environmental aims with socioeconomic development for a more sustainable future.

Furthermore, studies have provided evidence of successful integration. Australia has developed modular construction units using recycled plastics that meet both thermal and strength requirements (Wang et al., 2022). Trinidad and Tobago have explored plastic reuse through systems-level material flow analysis to support circular construction practices (Millette et al., 2019). These studies demonstrate the potential for Sri Lanka to adopt similar models, especially with collaboration between government and academia.

6. CONCLUSION AND RECOMMENDATIONS

In conclusion, the use of plastic waste as a construction material offers a practical and sustainable solution to Sri Lanka's growing environmental and material challenges. This study highlights that the Sri Lankan construction industry is aware of the potential to incorporate plastic waste into non-structural elements such as blocks, furniture, and insulation, which can help reduce landfill usage, lower costs, and promote innovation. However, key barriers such as concerns about long-term durability, lack of standards, limited awareness, and environmental risks like microplastic pollution still hinder widespread adoption. To effectively implement plastic-based construction, Sri Lanka must develop clear technical standards and regulatory frameworks to ensure safety and consistency in material performance. Furthermore, international collaboration and integration into national policy frameworks will further support the adoption of plastic-based construction, enabling Sri Lanka to lead in sustainable and green building practices in the region. Future research should focus on long-term performance testing of plastic-based materials in various climatic zones, and the development of eco-friendly plastic composites.

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PREDICTING COST ELEMENTS OF CONSTRUCTION PROJECTS USING SUPERVISED MACHINE LEARNING TECHNIQUES

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ABSTRACT

Accurately predicting construction project costs remains challenging due to their dynamic and complex nature. While traditional methods address most cost components based on resources it consumes or how such activities perform, certain elements like fuel often rely on expert judgment for validation or adjustment, as traditional methods frequently fail to capture all influencing project parameters. This research explores the feasibility of utilizing supervised Machine Learning (ML) techniques to predict these volatile cost elements, focusing specifically on fuel, a key project cost. The study addresses key gaps identified in the literature, particularly the need for models that can manage the uncertainty of specific cost elements and incorporate a broader range of influencing factors, including macroeconomic parameters. By leveraging historical data extracted from Enterprise Resource Planning (ERP) systems, alongside additional project attributes such as average fuel price and construction cost indices, this study demonstrates a novel, data driven approach to cost estimation. The methodology involved data preprocessing to ensure quality and consistency, followed by feature selection to identify the most relevant attributes influencing fuel cost. Several supervised ML models were compared, to identify model with superior performance. The chosen model was further optimized through iterative refinement techniques, to enhance its predictive accuracy and stability. The findings highlight the potential of supervised ML to revolutionize construction cost estimation practices, offering a more data driven, accurate, and efficient method for managing project budgets realistically.

Keywords: *Cost Estimation; Data Analytics; Enterprise Resource Planning; Machine Learning; Predictive Modelling.*

1. INTRODUCTION

The cost of a construction project is a complex amalgamation of various elements. Among the diverse tools available for detailing and deriving these cost elements, the Bill of Quantities (BOQ) is widely recognised and commonly used. Standard industry practices define the structure and item list within a BOQ, fostering a unified approach across

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different projects. Estimators typically derive the cost of each individual element through diverse methodologies, including resource-based, time-based, methodology-based, or expert opinion-based approaches. For certain elements such as energy, water, and fuel consumption, as well as staffing, plant, machinery, security, safety protocols, tools, scaffolding, and communication, estimators often rely heavily on expert judgment to adjust values based on historical data and professional experience to achieve more realistic figures.

However, this reliance on expert judgment and historical extrapolation presents significant limitations, particularly when confronted with the inherent variability of certain cost components. As observed by Elhag et al. (1998), traditional estimation methods frequently overlook critical contextual variables like contract type, site-specific challenges, and market volatility. Similarly, Hashemi et al. (2020) emphasised the inadequacy of linear, rule-based techniques in handling uncertain and interdependent cost determinants. The challenge of accurately forecasting these volatile elements is illustrated in Figure 1. This scatter plot, which spans a wide range of values for fuel cost percentage across 82 construction projects completed between 2008 and 2024, vividly demonstrates the substantial fluctuations and inherent unpredictability, underscoring the limitations of relying solely on traditional methods.

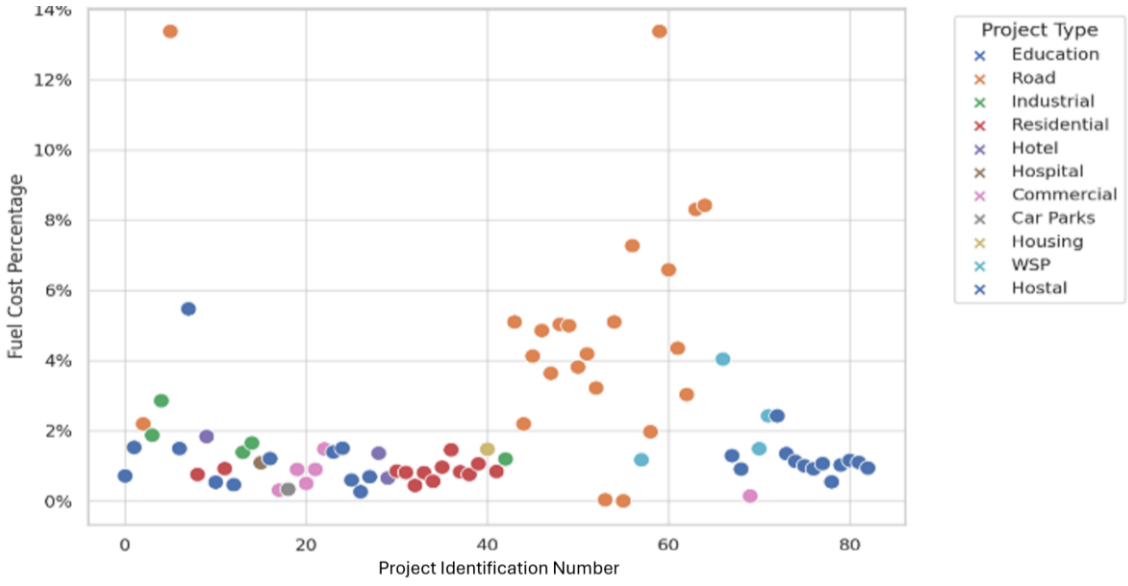


Figure 1. Fuel cost percentage by project type

To address these challenges, contemporary research increasingly advocates for data-driven approaches, particularly those based on ML. Predictive analytics and supervised ML models offer superior accuracy and flexibility compared to deterministic models. These models perform exceptionally well when trained on large, structured datasets, as they can uncover complex, nonlinear relationships among multiple variables that influence costs. Integrating ML techniques into the cost forecasting framework not only enhances the accuracy of estimates but also improves decision-making capabilities throughout the project lifecycle. As noted by Miranda et al. (2022), predictive analytics enables proactive budgeting, scenario analysis, and dynamic cost control, especially at the early stages of a project where uncertainty is highest.

This study adopts supervised ML techniques due to their proven effectiveness in predictive modelling when historical labelled datasets are available. Supervised ML involves learning a function that maps input variables to a known output variable, making it well-suited for tasks such as cost estimation, where both independent features and target cost elements are defined (Jordan & Mitchell, 2015). In contrast, unsupervised ML algorithms are typically employed for exploratory purposes, such as clustering or anomaly detection, where the output is not known in advance. The current study leverages historical project data with clearly defined cost outcomes specifically fuel expenditure which enables the use of supervised learning for accurate cost prediction. Moreover, supervised methods such as Random Forest and Gradient Boosting have demonstrated superior performance in construction cost forecasting due to their ability to model complex, non-linear relationships and handle high-dimensional data (Hashemi et al., 2020; Abed et al., 2022). Accordingly, supervised ML was selected as the most appropriate methodological approach to fulfil the study's objective of estimating volatile cost components using structured ERP datasets.

This research contributes to the ongoing transformation in construction cost estimation by evaluating the applicability of supervised ML for predicting fuel expenditure. The motivation for focusing on fuel costs stems from their demonstrated variability across different project types and durations, as highlighted in Figure 1. This variability provides an ideal test case for assessing the robustness and predictive power of ML models, not only for fuel but also for other volatile cost elements. Crucially, this study addresses the identified gaps in existing literature by incorporating both project-specific and broader economic variables, such as average fuel prices and Construction Industry Development Authority (CIDA) indices, which have often been neglected in previous ML cost estimation models. Through a systematic analysis of historical project data from an ERP system, this study evaluates the feasibility of utilising a supervised ML model to dynamically estimate the percentage of fuel costs. This process aims to validate the concept of employing ML models across various other cost elements and suggests wider implications for estimating similarly volatile components, moving beyond reliance on subjective estimations and contributing to more accurate, dynamic, and comprehensive cost management strategies.

2. LITERATURE REVIEW

The field of construction cost estimation has traditionally relied on methodologies developed over time, such as those based on resources, time, or expert opinion. However, recent years have witnessed the emergence of new concepts, notably Machine Learning (ML), which offer promising avenues for predicting construction project costs with greater accuracy and efficiency.

Early applications of ML in construction cost forecasting often utilised simpler regression techniques. For instance, Prasetyono et al. (2021) suggested the application of linear regression for forecasting construction costs in residential building projects, devising a model to predict future housing construction costs based on the year. Similarly, Suchetha et al. (2023) underscored the significance of ML in accurately predicting home costs to mitigate losses, asserting that linear regression yielded the highest accuracy among other methods like gradient boost and XGBoost regression. Expanding on regression techniques, Mahamid (2011) emphasised the development of early cost estimating models for road construction projects using multiple regression, formulating 11 models

with high coefficients of determination (R2 ranging from 0.92 to 0.98), demonstrating strong correlation with actual data and applicability for initial project stages.

More advanced ML techniques, particularly ensemble methods and deep learning architectures, have shown considerable promise in predicting construction costs. A systematic review by Abed et al. (2022) highlighted the growing adoption of ML methods in forecasting construction costs and underscored the superiority of ensemble learning models in managing nonlinear relationships and high-dimensional datasets. Recent advancements include models integrating deep neural networks (DNN) with validation units to improve predictive accuracy and interpretability in cost forecasting (Saeidlou & Ghadiminia, 2024).

Despite these advancements, several critical research gaps persist in the domain of construction cost estimation using ML. While most ML approaches focus on project-specific attributes such as labour, materials, and equipment, they often neglect broader economic variables such as inflation rates, price volatility, and market demand. Salleh et al. (2023) emphasised that integrating these external factors could significantly improve the adaptability of ML models to real-world conditions. This oversight limits the models' ability to provide holistic and accurate cost forecasts under fluctuating market conditions.

A significant challenge acknowledged in the literature is the difficulty in establishing a universally applicable set of attributes due to the unique characteristics of each building project. Salleh et al. (2023) observed that construction cost data were often fragmented, inconsistent, or incomplete, severely limiting the training of reliable predictive models. This underscores an urgent need for comprehensive and accessible data repositories to support the development of robust ML-based cost estimation tools.

There is an absence of ML models explicitly designed to predict individual building cost elements, largely due to the unavailability of rich, high-quality datasets for these specific components. While some studies, like Katyare et al. (2023) advocated for ML techniques to predict fuel costs by integrating IoT-based sensing data, the broader application of ML to other inherently volatile cost elements (like utilities or plant costs) remains underexplored. The discourse by Katyare et al. (2023) also highlighted challenges stemming from the lack of digitisation in the construction industry, which complicates the use of real-time data for ML applications.

Many existing models limit the number of variables considered due to concerns about manageability. However, expanding the feature set using techniques such as feature selection and dimensionality reduction could significantly enhance model performance without introducing excessive complexity. Salleh et al. (2023) identified an exhaustive compilation of 68 ranked attributes influencing building project costs but acknowledged that the applicability and relevance of these attributes can vary significantly across project types, affecting the generalizability and accuracy of ML models.

In summary, addressing these identified research gaps would significantly advance the domain of construction cost estimation. It would enable the creation of more accurate, dynamic, and comprehensive ML models that align with the evolving demands of the construction industry (Salleh et al., 2023; Katyare et al., 2023). The collaborative effort to overcome these challenges would pave the way for more effective cost management strategies, ultimately contributing to the enhanced sustainability and profitability of construction projects.

3. METHODOLOGY

This chapter presents the methodological framework adopted to predict the fuel cost of construction projects, utilizing ML techniques. This study followed a systematic approach that commenced with data extraction, followed by preprocessing, feature selection, and model evaluation. Once the best-performing model was identified, it underwent further optimisation and refinement for enhanced accuracy. Figure 2graphically illustrates the sequential processes involved in this study, from data acquisition to model deployment.

Google Colaboratory (Colab), a cloud-based computational environment, was utilised in this study for the development, training, and evaluation of ML models. As demonstrated by Ray et al. (2021), Colab enables real-time data processing, analysis, and visualisation within a browser-based interface. The platform supports the full ML workflow, from importing datasets to training classifiers and evaluating model performance, without the constraints of local hardware limitations. By executing code on Google's cloud servers, Colab provides access to advanced computational resources, including Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs), thereby significantly enhancing model training efficiency and scalability.

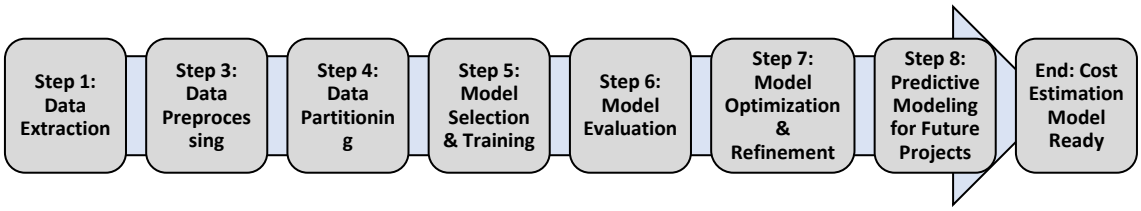


Figure 2. Proposed methodology for developing an ML model

3.1 DATA EXTRACTION

The initial phase of the research involved extracting historical data from the ERP system of a construction organisation. The extracted data comprised detailed records from 82 projects undertaken between 2008 and 2024. These records included various cost elements, such as fuel, labour, and machinery. Additionally, further project attributes not directly associated with the ERP-extracted data were incorporated

The initial phase of the research involved extracting historical data from the ERP system of a construction organisation. The extracted data comprises detailed records from 82 projects undertaken between 2008 and 2024. These records include various cost elements, such as fuel, labour, and machinery. Additionally, further project attributes were incorporated that were not associated with the extracted data.

The primary variables extracted from the ERP systems include:

- Project identification details: project number, project name
- Cost data: percentage of fuel cost, project cost
- Time-related data: time period of the project, start date of the project

The study incorporated additional data into the dataset related to the project, such as:

- Average fuel price for the duration of the project,
- Construction cost indices for the duration of the project published by the CIDA,
- Project type (e.g., residential, commercial, road, etc.),

- Project spread (horizontal or vertical),
- Height category (high-rise or low-rise),
- Type of crane (mobile crane or tower crane),
- Source of concrete (on-site ready-mix or externally sourced),
- Source of energy (generator power or electricity powered)

This structured data enabled the creation of a robust dataset, serving as the foundation for all subsequent phases of analysis. It enabled the development of a comprehensive dataset that incorporates macroeconomic and project-related attributes not previously found in research. Considering its generation from ERP records at the organisational level, it provides a standardised set of data that can be utilised across various projects within the organisation. Available information at the organisational level facilitated the analysis of different parameters derived from the dataset, as well as the inclusion of additional parameters that may influence fuel costs.

3.2 DATA PREPROCESSING

Given the complexity and heterogeneity of construction project data, preprocessing is a vital component of the methodological process. Data preprocessing ensures that the dataset is clean, consistent, and ready for analysis. This process involved several key tasks as follows:

3.2.1 Handling Missing Values

The dataset was examined for missing or incomplete data. Missing values were addressed using appropriate imputation methods.

3.2.2 Encoding Categorical Variables

ML models typically require all input features to be in numerical format. Therefore, categorical variables such as project type (residential, commercial, road) were transformed into numerical format through one hot encoding. This technique was chosen to avoid imposing an ordinal relationship between categories that are inherently non-ordinal.

3.2.3 Scaling and Normalization

To ensure that no single feature disproportionately influences the model, numeric features were normalized using the min max scaling method. This transformation scaled all numeric features to a common range, typically between 0 and 1, facilitating more effective model training, particularly for gradient-based algorithms such as Gradient Boosting Regressors.

3.3 FEATURE SELECTION AND VALIDATION

To enhance predictive accuracy and reduce the model's dimensionality, a feature selection process was applied before training. This process aimed to identify the most relevant project attributes that significantly influence the percentage of fuel cost. A correlation matrix was generated to quantify the linear relationships between all numerical variables and the target variable. Pearson's correlation coefficient was used due to its effectiveness in measuring the strength and direction of linear dependencies.

Initially, features with a correlation coefficient above a predefined threshold were selected. Those with negligible or inverse relationships were excluded to reduce noise

and avoid overfitting. Beyond purely statistical criteria, domain expertise was applied to retain variables known to influence fuel consumption, such as Contract Sum, CIDA Indices, Fuel Price, and Crane Type, even if their correlation strength was moderate. This hybrid approach ensured that variables with practical relevance were not overlooked solely due to statistical filtering.

Figure 3 visually represents the correlation values between selected parameters and the percentage of fuel cost.

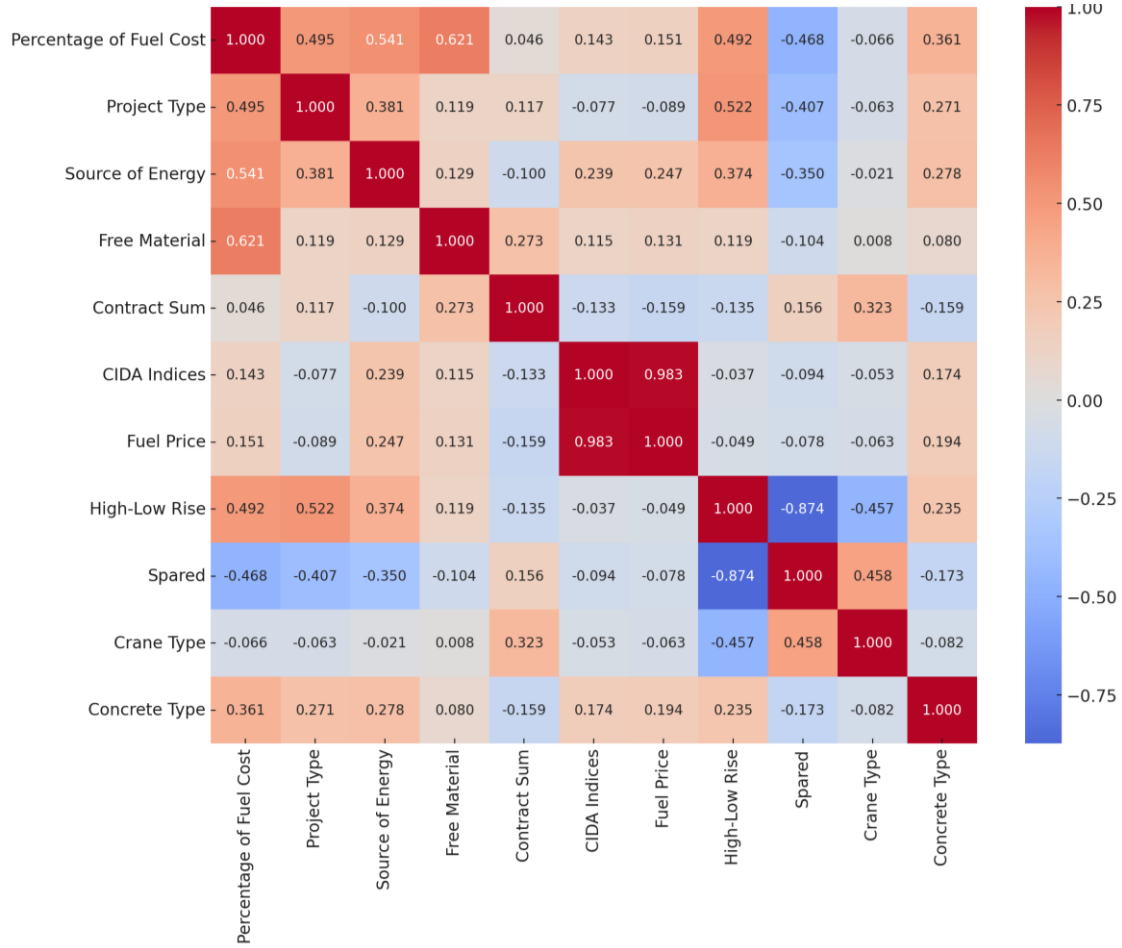


Figure 3: Correlation heatmap for feature selection

Table 1presents the properties and correlation values of each parameter in a tabular format, providing a clear overview of the selected features. This multi-step process resulted in a refined set of features that were subsequently used to train the ML models.

Table 1: Feature Selection.

Feature name	Type	Preprocessing applied	Correlation	Category
Free Material	Numerical	Normalized	0.621	Strong
Source of Energy	Categorical	One hot encoded	0.541	Strong
High-Low Rise	Categorical	One hot encoded	0.492	Strong
Project Type	Categorical	One hot encoded	0.486	Strong

Feature name	Type	Preprocessing applied	Correlation	Category
Project Spread	Categorical	One hot encoded	0.468	Strong
Concrete Type	Categorical	One hot encoded	0.361	Strong
Fuel Price	Numerical	Normalized	0.151	Weak
CIDA Indices	Numerical	Normalized	0.143	Weak
Crane Type	Categorical	One hot encoded	0.066	Weak
Contract Sum	Numerical	Normalized	0.046	Weak

3.4 DATA PARTITIONING

The researchers partitioned the dataset into training and testing subsets to facilitate the evaluation of model performance. The split was performed as follows:

- Training set: 80% of the dataset was allocated to training the ML models
- Testing set: The remaining 20% was reserved for testing and evaluating the generalisation capabilities of the trained models

A random state of 42 was used during the split to ensure that the partitioning was reproducible, which is critical for maintaining the integrity and consistency of the analysis across different iterations.

3.5 MODEL SELECTION AND TRAINING

Three supervised ML models were selected for experimentation based on their relevance to regression tasks, their ability to capture complex relationships, and their successful application in construction cost prediction research. These models, all part of the supervised learning paradigm given the availability of labelled historical data for training, include:

- Random Forest Regressor (RFR) is an ensemble learning method that operates by constructing multiple decision trees during training. It is particularly adept at handling datasets with both categorical and continuous variables, and it mitigates overfitting through its ensemble approach.
- Gradient Boosting Regressor (GBR) is another ensemble technique. Gradient Boosting constructs models sequentially to minimise prediction errors by combining weak learners. It is capable of capturing complex, non-linear relationships within the data.
- Support Vector Regressor (SVR) was included as it is effective for datasets with a smaller number of samples and works well for non-linear relationships through the application of kernel functions.

3.6 MODEL EVALUATION

Each model was evaluated using a set of standard performance metrics:

- Mean Absolute Error (MAE) measures the average magnitude of the errors in a set of predictions, without considering their direction.
- Mean Squared Error (MSE) quantifies the average squared difference between the predicted and actual values, penalising larger errors more than smaller ones.

- R-squared (R^2) provides a measure of how well the regression model captures the variance in the data. A higher R^2 indicates a better fit.

The model that exhibited the best performance metrics was selected as the final model for further optimization. The results of each model's performance are presented in Table 2.

Table 2: Model performance

Model Name	MAE	MSE	R-squared
R1 SVR	0.05230	0.002870	-20.08
R2 GBR	0.00861	0.000199	-0.464
R3 RFR	0.00848	0.000197	-0.446

3.7 MODEL OPTIMISATION AND ITERATIVE REFINEMENT

The selected model, identified as R3 (referring to the initial baseline Random Forest Regressor), was further optimised through a progressive series of strategies, culminating in version R8, as detailed in Table 3. R3 served as a baseline with default settings. R4 improved data partitioning through iterative random state search. R5 integrated 5-fold Cross-Validation (CV) for robust performance evaluation. R6 introduced prediction uncertainty via Confidence Intervals (CI) derived from K-Fold inference. R7 applied hyperparameter tuning using Randomised Search CV to optimise model architecture, significantly reducing error. Finally, R8 built on R7 by enforcing fold-specific preprocessing during K-Fold prediction, achieving the tightest confidence interval and highest prediction stability.

Table 3: Optimisation techniques used in Model R3 to R8

Model name	Optimisation techniques applied	Purpose/Benefit
R3	Baseline model using a simple train-test split with default RFR parameters.	Establishes a reference point for model performance with no tuning.
R4	Conducted randomised search over multiple random states (e.g., 0 to 99) for train-test split; selected split based on best performance.	Enhances generalisability by identifying a stable and optimal data partition.
R5	Integrated 5-fold CV during evaluation of the R4 model.	Improves performance reliability by mitigating variance across different training subsets.
R6	Extended R5 by incorporating fold level predictions to estimate CI for new project predictions.	Introduces prediction uncertainty, enhancing interpretability and decision confidence.
R7	Applied Randomised Search CV for hyperparameter tuning of RFR (e.g., n_estimators, max_depth, min_samples_split, min_samples_leaf, max_features, bootstrap) using 5-fold CV.	Achieves optimal model architecture, minimising error and maximising R^2.

Model name	Optimisation techniques applied	Purpose/Benefit
R8	Maintained R7 hyperparameters; added fold-specific preprocessing within each K-Fold iteration to generate predictions.	Delivers the most refined and stable inference process with the tightest CI and lowest variance, while preventing data leakage.

3.8 PREDICTIVE MODELLING FOR FUTURE PROJECTS

Once the models were optimised, they were utilised to predict future cost elements, with a specific focus on fuel consumption for new projects. The models utilised project-related attributes, including contract sum, project type, and fuel price, to generate predictions that inform project planning and budget allocation.

4. RESULTS/ANALYSIS AND DISCUSSION

4.1 RESULTS OVERVIEW

This research aimed to develop an accurate supervised ML model for predicting fuel cost percentages in construction projects. Following the development of the best-performing model, as detailed in the methodology chapter, this section describes the optimised model's evaluation and predicted values for new project parameters.

4.2 MODEL PERFORMANCE AND PREDICTION OUTCOMES

In the initial model selection phase, the Random Forest Regressor consistently outperformed the other models, namely Support Vector Regressor and Gradient Boosting Regressor, by exhibiting lower error rates and providing more accurate fuel cost predictions. As shown in Table 2, the SVR performed poorly, displaying significantly higher errors and a negative R-squared value, indicating its unsuitability for this specific prediction task.

The strengths of the RFR are particularly well-suited to the complexities of construction cost data. As an ensemble method, RFR builds multiple decision trees and averages their outputs. This structure effectively captures complex, non-linear relationships between project attributes and fuel cost components, which are characteristic of the dataset used, combining both numerical (e.g., contract sum, CIDA indices) and categorical variables (e.g., project type, energy source). RFR seamlessly handled these diverse data types without requiring extensive data transformations, unlike SVR, which relies heavily on kernel manipulation. By aggregating predictions from many individual decision trees trained on bootstrapped subsets, RFR provided strong generalization and robustness against overfitting, a common concern with highly variable project datasets. Furthermore, RFR provided intrinsic feature importance scores, which enhance the model's transparency and facilitate insights into which project features most influence fuel cost outcomes, proving valuable for construction management practitioners.

RFR outperformed the other models by exhibiting lower error rates and providing more accurate predictions of fuel costs. In contrast, the SVR performed poorly, displaying significantly higher errors and a negative R-squared value, indicating that it was unsuitable for this specific prediction task.

4.2.1 Optimised Model Performance

After comprehensive hyperparameter tuning on the selected RFR and iterative optimisation, the model's performance improved significantly.

Table 4 illustrates the progressive performance enhancement achieved across different optimisation stages (R3 to R8) for the selected project.

Model R7 demonstrated the highest analytical performance, as evidenced by the lowest Mean Absolute Error and Mean Squared Error alongside the highest R-squared (R^2) value. These metrics indicated that R7 offered the most accurate predictions and best explained the variance in fuel cost outcomes. In contrast, Model R8, while slightly less optimal in terms of MAE and R^2, excelled in predictive stability. It achieved the lowest standard deviation and produced the tightest 90% confidence interval, making its predictions highly consistent and reliable across different data partitions. Accordingly, R7 was the preferred model for analytical accuracy and variance explanation, while R8 was more suitable for practical deployment, where consistent and stable prediction intervals are essential. Therefore, Model R8 is recommended as the overall best model when both predictive accuracy and reliability are prioritized in real-world applications.

Table 4: Modelled performance improvement

Model	MAE	MSE	R^2	Predicted % Fuel Cost	90% Confidence Interval	Standard Deviation
R3	0.00779	0.00018	0.64411	3.74%	Wide	2.68%
R4	0.00417	0.00003	0.89626	4.35%	Wide	2.57%
R5	0.00384	0.00005	0.90581	4.14%	[0.82%, 7.47%]	2.02%
R6	0.01036	0.00038	0.44648	4.59%	[3.80%, 5.39%]	0.51%
R7	0.00294	0.00001	0.95506	4.17%	[3.50%, 4.51%]	0.30%
R8	0.00421	0.00002	0.92916	3.58%	[3.12%, 4.05%]	0.28%
Best	R7	R7	R7	R8	R8	R8

4.3 PREDICTED FUEL COSTS BY PROJECT TYPE

Once the model was optimised (specifically Model R8 for practical deployment), it was applied to predict fuel costs across a range of construction projects. The predicted values were based on the key project attributes identified in the feature importance analysis.

Table 5: Results for Different Project Characteristics presents the expected fuel cost percentages for various project types, including commercial, education, industrial, and road projects. This table provides a concrete demonstration of the model's ability to generate specific fuel cost predictions based on distinct project characteristics.

Table 5: Results for different project characteristics

Project No.	Project type	Actual fuel %	Predicted % of Model R7	90% Confidence intervals	Predicted % of Model R8	90% Confidence intervals
3-06600	Commercial	1.22%	1.33%	[1.26%,1.40%]	1.28%	[1.08%,1.49%]
3-06300	Education	0.93%	1.10%	[1.03%,1.16%]	0.97%	[0.92%,1.02%]

Project No.	Project type	Actual fuel %	Predicted % of Model R7	90% Confidence intervals	Predicted % of Model R8	90% Confidence intervals
3-06900	Education	1.45%	1.51%	[1.35%,1.69%]	1.56%	[1.37%,1.80%]
3-04800	Education	1.53%	1.35%	[1.21%,1.50%]	1.36%	[1.38%,1.99%]
3-04600	Education	1.42%	1.53%	[1.36%,1.66%]	1.42%	[1.30%,1.53%]
3-05800	Industrial	1.37%	1.97%	[1.70%,2.24%]	1.72%	[1.46%,1.97%]
3-06200	Industrial	2.32%	2.28%	[1.93%,2.63%]	2.11%	[1.82%,2.40%]
4-02200	Road	4.63%	3.71%	[3.51%,4.08%]	5.27%	[4.47%,6.07%]

4.4 FEATURE INFLUENCE ON PREDICTION OUTCOMES

The results from the optimised RFR confirmed the importance of certain features, as highlighted previously in the feature importance analysis (refer to Figure 3 and Table 1 in Methodology). By focusing on these critical features, the model provided more accurate and realistic predictions for fuel costs. These findings highlight the model's ability to identify significant drivers of fuel consumption, which is essential for data-driven decision-making in project management.

4.5 PRACTICAL IMPLICATIONS OF THE FINDINGS

The findings from this study had several practical applications for budgeting construction projects, including:

- The ability to accurately predict fuel costs based on project characteristics allowed for more precise budget planning. This is especially important for projects that are fuel intensive, such as road construction.
- Project could use the predictions to allocate resources more effectively, ensuring that fuel consumption is anticipated and accounted for throughout the project lifecycle.
- While the model focused on fuel costs, it was essential to explore adoptability to predict other cost elements, such as labour and equipment, thereby enhancing its applicability across various aspects of project management.

Supervised ML approach to predict other complex and often subjectively estimated cost elements, such as labour and equipment, thereby enhancing its applicability across various aspects of project management. This demonstrates the potential for a broader revolution in construction cost estimation from a subjective to a data-driven paradigm.

5. CONCLUSION

This study on predicting fuel costs for construction projects using Supervised ML techniques successfully demonstrated the possibility of utilising this approach in the presence of mutable variables affecting fuel costs. This underscores the potential for applying the same approach to other cost elements that often rely on human judgment, enabling confident data-driven predictions while overcoming the limitations of subjective estimations. The research marks a significant advancement towards enhancing the precision and reliability of cost estimations in the construction industry.

The historical data generated through the ERP application provided a richly structured dataset. This facilitated not merely overall cost prediction but specifically the prediction of individual cost elements like fuel, which in turn leads to greater accuracy in predicting the overall cost of construction projects.

The adoption of supervised ML techniques yielded several key benefits:

- Enabled the efficient processing and analysis of large-scale datasets, revealing underlying patterns and interdependencies that are not readily detectable through manual techniques
- Facilitated continuous improvement in predictive performance by learning iteratively from historical project data
- Enhanced the capacity to forecast future costs by incorporating dynamic relationships among variables and leveraging temporal trends
- Exhibited adaptability by updating models with newly available data, allowing for timely recalibration in response to shifting market conditions and project-specific variations.
- Reduced reliance on subjective estimations, thereby increasing the objectivity and reproducibility of cost forecasts

This study explicitly addressed key gaps identified in the literature, particularly the neglect of broader economic and dynamic variables by incorporating average fuel prices and CIDA indices, which improved the model's real-world applicability. Furthermore, by focusing on a specific and volatile cost element like fuel, the research provides a concrete example of how supervised ML can be applied to granular cost components, addressing the previous limited focus in this area. The utilization of a comprehensive feature set derived from ERP data also contributes to overcoming the issue of underutilized variables in traditional models.

However, several limitations are associated with the current ML model. The dataset was restricted to projects at a single organizational level, which may capture features related specifically to that organization. This could potentially affect the model's generalizability across different organizations, various geographical regions, or diverse construction types. Additionally, while the models included both project-specific and macroeconomic attributes, the exclusion of real-time or dynamic project updates may restrict the model's responsiveness to changing site conditions during ongoing projects.

Despite these limitations, while the Random Forest Regressor model after optimization demonstrated high predictive accuracy, there are several areas for further research and development:

- Integrating real time fuel consumption data from ongoing projects would provide dynamic updates to the model, further improving its accuracy and usefulness.
- Increasing the size and diversity of the dataset by including more projects, especially those with lower fuel consumption, would improve the model’s generalizability.
- Although the RFR performed well, exploring other ML techniques such as XGBoost or deep learning models could further enhance prediction capabilities, especially for complex cost components like labour or materials.

In conclusion, the application of supervised ML for cost estimation significantly enhanced the accuracy, consistency, and strategic utility of construction budgeting. This

approach not only supported informed decision-making, risk management, and planning but also offered a scalable framework for broader adoption across diverse cost elements. By harnessing both historical and current project data, ML-driven cost prediction frameworks have the potential to transform traditional cost estimation practices and improve overall project management efficiency within the construction sector.

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PRESENT REALITIES AND FUTURE DIRECTIONS OF AI INTEGRATION WITHIN BUILT ENVIRONMENT HIGHER EDUCATION

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ABSTRACT

Technological advancements in the construction industry driven by Artificial Intelligence (AI), mandate a significant re-evaluation of Built Environment Higher Education (BEHE). While the imperative for AI integration within BEHE is acknowledged, it remains underexplored. This study aims to identify the potential for AI integration within BEHE and assess its capacity to enhance the readiness of HE learners, trainers and the institutions to cater to the evolving demands. Data was collected through a literature review and nine semi-structured interviews among academics and industry practitioners across HE, construction, information technology, and manufacturing sectors of UK to identify current status quo of AI applications within BEHE, and potential integration of best practices from other sectors. Data was thematically analysed using NVivo14. The results show that the effective adoption of AI technology yields efficient outcomes in student learning, teaching efficacy, administrative processes including mentoring, inclusivity, quality assurance, research and entrepreneurship. The findings demonstrate that BEHE has not fully attained the effective utilisation of AI integration in its curriculum, capacity development is needed in pedagogical approaches, learning methodologies, and policy formulation. A successful achievement of these goals necessitates proactive stakeholder engagement and robust top-down support, including substantial investment in IT infrastructure, training and comprehensive dedication at individual, institutional and national policy levels.

Keywords: *Artificial Intelligence; Built environment; Higher Education; Sustainability; UK.*

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1. INTRODUCTION

The evolving landscape of artificial intelligence (AI) is the most important technological development during the first half of the 21st century. The profound effects of AI on higher education cannot be overlooked (Holmes, 2023). Higher Education Institutions (HEIs) are increasingly recognizing and focusing on the pivotal role of AI as an innovative technology that continues to reshape the educational landscape. The benefits of AI applications in HE, such as cognitive scaffolding provided by Intelligent Tutoring Systems (Paladines & Ramirez, 2020), Self-Regulated Learning and Mentoring (Nguyen & Barbieri, 2025), Automated Grading including personalised feedback, online/remote learning (Chen et al, 2020), Lifelong Learning (Rawas, 2023) and administrative processes (Parycek et al, 2023) are extensive and diverse. However, majority of academics remain uncertain about its effective usability and, more critically, what its integration truly entails for their profession, student learning and teaching methodologies (Hinojo-Lucena et al., 2019). Although there has been an increasing interest into this field, much of the research surrounding AI in HE is focused on the broader education systems (Zawacki-Richter et al., 2019), with limited research explaining the potential of AI integration to enhance current Built Environment Higher Education (BEHE). Hence, this paper identifies the potential for AI integration within BEHE and assess its capacity to enhance the readiness of HE learners, trainers and the institutions.

2. RESEARCH METHODOLOGY

This research adopted a qualitative research design approach with a view to gaining an in-depth understanding of the problem highlighted in section 1. A review of literature and standard documents (policy papers, UKHE frameworks) was conducted. Semi-structured interviews were the empirical data collection technique as it allowed a structured yet flexible approach. Two interview guidelines were developed to target two categories namely BEHE staff and industry professionals with some AI experience. Both guidelines were tested for clarity, readability and timing. Ethical approval was obtained prior to the formal interviews. The sample included a mixture of BEHE professionals and industry practitioners. 89 BE staff profiles of 33 UK HEIs were reviewed to identify the academics for interviews. 18 academics with profiles indicating familiarity with AI adoption were invited and 7 agreed to do so. Similarly, 2 industry practitioners from construction and manufacturing sectors also contributed by way of interviews.

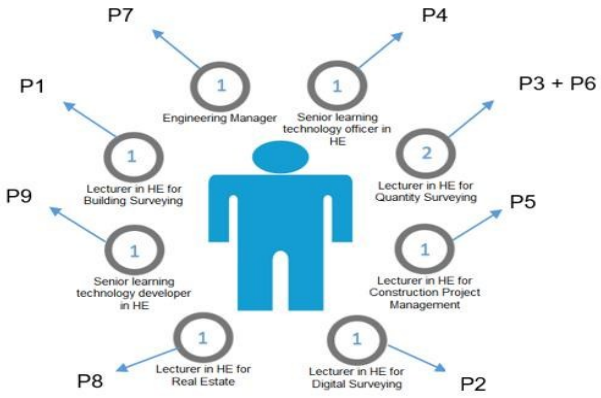


Figure 1: Interviewees' profiles

All interviews were conducted online via MS Teams, primarily for the convenience of remote participation and the advantage of automated transcription. Key themes and patterns were identified by scanning each transcript and were coded accordingly. Cross analysis was undertaken to address overlapping topics. Identified themes were further filtered into sub-themes to establish relationships and patterns.

3. AI APPLICATIONS IN HIGHER EDUCATION

The UKHE landscape is evolving due to several external factors such as the resistant to embrace innovative technologies, changing student demographics and significant demand for student support. The Higher Education Students Statistics Agency (2024) declares 16.5% of differently abled learners (i.e., 484,000) in UKHE sectors where demand for additional support is highly required. Hence innovative mechanisms need to be adopted to cater to such demands. Literature acknowledges the ability of AI to improve HE (Luckin et al., 2016), whilst offering benefits for HE stakeholders, including learners, trainers, supportive staff, HEIs, funding, policy and professional bodies through system innovation. Intelligent Tutoring Systems (ITS) is a common theme in AI research in HE, falling under the umbrella of knowledge-based systems. ITS can be defined as, computer programs that provide instructions adapted to the needs of individual learners (Paladines & Ramirez, 2020). ITS outperformed traditional classroom instruction, reading printed text, computer assisted instruction, and laboratory or homework assignments (Steenbergen-Hu & Cooper, 2014). However, ITS is still not widely adopted in HEIs (Weitekamp et al., 2020). Apart from that, there are several AI adoptions in administrative processes such as student selection and enrolment, monitor dropout rates, timetabling, student support and analyse group behaviour trends. These programmes use data to forecast trends and modify instruction for next pupils (Bates et al., 2020). Applications of AI in HE has been categorised into several categories (Chen et al., 2020; Popenici & Kerr, 2017; Zawacki-Ritcher et al., 2019).

Table 1: Applications of AI within higher education
Adapted from: (Zawacki-Ritcher et al., 2019)

Category	Application
Profiling and prediction	Admission decision and course scheduling
	Student models and academic achievement
	Drop-out and retention
Assessment and evaluation	Automated grading
	Feedback
	Evaluation of student understanding, engagement, and academic integrity
Adaptive systems and personalisation	Evaluation of teaching
	Teaching course content
	Recommending/providing personalised content
	Supporting teachers in learning and teaching design
	Using academic data to monitor and guide students
Intelligent Tutoring Systems	Teaching course content
	Diagnosing strengths or gaps in student knowledge
	Curating learning materials based on student needs

Even though the potential applications of AI in HE is commended, the limited discussions in placed in relation to the risks and ethical ramifications of using AI in education (Zawacki-Ritcher et al., 2019). Hence without addressing this element it is somewhat challenging to integrate AI into HE.

The Institute for Ethical AI in Education's Ethical Framework for AI in Education (2021) noted that the laying the responsibility of AI education solely on staff members would be unreasonable. Rather, the institution must take the lead to facilitate this learning. Hence, it is essential for institutions to engage in discussions with HE stakeholders regarding the implication of AI on administrative, teaching and learning practices (Bearman et al., 2022). Furthermore, before fully implementing AI throughout the organisation, an ethical governance framework must be established to ensure responsible AI use and avoid unintended consequence (Défense Innovation Board, 2019). Additionally, classes and training programs should be implemented to equip staff with the skills and knowledge necessary in the future (Luckin et al., 2022).

The collaboration between HEIs, policy makers and funding agencies are required, in terms of support, funding and governance. Department of Science, Innovation and Technology (2019) explains that National AI strategy (2022) will focus on investment, support, and governance, emphasizing the government's commitment to facilitating AI integration within HE.

3.1 BUILT ENVIRONMENT HIGHER EDUCATION AND AI STATUS-QUO

Built Environment HE is typically an inter/multi-disciplinary field of study that aims to recognise design, procurement, construction and in-use of human-made spaces and systems effectively. Study programs generally follow a holistic and integrated approach and consider the entire lifecycle and interconnectedness of products and processes, often incorporating complex social, economic, and environmental considerations alongside technical ones.

AI offers potentially ground-breaking methods (Popenici & Kerr, 2017). It is essential to stay current with technological developments as HEIs play a vital role in producing market-ready professional for the built environment (Akour & Alenezi, 2022). The growth of the construction industry faces challenges in relation to cost overruns, health and safety, productivity, and skilled labour. The industry is one of the least advanced digitally, making project management unnecessarily time-consuming and complicated (Abioye et al., 2021; Bello et al., 2021; Bughin et al., 2017). AI has vast capabilities yet is less commonly used in the construction industry compared to other industries. AI is particularly useful during the pre-construction phases of construction projects due to its ability to streamline complex processes by big data analytics, reducing time spent on routine tasks (Regona et al., 2022). The fragmentated nature of the industry, stakeholders impacts and influence on project objectives presents significant challenges in implementing such innovative applications.

AI integration within BEHE can be explored through the lenses of various stakeholders. In relation to learners', AI implementation can reward in several ways such as ITS to create personalized learning, and profiling and prediction to enhance student engagement (Zawacki-Richter et al., 2019). Trainers/Academics in HE need to be proficient enough in AI to teach their students exactly how to adopt this technology in their learning (Ng et al., 2023). However, the scarcity of educators with such knowledge and skills leads to a

substantial investment in time and money to upskill them (Ng et al., 2023). This will not be something that comes easy due to the common perception of AI being a threat to educators' jobs, causing a clear resistance to change (Humble & Mozelius, 2022). To address this, efforts must be made to raise awareness and educate HE staff about the potential benefits of AI in HE for themselves. University leaders have conveyed that AI will serve as a complement to human input rather than a replacement (Cremer & Kasparov, 2021). It's crucial to reiterate this message to the educators through adequate training and education.

The significance of training and educating AI in the context of BEHE is growing rapidly, especially as AI applications are expected to play a crucial role in construction education (Zawacki-Richter et al., 2019). Whilst AI applications in construction are currently in their infancy, it's inevitable that they will become a necessary tool to improve project cost, quality, and development time. As new technologies emerge, teaching construction will inevitably change, requiring staff members to revisit their teaching methodologies (Qureshi, 2020). It is essential to shift the focus on education towards teaching students how to apply and use information effectively, rather than just memorizing it. This shift prepares learners for a rapidly changing and technology-driven workforce, allowing them to become more adaptable and flexible in their approach to work (Brown, 2023). To bridge the gap between industry and academic institutions, it is crucial to acknowledge that education and training serve as long-term methods of disseminating new knowledge to the industry (Goh, 2006) and vice versa. This emphasises the importance of teaching graduates advanced technological skills and knowledge, such as AI, through education and training including work-based learning and off the job training. Lack of a clear roadmap or action plan impedes practical implementation of these improvements in BEHE.

4. KEY FINDINGS

This section discusses the results and the emerging discussion with regard to AI integration within BEHE.

4.1 CHALLENGES OF AI INTEGRATION WITHIN BEHE

Potential integration of AI into existing curriculum is one of the starting but challenging endeavours for HEIs as there is less flexibility in programs to adopt such changes immediately as significant program amendments take place in periodic program reviews. The interviewees agreed that they expect AI revolution in most of the elements of BEHE including teaching (course materials, delivery, marking and feedback, methodology etc), learning (assessment and feedback, engagement, support and mentoring, reflection, creativity, risk etc), institutional and national policies (new guidelines/legislations, dealing with fake news, transparency etc). For example, Interviewee P4 mentioned that "*you could train something to assess in a similar way that you are doing, and a huge benefit as well for that might be formative feedback so that machines might begin to help students with very fast feedback*."

The challenges of integrating AI into BEHE were frequently mentioned by the interview participants and are represented in Figure 2.

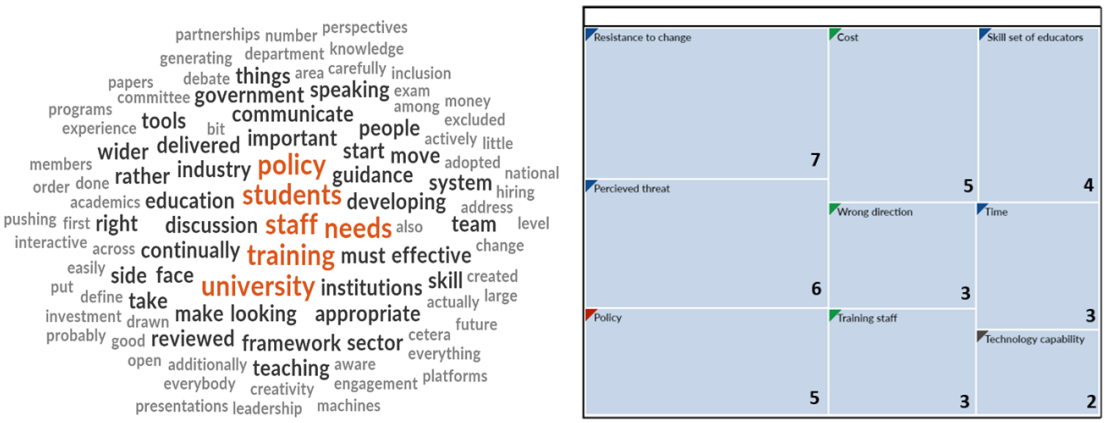


Figure 2: Challenges of AI integration in BEHE

Resistance to change by the staff, job security, lack of clear policies (institutional and national level) were highlighted. In some instances, institutional shifts in wrong directions by potentially deciding to restrict students from using AI instead of allowing them to use it effectively was also identified as a challenge. Also noted was the limited compatibility of existing IT infrastructure to adopt such technologies, an indication that AI technology may not be mature enough to be readily integrated into HE.

The identified challenges were further clustered into different tiers. For example, 'resistance to change', 'perceived threat' skills of educators and time requirements for implementation and training need to be addressed in individual level (learner, trainer); 'staff training', 'cost,' in institutional level (HEIs, organisations) and 'policy' (Authorities, Government).

4.2 BENEFITS OF AI INTEGRATION WITHIN BEHE

Similarly, benefits of AI integration also acknowledged, where P9 noted that "*AI can be used to create new forms of assessment that are more effective, making teaching easier, and promoting inclusivity within academic institutions"*. Also, faster feedback (P4, P6) and identifying design flaws early in project design (P1).

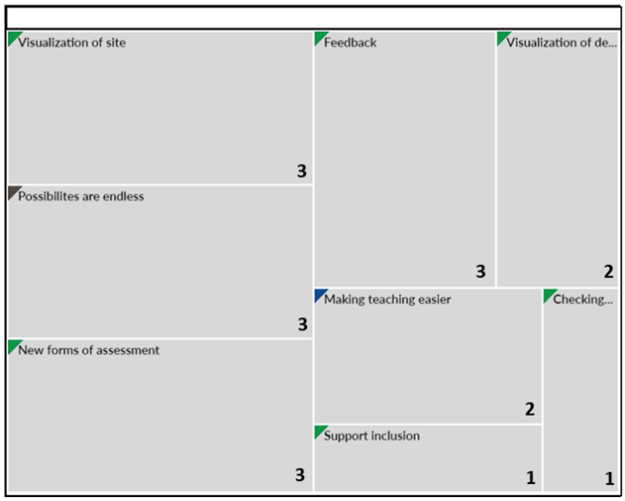


Figure 3: Identified benefits of Artificial Intelligence in BEHE

The results were further analysed in terms of the benefits of implementing AI within BEHE on various stakeholders (Fig 3), with a view to supporting the development of the necessary steps for full implementation and to reap the benefits of AI in BEHE.

4.3 KEY RECOMMENDATIONS

However, findings also show that next steps do require collaboration between all stakeholders, where P8, stated that "*there needs to be stronger partnerships between universities and the industry"* and supportively P4, noted that "a*ll institutions now must get on the wider debate about AI…and institutions need to start pushing students to think about it*." The importance of staff/trainers upgrading their skills to adapt to the evolving role of educating learners is required. It is crucial for all stakeholders to understand the ethical implications of using AI in BEHE before implementation.

5. DISCUSSION

The findings on AI experience among participants reveal varying levels of familiarity in different AI areas. The study notes limited AI application in BEHE, with only two areas directly related to its curriculum. Participants suggest a need for greater AI exposure in BEHE and identify it as a promising development for BEHE. This challenge aligns with Ng et al.'s (2023) observation of the scarcity of qualified educators with the necessary AI knowledge and skills. This indicates that AI is perceived as a useful tool to complement human input, aligning with the view of Cremer and Kasparov (2021).

The findings identify six potential avenues for integrating AI into BEHE. Participants believe that incorporating AI into existing courses would effectively prepare students for the evolving future of the construction industry. This finding is supported by P3 "*I think we (educators) need to be champions of this (AI)…in order to make our students relevant in the workplace*". P6 explained "*AI will keep you (students) relevant*". Previous studies have also supported the idea that it's crucial to keep up with technological advancements in order to produce future professionals for the construction industry (Akour & Alenezi, 2022). This emphasizes the need to integrate AI into existing curriculum to enable graduates to be well-prepared for the future of the industry, it's clear that participants are aware of this. Also, participants believe that new courses and programs should be designed with AI in mind to keep students relevant including assessment and grading. Participants see potential benefits in using AI-based tools to assess student performance and provide feedback. Benefits have also been identified in previous research (Zawacki-Ritcher et al., 2019). P5 stated "*it could play a critical role in assessing the quality of work that is being submitted.*" Whilst P4 noted "*you could train something to assess in a similar way that you're doing and a huge benefit as well for that might be formative feedback*". However, other participants remain sceptical due to the lack of trust in AI and the belief that human judgement is still essential, along with the opinion that the technology capability is not advanced enough. P2 stated "*I won't rely on them. I might use them as training or curiosity, but I won't rely on their final results. AI isn't ready*". Whist P7 also mentioned "*I think the future, definitely, but at the moment the technology is not mature enough.*"

Overall data suggests a positive interest integrating AI into BEHE, with potential benefits through multiple avenues. Barriers remain including lack of knowledge, skills, trust, and technology maturity. Findings have potential to enable institutions and educators to equip students with necessary skills to thrive in evolving construction industry. Results further

reveal insights into AI implementation within BEHE, highlighting it complexity and involvement of diverse stakeholders, with a strong emphasis on learners as primary beneficiaries. However, this also suggests other stakeholders may lack awareness of AI's broader benefits. Stakeholders must be informed of AI's full potential to make informed decisions about implementation. Past research identifies benefits (Luckin et al., 2016), yet stakeholder awareness appears incomplete. One of the key findings is that the majority of challenges relate to the staff/educator. This suggests that educators play a critical role in the successful implementation of AI in BEHE. Resistance to change and perceived threats were identified as the most common challenges facing educators. This finding is not surprising given that implementing new technologies, such as AI, can be disruptive and requires educators to learn new skills and adapt to new teaching methods (Ng et al., 2023).

Findings further highlight the importance of providing adequate training and support to educators to help them overcomes these challenges. Educators need to understand the benefits of AI and how it can enhance their teaching methods, rather than perceive it as a threat. Hence the need of institutional support and responsibility is noted. As per P5, "*I think universities have to take the first step; they need to open up the discussions wider among staff. There needs to be inclusion of those that will be using the AI interactive platforms, most academics should be drawn into the discussion.*" Whilst P9 also said "*speaking to staff to get their perspectives on it and to make sure that we can continually update and move with things as it as they move*". In addition, the study emphasizes the need for policymakers (government) and institutions to work together to address the challenges facing educators. Policymakers need to develop clear policies and guidelines that support the integration of AI in BEHE and address any concerns or issues that may arise. Institutions also need to develop strategies for funding and resource allocation to support AI implementation, as well as providing training and support to educators to help them integrate AI effectively.

5.1 IMPACT ON STAKEHOLDERS

The stakeholders were clustered into three main domains including individuals, Institutions, and the society. Each stakeholder is impacted significantly by the implementation of AI, as evidenced in the findings.

5.1.1 Individual Level (Learners and Trainers)

It is evident that students are most likely to be impacted positively by the implementation of AI in BEHE. In terms of preparedness findings suggest that the majority of participants believe that students are well-prepared to adopt AI in their university experience, primarily due to their existing technological skills. This belief is supported by the fact that the current generation has grown up in a world where technology is an integral part of their lives, which has made them more adaptable to technological advancements such as AI. Supportively, P2 said "*this generation's mindset is pretty much adaptable to the technology more than any other generation; so that's something making them understanding AI a bit easier.*" P1 also mentioned "*continuing along the line of technological skills.*" Additionally, the ongoing discussions about the ethical implications of AI would further ease the integration of AI into the curriculum. This can facilitate the seamless integration of AI tools into the curriculum while avoiding any negative ethical implications. P4 identified this "s*omebody must communicate to students to say when and where and how they can use these sorts of tools*." The findings suggest that the

implementation of AI in HE has significant impacts for the role of staff (academic and administrative). The most identified impact on the role of the academic staff in BEHE is upskilling, which indicates that educators must learn new skills and knowledge to be able to teach and support students effectively in the context of AI. Supportively, P2 explains *"I should be up to date, I should teach myself, then I should be able to teach the student."* This can impact the role of the educator either positively or negatively. On one hand, upskilling can provide educators with new tools and techniques to enhance their teaching and better prepare students for the evolving job market. However, on the other hand, upskilling can also be a significant challenge for educators, particularly to those less familiar with technology. There may be a steep learning curve associated with adopting AI, and educators may need to invest significant time and effort to learn how to use them effectively.

Potential new ways of assessing students due to AI integration may mean that the traditional methods of evaluation may no longer be sufficient to measure students' success in the context of BEHE. This finding suggests that educators must explore new assessment methods that consider the skills and knowledge required for working with AI. Also, participants revealed the scary potential for AI to automate or replace their jobs. Many negative views were identified around this area. P1 stated *"I think in the early stages. I see it as a threat as an educator…because it's something that I can't use…I will see it as a hassle if I have to learn it."* This reinforces the previous point that educators need to understand the benefits of AI and how it can enhance their teaching methods, rather than perceive it as a threat.

Overall, the findings suggest that educators must be proactive in preparing themselves for the introduction of AI into the BEHE. They will be impacted significantly, and must make effort to upskill themselves, adopt new assessment methods, adapt to changing job requirements, and be open to new ways of teaching and operating in the classroom, in order to stay relevant and effective in their job.

5.1.2 Institutional Level (HEIs, Professional and Funding Bodies)

Integrating AI into BEHE presents significant requirements and demands for HEIs. Funding, guidance, and policy are critical to successful implementation, without which AI integration will be challenging. Identifying 'discussions' as the most crucial institutions step for sustainable AI integration in BEHE highlights the importance of stakeholder communication and collaboration. Success will require active participation from all relevant parties. Funding was also identified as a critical institutional next step, which suggests that HEIs will need to allocate appropriate resources to AI integration. This is particularly important given the high cost of implementing and maintaining AI technology in educational setting. The literature review highlights the importance of addressing ethical considerations before implementing AI in HEIs. Privacy and data sharing, as well as bias in data, are the most identified ethical issues, and HEIs must thoroughly understand these implications before integrating AI into BEHE programs.

The impact and role of the government for AI implementation in BEHE is significant. The participants acknowledged the involvement of the government in establishing frameworks and policies that facilitate universities in their ethical and accurate incorporation of AI. P4 identified that *"regulatory frameworks are needed to be created by governments around how this gets adopted."* Whilst P5 also said "*maybe there should be a national framework in the use of AI rather than the university."*

In summary, the findings provide critical insights into the impacts and requirements of AI integration in HEIs allowing them to develop effective strategies that consider all stakeholders.

6. CONCLUSIONS

This study aimed to investigate the potential for integrating AI technologies into Built Environment Higher Education (BEHE) and evaluate their impact on HE stakeholders. A qualitative analysis of stakeholder experiences and perspectives revealed that AI integration in BEHE offers extensive possibilities and substantial benefits for students including differently abled, institutions, educators, and the construction industry. Successful integration necessitates active involvement from all stakeholders, who operate within a defined hierarchy.

The government holds a vital role in establishing clear ethical frameworks and guidelines to ensure AI's successful adoption across institutions. This includes, addressing data security, finding the right mix of human - AI led education, promoting transparency and equity, and mitigating the risk of discrimination. HEIs are then responsible for communicating these frameworks to all staff and providing adequate training and guidance. Educators are arguably the most affected by AI implementation, as their job roles will significantly evolve. They must proactively develop new skills and maintain their knowledge of AI technology to remain effective and relevant. Students as the primary stakeholders and integrating AI into the BEHE curriculum is anticipated to profoundly enhance their readiness for the evolving construction industry. By equipping students with the necessary skills and tools to effectively utilize AI systems, the construction industry can overcome its current challenges. Fully assessing the impact of AI integration in BEHE is difficult without comprehensive implementation. Therefore, future research should focus on case studies where AI has been thoroughly tested or fully incorporated into BEHE, providing a more complete understanding of its benefits and limitations. The findings further recommended the need of organizational strategy and roadmap, along with ethical and legal frameworks, to govern the appropriate use of AI for successful implementation.

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PRIVATE SECTOR ROLE AS A KEY STAKEHOLDER TOWARDS THE CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY IN SRI LANKA

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ABSTRACT

The construction industry has become a major cause of environmental pollution as it consumes large number of natural resources and energy. Additionally, large amount of waste is added to the environment due to construction activities. Accordingly, protecting the environment from harmful construction activities is a major responsibility of the construction industry. Therefore, the concept of circular economy (CE) has gained worldwide attention as a solution to material waste in the construction industry, as it aims on more sustainable economy by designing products and processes where resources are efficiently and continuously cycled. However, the implementation of CE in the Sri Lankan construction industry is still at an immature stage. Therefore, this study aims to explore the role of the private sector and its potential contribution to the implementation of the CE in the built environment of Sri Lanka. This study has adopted the mixed method and findings emphasize even though that there are many benefits of implementing CE principles in the construction industry, CE principles are still not implemented satisfactorily in the built environment in the Sri Lankan construction industry, at least in the private sector. Also, the findings of the research emphasize that there are barriers under different types such as, technological, social and political for the private sector to implement CE in Sri Lanka's built environment.

Keywords: *Circular Economy; Construction Industry; Private Sector; Sri Lanka.*

1. INTRODUCTION

The construction industry plays a very important role in the development of a country. It contributes significantly to the Gross Domestic Product (GDP) as well as the Gross National Product (GNP). However, various issues have arisen due to activities related to the construction sector and construction waste has become a major issue. It has become a serious environmental problem (T. G. Weerakoon et al., 2023). As currently practicing linear economic model in the construction sector mostly affects this. Due to that the construction industry produces about 25% of solid waste and extracts more than 30% of natural resources (Owojori & Okoro, 2022).

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As a result, circular economy (CE) is getting the global attention as a major support in order to address the construction waste management. The CE model, as proposed by the Ellen MacArthur Foundation, is an environmentally friendly industrial system that aims to minimize waste and maximize resource use (Geissdoerfer et al., 2017). CE is a multi-level resource use system that requires the complete closure of all resource loops, with recycling and other practices contributing to its success. The private sector, which contributes to 90% of employment and contributes to the supply of goods and services, plays a crucial role in implementing CE (Heshmati, 2017).

However, the private sector's contribution to sustainability in the built environment is essential, as the government cannot manage the built environment alone. In the construction industry, public-private partnerships (PPPs) account for significant emissions and impacts on economic sustainability and the environment. In the European Union, PPP projects account for 50% of raw material use, 40% of energy consumption, 36% of greenhouse gas emissions, and 33% of water consumption (Owojori & Okoro, 2022).

The private sector's role in the CE in the built environment in Sri Lanka is under-researched, and this research aims to study the role of the private sector as a key stakeholder for the CE in the built environment. By focusing on the private sector's role in implementing CE, Sri Lanka can contribute to a more sustainable economy and reduce environmental challenges such as resource depletion, urbanization, and climate change (T. G. Weerakoon et al., 2023).

Construction-related activities pose a significant challenge to the global construction industry, leading to the need for CE solutions (Anastasiades et al., 2023). In Sri Lanka, the construction industry is also grappling with waste generation and environmental pollution. Limited research has been conducted on CE implementation in the construction sector, focusing on monitoring measures, barriers, and drivers. However, the focus on stakeholders in the built environment is limited, with the private sector contributing significantly to adverse environmental effects. This research aims to investigate how the private sector can contribute to CE in Sri Lanka's construction industry (Illankoon & Vithanage, 2023).

Accordingly, the aim of the study; which is to explore the role of the private sector and its potential contribution to the implement of the CE in the Construction industry of Sri Lanka is achieved through four major objectives: (1) To identify circular economy principles currently being implemented by the private sector in the built environment in the global and local context, (2) To explore the benefits to the private sector from using the circular economy principles in the built environment in the global and local context, (3) To identify the challenges faced by the private sector in using the circular economy principles in the global and local context and (4) To suggest recommendations to increase the private sector's contribution to the circular economy in the built environment in Sri Lanka (Adams et al., 2017).

2. LITERATURE REVIEW

2.1 CIRCULAR ECONOMY DEFINITION

The Ellen MacArthur Foundation defines the CE as an industrial system that is restorative or regenerative by design, replacing the end-of-life concept with restoration, shifting

towards renewable energy, eliminating toxic chemicals, and aiming for waste elimination through superior design of materials, products, systems, and business models (Guerra & Leite, 2021). CE promotes reuse/recycling of materials, goods, and components to reduce waste generation, minimize resource input and waste, emission, and energy leakage, and optimize resource flow through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. CE is a multi-level resource use system that ensures the complete closure of all resource loops, aiming to eliminate waste and pollution (Ishan et al., 2023).

2.2 IMPORTANCE OF CIRCULAR ECONOMY

The construction industry is a significant contributor to environmental pollution, generating significant waste and material losses (Pan et al., 2015). The linear economic model of "take-make-use-dispose" has failed to address sustainability challenges, particularly in renovation and maintenance. The linear economy produces 25% of solid waste in the construction industry and extracts over 30% of natural resources. In Sri Lanka, construction activities generate 14% of cement, 14% of brick, 10% of ceramic tile, and 10% of wood waste. To address these issues, a sustainable solution is to adopt the CE principles (Kulatunga et al., 2006). CE principles can help achieve resource efficiency in the construction industry, and as the use of CE in Sri Lanka is low, it is crucial to embrace it for the ever-expanding construction industry. By adopting CE principles, the construction industry can reduce waste generation, improve resource efficiency, and contribute to a more sustainable future (P. Weerakoon & Thayaparan, 2023).

2.3 AWARENESS ON CE IN THE CONSTRUCTION INDUSTRY

2.3.1 Global Awareness

As mentioned previously, CE is a major sensation globally. Accordingly, to get a proper understanding regarding the CE awareness, implementation and practices along with the current CE principles in the global context, past studies were reviewed. As per the research studies carried out in the building industry, the European Union (EU) has taken the lead in promoting CE principles (Mahpour, 2018). Policies like the Waste Framework Directive and the EU Circular Economy Action Plan promote the use of sustainable materials and set greater recycling goals. By 2050, nations like the Netherlands and Denmark hope to create a circular construction industry with a focus on closed-loop technology and resource efficiency. The usage of circular buildings with modular designs that facilitate simple disassembly and material reuse, for instance, has been pioneered by the Netherlands. In a similar vein, Denmark has enforced strict recycling laws for construction debris, guaranteeing that materials like wood and concrete are used again rather than being thrown away.

Moreover, while advancing more slowly than in Europe, North America is becoming more conscious of the circular economy's concepts in the building industry (Cruz Rios et al., 2021). Waste reduction and material recycling are two examples of sustainable construction practices that are promoted by the U.S. Green construction Council (USGBC) and its LEED (Leadership in Energy and Environmental Design) certification. However, rather than being required by law, the adoption of CE ideas is mostly driven by the market. Through programs like The National Zero Waste Council, which encourages the reuse of building materials, Canada has made progress in incorporating circular

construction (Guerra & Leite, 2021). In order to integrate circular ideas into urban development, cities such as Toronto and Vancouver have also set high sustainability targets.

Construction industry's understanding of CE is still in its infancy in Latin America and Africa. Financial limitations, a lack of policy enforcement, and inadequate waste management infrastructure are the main obstacles. Nonetheless, certain projects are gaining momentum, such as sustainable home developments that use locally produced and repurposed materials. To encourage sustainable building, Latin American nations like Brazil and Mexico are looking at LEED-style green building certifications. Earth-based building methods, such as compressed earth blocks, are being promoted by organizations in Africa as a sustainable substitute for resource-intensive materials like concrete (Hart et al., 2019).

2.3.2 Local Awareness

As the CE is playing a new role in the Sri Lankan construction industry, it has not been properly implemented locally, while there is also a lack of awareness. Therefore, the study focused on the research carried out in the area of CE in the construction industry. Table 1 provides a summary of the identified research (P. Weerakoon & Thayaparan, 2023).

Table 1: CE awareness in Sri Lanka

Year	Title	Studied Area	Reference
2021	A case study on the application of circular economy principles in the pre-construction phase in the Sri Lankan construction industry	Investigating the use of circular economy in the pre-construction phase of construction projects	Wijewansha et al., (2021)
2023	Evaluation of the adoption of circular economy framework in the construction industry of Sri Lanka	Determine the potential and barriers for circular economy implementation in the construction sector in Sri Lanka	T. G. Weerakoon et al., (2023)
2023	Examining barriers to the adoption of circular economy practices in the built environment of Sri Lanka	Identify barriers to circular economy implementation	P. Weerakoon & Thayaparan, (2023)
2023	Circular economy approaches for waste management in Sri Lanka, emphasizing demolition, repurposing, material recovery, and production phases	Analyse the implementation of circular economy strategies in the construction sector	Victar & Waidyasekara, (2023)
2023	Highly efficient circular economy practices across the life cycle of construction projects	Investigating the most effective circular ecoomy practices at each stage of a construction project's life cycle	Ishan et al., (2023)

Year	Title	Studied Area	Reference
2023	Incorporating circular economy principles into modular construction for enhanced sustainability	Integrating circular economy principles into Modular Construction (MC) processes	Garusinghe et al., (2023)
2023	The contribution of quantity surveyors to circular economy principles in the pre-contract phase of construction projects in Sri Lanka	The role of quantity surveyors about circular economy principles at the pre-contract stage	Jayawardhana & Withanage, (2023)

2.4 PRINCIPLES OF CIRCULAR ECONOMY IN THE CONSTRUCTION INDUSTRY

Although CE systems are currently being implemented, implementing process of CE concept need to be address systematically. Accordingly, CE goals and principles need to be better considered and translated into actions, and more coordinated actions among different levels of implementation are necessary (Suárez-Eiroa et al., 2019). Initially, the CE concept was based on the 3R principle, i.e., reduce, reuse, recycle. The principle of reduce improves the efficiency of production and consumption and reduces the input of primary energy, raw materials and waste.

For the past decade, CE has been discussed in-lining with different principles and frameworks (Amudjie et al., 2023). Recently conducted study by Amudjie, et al. (2023), summarize the currently existing and practicing CE principles briefly. Accordingly, R models were identified. Among these R models the most common and the convenient one is the 3R principle, which refers to the Reduce-Reuse-Recycle model (Munaro & Tavares, 2023).

According to the study done by Amudijie, et al. (2023), principles of CE can be summarized as presented in Table 2.

Table 2: Summary of CE principles

CE Principle	Concept of the Principle	Source of reference
3R Model	Reduce- Recycle- Reuse model	Patwa et al., (2021)
6R Model	Reuse- Recycle- Redesign- Remanufacture- Reduce- Recover model	Geissdoerfer et al., (2017)
9R Model	Refuse- Reduce- Reuse- Repair- Refurbish- Remanufacture- Repurpose- Recycle and Recover	van Buren et al., (2016)
5R Model	Rethink- Reduce- Reuse- Repair- Recycle	Ping Tserng et al., (2021)
10R Model	Recover- Recycle- Repurpose-Remanufacture- Refurbish- Repair- Reuse- Reduce- Rethink and Refuse	Potting et al., (2016)
11R Model	Recover- Recycle- Repurpose- Remanufacture- Refurbish- Repair- Reuse- Reduce- Rethink- Refuse and Replace	Çimen, (2021)

However, according to Acevedo-García et al., (2020), the most common and applicable method of CE principles has identified as the 6R principle. Over and above that Kosanović et al., (2021) have identified a slightly different set of CE principles which also can be applicable in the construction industry and summarized in Table 3.

Table 3: Principles of circularity

	Circularity Principle (CP)
CP1	Circular Supply
CP2	Decreased Material Use
CP3	(De)construction Waste Reduction
CP4	Long-lasting Use
CP5	Easy Repair and Maintenance
CP6	Upgrade Sharing Product as a Service
CP7	Reselling
CP8	Reuse
CP9	Recycling
CP10	Recovery

It can be commonly understood that most common CE principles are mainly dealing with the different 'R' models, and these different concepts are practiced in different perspectives in the construction industry.

3. METHODOLOGY

This study used a mixed method approach by gathering data in both quantitative and qualitative base. Accordingly, both expert interviews and questionnaire surveys were carried out. The questionnaire survey was distributed among professionals in various disciplines, with an 84% response rate. Consequently, the survey collected quantitative data from 42 construction industry professionals, including project managers, engineers, quantity surveyors, and architects. Moreover, the literature review covered CE definitions, the importance of CE in global and local contexts, and CE research conducted globally and locally in the construction sector. Six expert interviews were conducted with construction industry professionals, selected based on purposive sampling techniques. Through expert interviews, the benefits of CE principles in the local context were identified, along with the challenges faced by the private sector in applying CE principles. Specifically, both primary data and secondary data were collected. Objective one was achieved through a literature review and collected data was verified using expert interviews. Data for objectives two, three and four were collected through questionnaire surveys and validated through expert interviews. The data collected was analysed using manual analysis with the support of Microsoft Excel tools.

4. DATA ANALYSIS AND DISCUSSION

4.1 EXPERT INTERVIEWS

Six expert interviews were carried out and participants represent various areas in the industry; Accordingly, the team was compiled with three project managers, two charted civil engineers and a Charted Quantity Surveyor who have industry experience for more than 15 years. Interview guideline was classified under three main themes, where majorly focus on research objectives. Following presented is the summary on the experts' point of view on the particular themes.

4.1.1 Theme 1- Implementation of Circular Economy (CE) Principles in the Sri Lankan Construction Industry

According to the experts, foreign countries have paid special attention to implementing CE principles to the construction practices massively and two experts out of six emphasized that USA and European countries have paid special attention to these principles. Interviewees emphasized that some projects in private sector have implemented CE principles up to a certain extent in the Sri Lankan context, but it is very low when compared with foreign countries. Additionally, interviewees, mentioned that the 3R principle; Reduce, Reuse and Recycle which were also identified as the basic CE principles, are currently being practiced, but the implementation and the practice of the rest of the principles such as repair, renewability, repurpose etc. is in a poor level.

Additionally, in the perspective of reduction, reducing the construction waste, reducing the energy and water consumption has been addressed. And also, the experts stated that, alterations have been introduced for some of the existing construction materials as a result of CE practices.

Interviewees highlighted the principle of recycling in construction is practiced during the reuse of materials like valves and aluminium. They highlighted the use of system formwork for large-scale projects and the recycling of old iron and aluminium, as well as paint and bathroom fittings. Furthermore, interviewees stated that CE principles such as repurpose, refurbishment, renewable, and reconsideration in the construction industry is a key focus of the Green Building Council of Sri Lanka (GBCSL). Examples for implementing such CE principles in the construction industry include landfills, recycling, and reusing waste. The use of alternative fuels like waste clothing, oil, and wood dust can reduce coal usage by 50%. Moreover, building design incorporates large openings for natural airflow and proper sunlight orientation. INSEE Cement and INSEE Eco cycle Lanka are examples of projects implementing CE principles in the private sector.

4.1.2 Theme 2- Benefits of Implementing CE for the Private Sector in Sri Lankan Construction Industry

Majority of the interviewees emphasized that CE implementations in the private sector in Sri Lankan's construction sector can significantly reduce material wastage and resource wastage, which can be identified as a massive benefit in the first place. Accordingly, experts stated that technological monitoring of material wastage allows for control and decision-making, while computerized systems can monitor energy consumption and water usage which make a positive impact on the industry. Moreover, precast concrete and sustainable building components can reduce cement requirements and heat inside buildings. Therefore, as per the experts, CE principles are profitable in the long run, even

with higher initial costs for special technical equipment and materials. They can reduce raw material, plant, and labour costs, and contribute to environmental protection. Despite the increase in implementation of CE principles in the Sri Lankan construction industry, environmental pollution remains unsatisfactory. Most large-scale industrial companies focus on short-term profits rather than preserving the environment. Despite this, CE principles are being implemented in the private sector, contributing positively to the preservation of resources and the environment for future generations.

4.1.3 Theme 3- Suggestions to Improve the Circular Economy Practices in the Sri Lankan Built Environment

Even though the implementation of the CE principles in the Sri Lankan construction industry has increased, environmental pollution remains a significant issue. Large-scale industrial companies have primarily focused on CE principles, while small and medium-sized companies have not. Accordingly, to address this, several suggestions have been presented by the experts, including educating society, establishing rules and regulations, conducting training programs, setting up incentive schemes, limiting energy supply, and not approving designs incompatible with CE principles. Moreover, experts stated that, Government support is crucial for implementing CE principles in the construction industry, as it is difficult for the private sector to carry out alone. Government funds and incentives should be provided to promote CE principles within the local built environment. The initial cost of implementing CE is high, so investors should be sought. In addition to that, using high-quality materials for construction can support implementing CE. Further, commencing construction after all designs are completed can minimize defects and re-construction. Promoting green practices and renewable energy also can enhance the concept of CE. Moreover, following suggestions were raised; companies can motivate their employees to implement CE by offering awards and competition, concepts like Zero Energy Building (ZEB) and Net Zero Energy (NZE) can also help reduce electricity consumption and save the environment.

4.2 QUESTIONNAIRE SURVEYS

4.2.1 Demographical Data

The questionnaire survey was carried out with the professionals who are with construction industry experience. The questionnaire was distributed among 50 professionals, and the response rate was recorded as 84%, which consists of 33.33% each of civil engineers and quantity surveyors and 14.29%, 11.9%, 4.76% and 2.38% respectively from the backgrounds of electrical and mechanical engineering, architecture and project management. Meanwhile there are 14 employees in each group, with the majority of responders having 0–5 and 5–10 years of work experience. Eleven employees, representing a moderate proportion, fall into the 10- to 15-year experience category. There are only three employees in the 15–20-year experienced category, which has the lowest representation.

4.2.2 Contextual Data

Contextual data was considered under couple of areas, which has been summarized in the Table 4.

Table 4: Summary of collected data

Questioned Area	Summary of the Data
Awareness on CE principles	The survey shows that 76.2% of industry professionals are aware of the benefits of circular economy principles, while 14.3% are not, and only 9.5% have a comprehensive understanding.
Benefits of implementing CE to the private sector	The survey revealed that 34.1% of respondents believe that implementing CE principles to minimize waste generation and reduce costs as the main benefit followed by 26.8% who believe it is long-term cost reduction. 19.5% believe resource efficiency and long-term profit are the main benefits. Implementing these principles has enabled efficient use of materials and resources, reduced project costs, and reduced energy consumption. A small percentage of respondents believe it contributes to increased company profits. Overall, 81% of respondents believe the circular economy concept will benefit their organization in the long run while the rest 19% do not have a clear picture about the benefits.
Barriers of implementing CE	The majority of respondents, 42.9% identified limited access to resources, such as trained workforce and modernized equipment, as a barrier. Additionally, 28.6% identified lack of financial resources, 19% mentioned low demand for circular economy implementation, and 9.5% stated lack of public sector support as the additional barriers.

Furthermore, with a broad focus on the barriers to implementing CE principles in Sri Lanka's construction sector, political and regulatory barriers, social barriers, and technological barriers were identified. The following figures show the barriers identified according to the respondents.

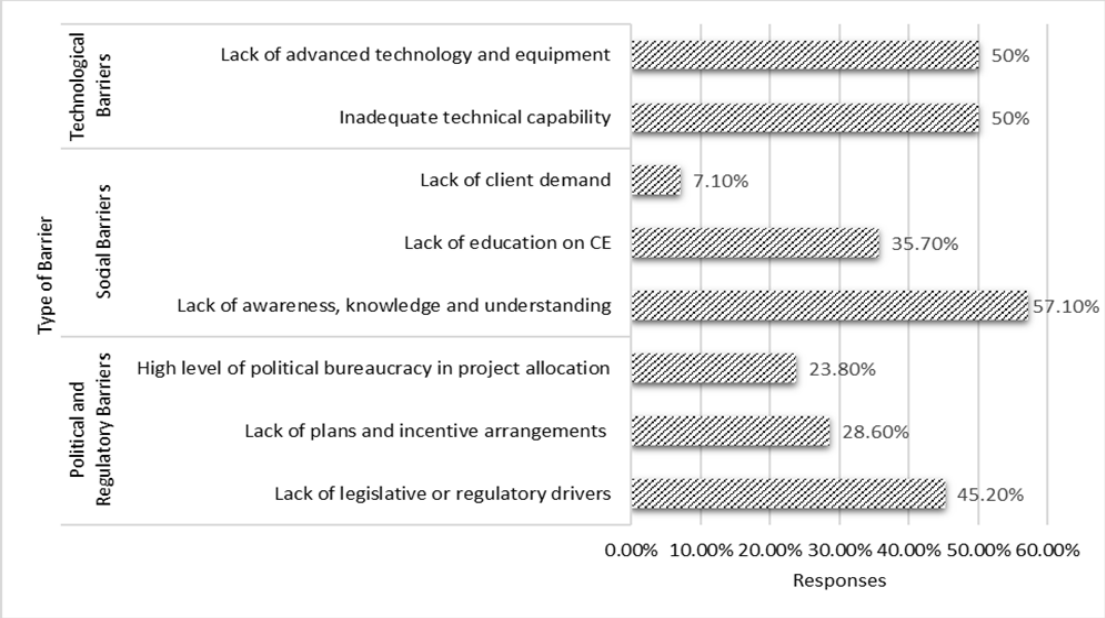


Figure 1: Barriers for implementing CE principles

According to the collected data, considering the political and regulatory barriers of implementing CE in private sector, majority highlighted lack of legislative or regulatory

drivers and it was 45.2%, meanwhile the rest stated lack of plans and incentives as well as high level of political bureaucracy in project allocation also has a certain impact on implementing CE principles in the construction industry. In account of social barriers, majority of respondents; 57.1% identified lack of awareness, knowledge, and understanding on the CE concept as the main barrier, also, 35.7% have identified lack of education on CE strategies among stakeholders while, 7.1% of the respondents identified lack of client demand as a barrier to implement CE principles in construction industry. Finally on the aspect of technological barriers, 50% of the respondents identified inadequate technical capability and expertise in CE as a barrier, while the other 50% of the respondents identified lack of advanced technology and equipment to implement CE as the main technological barrier.

As the latter part of the questionnaire, participants were questioned regarding the recommendations to increase the contribution of the private sector to the circular economy in the construction sector in Sri Lanka. Accordingly, 45.2% of respondents emphasized that it is important to introduce special benefit schemes for the private sector stakeholders in the construction industry. Meanwhile 28.4% of respondents recommend training sessions for private sector parties in the construction industry and 14.3% of respondents recommended introducing technology facilities for CE practices in the Construction industry. Finally, 11.9% of respondents recommended developing regulations to adopt the CE concept in the construction industry.

The implementation of CE principles in the construction industry in Sri Lanka is relatively low, compared to countries like the USA and Europe. However, the private sector is increasingly adopting CE principles, such as reducing waste generation, reducing energy consumption, and using building demolition waste for landfills. The 3R principles of reduce, reuse, recycle, repurpose, rethink, renewability, refurbish, and recover are being implemented, but small and medium-scale construction companies are not paying attention to these principles.

The research confirms that adopting CE principles can bring long-term benefits to the private sector, including financial savings, environmental sustainability, and increased profitability. However, the private sector faces challenges such as limited access to resources, financial constraints, low client demand, and lack of public sector support.

To increase the private sector's contribution to the circular economy, the research recommends introducing special benefit schemes, conducting training sessions, and establishing necessary laws and regulations. Additionally, awarding certificates and recognition to companies that excel in CE implementation can encourage others to adopt the concept. Government support is also essential for the successful implementation of CE principles in the construction industry.

5. CONCLUSIONS

Initially the study focused on the CE principles currently being implemented by the private sector in the built environment in the global and local context and the as per the collected data primarily and secondarily, emphasized that although there are several CE principles currently operating in the Sri Lankan construction industry, compared to the global context, the implementation of CE principles in the Sri Lankan construction industry is in a low level. Secondly the attention was caught on the point, how the CE implementation could positively be impacted on private sector in Sri Lanka. Accordingly,

the findings showed that the private sector can achieve many benefits by using CE principles, such as minimization of waste generation, long-term cost reduction and resource efficiency, long-term profitability etc.

Thirdly, consideration was paid on the challenges faced by the private sector in using the CE principles. Accordingly, the results showed that various barriers arise for the private sector in implementing CE principles. Limited access to adequate resources such as a trained workforce and modernized equipment, lack of financial resources, low client demand for CE and lack of adequate support and incentives from the public sector were identified as the barriers to implementing CE in private sector. Final objective was to propose suggestions to increase the private sector's contribution to the circular economy in the built environment in Sri Lanka. Several proposals were put forward to as suggestions. In summary, Introduction of special benefit schemes for private sector stakeholders in the construction industry by government authorities involved in the construction industry, conducting training sessions for private sector stakeholders, introducing technologies facilitating circular economy practices and developing regulations to adopt the circular economy concept in the construction industry were suggested by the participants.

5.1 RECOMMENDATIONS AND LIMITATIONS

In conclusion the proposed recommendations can be summarized as, introduction of special benefit schemes by the government such as, tax subsidies and incentives for companies that follow CE principles, and awards etc. Moreover, conduction training sessions, use of advanced technical facilities and development of regulatory frameworks were recommended. The research study is mainly focused on the potential contribution of implementing CE principles in the private sector construction industry in Sri Lanka.

5.2 WAY FORWARD

As a suggestion to future studies, examining the readiness of other construction professionals (government agencies, academics, and civil society) to embrace this concept, and analyse the cost-effectiveness of adopting CE principles in the construction sector compared to the linear economy concept, can be considered.

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PROJECT DATA RESPONSIBILITIES FOR CARBON ASSESSMENT IN SRI LANKAN CONSTRUCTION INDUSTRY

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ABSTRACT

The construction industry is a significant contributor to global greenhouse gas emissions, driven by both embodied and operational carbon emissions. In Sri Lanka, the lack of a national standard and limited availability of local data have constrained effective carbon measurement and reduction. This study explores stakeholder data responsibilities in carbon assessment, focusing on the Sri Lankan construction sector. Drawing on semi-structured interviews with 18 experts, the research identifies the process-based Life Cycle Assessment (LCA) method as the most appropriate for project-level carbon quantification. In contrast, the input-output method is recognised as a practical alternative in data-scarce situations. The study highlights the importance of stakeholder engagement across life cycle stages, with clients responsible for setting sustainability goals, consultants for conducting carbon calculations, contractors for collecting project data, and government bodies for establishing regulatory guidance. Key data types and stakeholder contributions are identified across construction stages, offering insights to enhance the accuracy and credibility of carbon assessments. The findings offer practical recommendations to promote more sustainable practices and enhance carbon accountability in Sri Lanka's construction industry.

Keywords: *Carbon Assessment; Construction Industry; Data Management; Life Cycle Assessment (LCA).*

1. INTRODUCTION

The global construction industry has a considerable impact on society and the environment (Crawford, 2022). Moreover, it is recognised as a major contributor to greenhouse gas (GHG) emissions, which in turn affects climate change and global warming (Labaran et al., 2021). While numerous studies have highlighted the significance of carbon assessment and emission-reducing policies for the built environment (Xu & Macaskill, 2023), developing countries are aiming to implement effective policies to reduce greenhouse gas emissions by 37% within the next decade (Berlie, 2018). Moreover, international policies have specified principles and guidelines for quantifying the carbon footprint (Kumari et al., 2022).

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Accurate carbon assessment in construction relies on the use of reliable data, which plays a significant role in reducing carbon emissions (Lai et al., 2023). According to Zhu et al. (2023) and Du et al. (2018), the most prominently used carbon assessment method in construction is life cycle assessment (LCA), which is further categorised as process-based analysis, input-output analysis (IOA) and hybrid analysis. In the Sri Lankan context, both process-based analysis and input-output analysis (IOA) approaches are employed, depending on the availability of data (Kumanayake & Luo, 2018a). When comparing them, the input-output method focuses on product groups in the economy, while the process-based method focuses on specific products and services (Han et al., 2022). However, due to a lack of embodied carbon coefficient data for SL, they often rely on international databases such as the Inventory of Carbon and Energy (ICE) or adjust such data for each condition to perform the carbon calculations (Kumanayake & Luo, 2018a). This emphasised a critical gap in the absence of a national database and a standardised method for data collecting, reporting, and management in the Sri Lankan context (Kumanayake & Luo, 2018a).

The effectiveness of carbon assessment is further influenced by the diverse roles and responsibilities of stakeholders involved in the project lifecycle (Xu & Macaskill, 2023). Therefore, clearly defined data responsibilities and data collection processes are crucial for facilitating reliable carbon assessments. However, currently there is no standardised guideline for stakeholder roles and responsibilities in carbon data management and reporting within the Sri Lankan construction industry (Kumanayake & Luo, 2018a).

Addressing this knowledge gap in existing literature, this study aims to explore the Project Data Responsibilities of stakeholders for carbon assessment in the Sri Lankan construction industry. It seeks to identify the carbon assessment methods currently used in the Sri Lankan construction industry, determine the roles and responsibilities of stakeholders in carbon assessment, and assess the specific data contributions of stakeholders throughout the building's life cycle. By clarifying stakeholder data roles and establishing standardised processes, this research aims to enhance the accuracy and reliability of carbon assessments, supporting Sri Lanka's efforts toward sustainable construction and effective climate change mitigation actions.

2. LITERATURE REVIEW

2.1 GLOBAL CARBON EMISSIONS

Carbon emissions have increased due to economic and population growth, with carbon dioxide being the dominant greenhouse gas (Xiong et al., 2024). Human activities, such as the use of fossil fuels and cement production, contribute to around 80% of global GHG emissions. The construction sector alone is responsible for 30–40% of these emissions (Zhang & Zhang, 2020). Both embodied and operational carbon emissions of buildings and infrastructures are responsible for these emissions (Mohebbi et al., 2021). Despite this impact, Yang et al. (2018) highlight that the construction industry has not prioritised emission management. Emissions are typically categorised into Scope 1, 2, and 3 for structured reporting (Kim & Kim, 2021). However, Jusoh and Hashim (2018) emphasise that having sufficient data on GHG emissions is essential to support the effective development of climate policies.

2.2 ACTIONS TOWARDS GLOBAL EMISSIONS REDUCTION

Since the late 20th century, international agreements such as the Kyoto Protocol and the Paris Agreement have been introduced to slow down climate change by reducing GHGs (Liu et al., 2022). The Kyoto Protocol focuses on all six major GHGs, while the Paris Agreement aims to limit global warming between 1.5°C and 2°C (Kuriyama & Abe, 2018). Therefore, achieving carbon neutrality by reducing CO2 emissions has become a global priority, with the introduction of net-zero goals to minimise climate change (Huang & Zhai, 2021).

In Sri Lanka, efforts to measure building-related energy use and CO_2 emissions have begun to emerge. Kumanayake et al. (2018) emphasise the importance of this data as a foundation for national mitigation strategies. Therefore, a detailed assessment of construction carbon emissions is very important for policy regulations and carbon emission reduction (Kumanayake et al., 2018; Hung et al., 2019).

2.3 CARBON ASSESSMENT METHODS IN THE CONSTRUCTION INDUSTRY

Several methods are used to calculate construction-related carbon emissions. Among them, Life Cycle Assessment process-based analysis (LCA) and Input-Output Analysis (IOA) are the most widely adopted (Xiong et al., 2024). LCA is more suitable for project-level evaluations, as it tracks emissions throughout the life cycle of a building. In contrast, IOA offers a broader view by analysing economic flows between industries, making it better suited for regional or national studies (Xiong et al., 2024). However, each method has limitations. IOA lacks specificity for individual projects, while process-based method can be data-intensive and time-consuming. To bridge this gap, some studies have used Hybrid LCA, which combines both approaches. This method enhances accuracy but increases complexity and data requirements (Luo et al., 2019).

Beyond the core methods, techniques such as the Emission Factor method and Real Measurement Method are also used in certain contexts. In Sri Lanka, LCA is the primary carbon assessment method used in the construction industry (Nawarathna et al., 2021). Nevertheless, local applications often rely on international datasets due to the absence of Sri Lanka-specific emission factors. This reliance compromises the accuracy and relevance of the results (Kumanayake & Luo, 2018a).

2.4 DATA TYPES USED FOR CARBON ASSESSMENT IN DIFFERENT LIFE CYCLE STAGES

Input data is generally divided into two types as data stored in databases (materials, construction activities, and energy sources) and user-entered data like material quantities, energy consumption, and project-specific information (Kumanayake & Luo, 2018a). These data are collected from various existing databases, standards, and reports. However, due to regional differences, climate, geography, and technology and construction practices the significant variations can happen in the LCA outcomes (Kumanayake & Luo, 2018a). This highlights the need for country-specific data to accurately reflect local energy and carbon emissions (Kumanayake & Luo, 2018a). Moreover, depending on the calculation method, the results differ even for the same building, as each relies on different data sources (Lu et al., 2024). Table 1 demonstrates the data types used in carbon calculations in each stage.

Table 1: Data types used for carbon assessment in different life cycle stages

Stage	Data type	1	2	3	4	5	6	7	8	9	10
Raw material supply	Material type	X							X		
	Energy use intensity	X									
	Carbon emission coefficients of materials				X			X		X	
	Material quantity					X		X	X	X	
	Material embodied carbon factor			X		X					
Transportation for production and distribution	Type of vehicle		X		X		X				
	Capacity of vehicle				X						X
	Fuel type				X						
	Transportation distance		X	X	X	X	X	X	X	X	X
	Weight of material					X	X	X		X	X
	Carbon emission factor				X		X	X	X	X	X
	Number of trips			X							
Manufacturing	Energy consumption	X			X						X
	Carbon emission factor	X	X		X		X		X		
	Material Qty		X	X	X		X				X
	Total no. of materials	X		X	X						X
	Types of machinery				X		X				
Construction	No. of construction activities			X	X				X		X
	Qty of construction activity				X				X		X
	Fuel/electricity use rate			X	X					X	X
	Carbon emission factors			X	X			X	X	X	
	Quantity of materials					X					
	Site waste					X					
	Machinery use							X	X	X	
	Working time of the machinery								X		
Operation stage	No. of energy sources				X						
	Average annual energy consumption			X	X		X	X	X	X	X
	Carbon emission coefficient			X	X						
	Life span of building			X	X				X	X	X
	Average life span of building material				X					X	X
	Material qty required for repairs and replacement			X						X	
	Repair/replacement rate for material			X	X					X	X
	Carbon emission factor of replacing/installing material			X						X	

Stage	Data type	1	2	3	4	5	6	7	8	9	10
	Refrigerant consumption					X		X		X	
	Annual leakage rate					X					
	Performance of cooling systems						X	X			
End of life	No. of demolition activities			X	X				X	X	X
	Quantity of demolition activity			X	X				X		X
	Carbon emission factor			X	X				X	X	
	Number of trips			X			X				
	Distance			X			X				X
	Area of the building						X	X			X
	Average waste amount per m^2						X				
	Energy consumption										X

[1] (Zhang et al., 2019), [2] (Royal Institution of Chartered Surveyors, 2012), [3] (Kumanayake & Luo, 2018b), [4] (Kumanayake & Luo, 2018a), [5] (Royal Institution of Chartered Surveyors, 2012), [6] (Zhang, X. & Wang, F., 2015), [7] (Zhao et al., 2024), [8] (Zhang, Z. & Wang, B., 2015), [9] (Shang & Geng, 2021), [10] (Chou & Yeh, 2015)

Carbon assessments rely on both database values (e.g., emission factors, material types) and user-entered data (e.g., quantities, distances, energy use) (Kumanayake & Luo, 2018a). Table 1 shows that stages like raw material supply, transportation, and operation require the most diverse data inputs. For instance, transport depends on fuel type, trip count, and distance, while the operation stage involves energy sources, building lifespan, and replacement rates. These variations show that different stages demand different data depths, and results can vary significantly depending on the method and data used (Lu et al., 2024). In Sri Lanka, the lack of local data often leads to the use of foreign databases, reducing the reliability of results (Kumanayake & Luo, 2018a). This risks misleading decisions and weakening carbon reduction strategies. Developing a national carbon data system is therefore critical to support accurate assessments and align with net-zero goals (Dong et al., 2023; Xu & Macaskill, 2023).

Developing countries like Sri Lanka face challenges due to the lack of reliable data and carbon-related studies, making it essential to develop national databases for accurate analysis (Kumanayake et al., 2018a). Without reliable data, stakeholders like governments, developers, and builders risk making incorrect assumptions, setting unrealistic targets, and implementing ineffective policies, potentially undermining net-zero goals (Xu & Macaskill, 2023). Therefore, in LCA, accurate data collection is foundational to avoid overestimating or underestimating emissions, which impacts the decision-making process in the construction industry (Andreux & Henrysson, 2023).

2.5 STAKEHOLDERS INVOLVED IN THE CONSTRUCTION CARBON ASSESSMENT

Stakeholders play a critical role in the successful adoption and implementation of relevant net-zero strategies and carbon reduction policies (Falana et al., 2024a). Collaboration among stakeholders has been identified as a key strategy in realising net-zero carbon buildings for the integration of carbon reduction practices in achieving green building objectives (Falana et al., 2024a). While green building principles recognise the

importance of stakeholder contributions, especially in data management and emissions tracking, most countries still lack clearly defined stakeholder roles specifically for carbon assessment.

Green buildings target reducing carbon emissions during all lifecycle phases, with the contribution of stakeholders in minimising carbon impacts (Kaya & Scolaro, 2023). Therefore, those key Stakeholders were identified, such as clients, contractors, architects, engineers, manufacturers, facilities managers, governments and non-government organisations, who need to be actively involved in managing emission-related data across the building life cycle (Falana et al., 2024b). Despite the growing relevance of stakeholder engagement, existing studies rarely explore their specific responsibilities in emission tracking across life cycle stages, indicating a critical gap in both research and practice (Falana et al., 2024a).

3. RESEARCH METHOD

Research is a systematic approach that discovers new knowledge, verifying existing facts, analysing their relationship to formulate theories that explain phenomena (Bhagyamma & Ramesh, 2023). The choice of a suitable research approach among qualitative, quantitative and mixed approaches depends on the nature of the available information for the study (Pandey & Pandey, 2015). The qualitative approach is exploratory, suited for the discovery of new insights and the formulation of new theories, while the quantitative approach is basically used for measuring and analysing numerical data (Kothari, 2004; Taherdoost, 2022). The mixed method approach is a combination of both quantitative and qualitative approaches, which expand the findings of one method by using the other and then mix the data in analysis and get the results (Abutabenjeh & Jaradat, 2018). Therefore, to explore new insights of this novel concept in-depth, this study employed the qualitative approach.

Interviews provide a straightforward approach to gathering details in-depth, where there is less knowledge to explore. There are three types of interviews as structured, semi-structured and unstructured interviews. Out of them, semi-structured interviews are widely used as they allow flexibility to discover new ideas from experts. Therefore, the data collected through semi-structured interviews in this study. The qualitative data was analysed using thematic analysis with the aid of NVivo software to ensure the clarity of the data analysis. The profile of the experts who participated in the interviews is summarised in Table 2, providing an overview of their experience, qualifications and areas of expertise.

Table 2: Details of the experts

Int. code	Designation	Experience		Qualifications
		Cons.	Carb.	
E1	Senior Lecturer	12+	5+	GREEN SLAccP, Research publications in carbon assessment
E2	Senior Professor	0	12+	Research publications related in carbon assessment, Founder of carbon calculating software
E3	Senior Professor	25+	15+	Research publications in Carbon assessment, GREEN SLAccP

Int. code	Designation	Experience		Qualifications
		Cons.	Carb.	
E4	Researcher	7+	5+	Research publications in carbon assessment, GREEN SLAccP
E5	Senior lecturer	11+	5+	Research on embodied carbon-related emissions in buildings
E6	Lecturer	6+	5+	Facilities manager and Health and Safety officer in the manufacturing industry
E7	Researcher Assistant	5+	7+	PhD in sustainable built environment, construction LCA-based publications and sustainability manufacturing
E8	Lecturer	10+	5+	Research publications related to sustainable construction and building carbon emissions.
E9	Senior Lecturer	8+	6+	Research related to sustainable built environment, GREEN SLAccP, Carbon Assessment consultant
E10	Manager (Sustainability)	-	10+	Verification, certification, and advisory services for an organisation's carbon emissions
E11	Green Building Analyst	5+	5+	Master's in sustainable construction architecture, involved in LCA carbon assessment, IGBC Accredited Professional
E12	Project Lead	8+	7+	Visiting Lecturer and Project Evaluator, Former General Manager at GBSL, External Carbon Consultant, GREEN SLAccP, Civil Engineer
E13	Acting Chief Executive Officer	-	10+	Carbon verification in organisations and services, GHG auditing
E14	Executive Envir. Sustainability	5+	4+	LEED & Green Building Certification and Rectification
E15	Senior Engineer (Green projects)	9+	6+	Involved in Carbon footprint assessment and LCA of buildings, LEED Green Associate, IGBC Accredited Professional
E16	General Manager	25+	5+	Green auditing, GREEN SLAccP
E17	General Manager	30+	-	Involved in Green buildings and low-energy embodied materials selection, green accreditation practices
E18	Senior QS	30+	5+	Involved in sustainable construction practices

As presented in Table 2, 18 Experts were selected under three categories as academia, carbon analysts and construction professionals. Their selection criteria were having more than 5 years of experience in the construction industry and a carbon assessment to ensure their knowledge aligned with the objectives of the research.

4. RESEARCH FINDINGS

4.1 CARBON ASSESSMENT APPROACHES IN THE CONSTRUCTION INDUSTRY

The interview findings revealed that the primary carbon assessment methods are process-based LCA, input-output and hybrid approaches. The majority of the interviewees (E3, E4, E5, E6, E7, E9, E10, E16) highlighted the suitability of the process-based LCA method in the construction industry. They cited its ability to provide comprehensive and detailed emission calculations across all stages of a building's life cycle, including embodied and operational carbon. However, the E1, E3, E5, and E8 groups of experts suggested the input-out method as a viable option due to the practical availability of data. Additionally, E10, E11, E18, and E16 experts recommended the use of international standards, such as the GHG Protocol, ISO 14064-1, and ISO 14064-2, as well as methods specified in BRE and EN standards for carbon assessment. However, 70% of the interviewees selected the process-based LCA method as the most suitable carbon assessment approach for the Sri Lankan context. As identified, the reason for this preference was the ability to provide detailed and accurate emission calculations than the other methods. Five experts acknowledged the challenges associated with data availability and suggested applying input-output approach in cases where data is limited.

The literature findings summarise that the most used carbon assessment approach is life cycle assessment (LCA), according to the authors Xiong et al. (2024) and Zhang et al. (2019). Further studies confirmed that the process-based method is the most accurate LCA method suitable for single-building carbon emission assessment. In contrast, the input-output method is suitable for sector-level or region-level calculations (Liu et al., 2022). However, in the existing literature, no specific method has been suggested for Sri Lanka. Few studies by Kumanayake and Luo (2018a), Nawarathna et al. (2021) have been carried out in Sri Lanka using the LCA approach.

Through the expert interviews, both process-based methods and input-output methods were suggested for Sri Lanka, while some experts recommended the process-based method as the most ideal method due to its clarity few experts suggested input input-output method due to a lack of data in the current situation. Therefore, based on the literature findings and confirmation by the opinions of the majority of experts, the process-based method can be proposed as the most suitable approach for carbon assessment in the Sri Lankan construction industry.

4.2 STAKEHOLDERS' ROLES AND RESPONSIBILITIES IN CARBON ASSESSMENT AND CARBON DATA MANAGEMENT

The findings of expert interviews confirmed a significant gap in defining clear roles and responsibilities for carbon assessment and data management in the Sri Lankan construction industry. Most experts agree that the absence of defined roles and responsibilities among stakeholders, as well as inadequate regulatory requirements, has led to inefficiencies and inaccuracies in carbon reporting.

The client or developer is identified as the primary stakeholder responsible for initiating the carbon assessment by setting up sustainable goals. However, E3, E7, E11, and E13 highlighted that they are not directly involved in providing specific data for the calculations. E16 noted two primary responsibilities: setting the objectives and allocating funding. Consultants are identified as the key stakeholders in conducting carbon

calculations and providing guidance. Contractors play a central role in data collection, collaborating with suppliers and manufacturers to gather data on materials and processes, as well as collecting on-site emissions data. The experts also highlighted that the government is responsible for setting out regulations and standards to promote the concept, though their current efforts are not sufficient. E16 highlighted the significance of government encouragement to make this a success, while E3 mentioned some government contributions, such as the Blue-Green economy and material rating systems in the Construction Industry Development Authority (CIDA). As identified, non-governmental organisations like the Green Building Council Sri Lanka (GBCSL) also carry a similar responsibility in promoting green building practices within the community through training and accreditation; however, according to the E10, their influence is constrained without stronger government support.

Although the previous literature has not defined any clear role and responsibility for stakeholders in carbon calculations and carbon data management, Fenner et al. (2018), and Kaya and Scolaro (2023) noted the stakeholder involvement in green buildings. Therefore, stakeholder roles were defined through expert opinions as the client and the consultants are responsible for doing the calculation, while the contractor plays a major role in providing and collecting data. Contractors should communicate with the other stakeholders, like manufacturers, suppliers and subcontractors, to acquire data and need to provide it to the consultant. Facilities managers are the key people to collect operation stage data, and at the end, demolition contractors or waste management authorities will be involved as per the requirements of the client.

4.3 DATA CONTRIBUTIONS OF STAKEHOLDERS IN LIFE CYCLE STAGES

The extraction of raw materials stage and the manufacturing stage are considered similar stages for carbon assessment due to the method of conducting carbon calculations. The manufacturer is identified as the primary stakeholder responsible for providing carbon-related data in both stages, according to the opinion of the majority of experts, where 11 experts suggested the extraction stage, and 13 experts suggested the manufacturing stage. The supplier is the next most important stakeholder, as they provide data on material transport and the embodied carbon of the product. However, as highlighted by experts E1, E11, and E15, suppliers and manufacturers typically pass this data to the contractor, who is responsible for collecting all the data and providing it to the consultant who is performing the actual carbon calculations. The key data types required for carbon calculations in these stages include emission factors, material quantities, and energy consumption. Experts such as E2, E8, E9, and E11 emphasised the use of Environmental Product Declarations (EPDs), while E3 and E4 mentioned databases like ICE to acquire carbon coefficients for materials. However, experts highlighted the importance of emission factors for fuel and electricity and proposed the use of recycled materials as a data type, which is less emphasised in existing literature.

During the construction stage, all experts noted that the contractor has a central responsibility for collecting carbon data, with the support of other stakeholders, including subcontractors, suppliers, and industry practitioners. Essential data types include energy consumption (electricity and fuel), machinery usage (number of working hours and construction activities), emission factor and waste generation. In the qualitative data analysis, the term “emission factors” is used to represent all carbon emission factors related to materials, fuel, and electricity for ease of presentation. As emphasised by E7,

these data points can vary depending on the specific processes used on-site. The new data type identified through the interviews was water usage at the site.

The transport stage involves multiple phases, and Experts E3, E5, E7, and E16 emphasised that transportation can occur in various modes, such as direct supply to the site, like river sand or through intermediate manufacturing facilities. E16 further explained that the data types required for carbon assessment remain consistent across these modes. The contractor is identified as the main responsible stakeholder by the majority of interviewees for collecting transport-related data, while the suppliers, manufacturers and logistic companies also have a shared responsibility. The key data types in the transport stage include total distance, vehicle type, capacity, fuel type, and carbon coefficients of fuel. Total distance is taken by considering the number of vehicles and trips, and experts E7 and E11 argued that vehicle type is sufficient instead of capacity and fuel type. Even though only Kumanayake and Luo (2018a) have identified "fuel type", it is an important data type in this stage of calculations, according to the experts.

In the operation stage, almost all interviewees agreed that the facilities manager plays the key role in data collection and management. E17 noted that the client also has an indirect involvement in delegating the responsibility to the facilities manager. The significant data types in this stage are energy consumption (electricity, fuel, and water) and their emission factors. As additional data type, waste quantity, water quantity, and solar energy consumption were identified through expert interviews. Since the embodied energy is already calculated in the previous stages, the interviewees argued that "amount of original building materials" and "life span of building materials" data do not need to be collected in this stage.

The end-of-life stage is considered the most challenging due to the lack of reliable data. Facilities managers, Demolition contractors, and waste management companies are identified as the main responsible stakeholders for capturing data on demolition transport, waste quantities, and recycled materials in this stage. However, E11 mentioned that they rely on assumptions in practice due to the unavailability of data even in the global context. Energy consumption, particularly fuel use during demolition, and the quantity of recycled materials are critical data types. Moreover, experts argued that the quantity of demolished activity and the quantity of demolished material are similar, and there is no need to have both in calculations.

5. CONCLUSION

This research addresses the timely issue of carbon assessment within the local construction context by identifying Project Data Responsibilities in carbon assessment, which primarily clarifies stakeholder roles and data handling procedures. The research confirms that the process-based LCA is the most appropriate technique for detailed and accurate carbon assessment, but is hampered in practice by a lack of localised data and standard protocols. Not having precisely outlined duties for stakeholders related to this process has been identified as a major factor that negatively impacts the current carbon assessment procedure in the local context. The study offers a systematic approach to reliable data collection and carbon reporting, precisely outlining the responsibilities of clients, consultants, contractors, suppliers, manufacturers, facilities managers, and regulatory bodies throughout the project lifecycle. Its application will add credibility to carbon analyses, enable more realistic policy and project objectives, and allow effective

emissions reduction strategies to be developed. However, this is limited to the Sri Lankan building projects, and this study provides a clear pathway to collect, report and manage carbon-related data needed for the calculations with their responsible stakeholders. Therefore, the findings facilitate the proper implementation of accurate carbon assessments to achieve sustainable construction goals in Sri Lanka and alignment with global climate objectives.

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RAINWATER HARVESTING SYSTEMS AS A SUSTAINABLE WATER MANAGEMENT STRATEGY: ADDRESSING WATER SECURITY CHALLENGES IN SRI LANKAN BUILDINGS

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ABSTRACT

Water scarcity has emerged as a critical challenge with wide-ranging implications for economic development, public health, and ecological balance. Despite receiving approximately 2,000 mm of annual rainfall, Sri Lanka struggles with inefficient rainwater capture, resulting in significant runoff losses and growing urban water stress. While rainwater harvesting systems (RWHS) have been recognized for their sustainability potential, existing studies rarely examine the critical gap between policy mandates and their practical implementation in urban buildings. This paper addresses this gap by critically evaluating RWHS as a decentralized water management strategy for Sri Lankan buildings, with a focus on bridging policy–practice disconnects. Drawing on empirical evidence, policy documents, and comparative global practices, the study analyzes RWHS design elements, treatment technologies, performance indicators, and institutional frameworks. Case studies demonstrate that well-designed RWHS can reduce reliance on conventional water supplies by over 70% in institutional and commercial settings, while also contributing to stormwater management and climate resilience. However, widespread adoption remains constrained by inconsistent enforcement, limited incentives, and insufficient public awareness. This paper offers context-specific recommendations for integrating RWHS into urban planning and building codes more effectively. By clarifying these implementation barriers and solutions, the study contributes new insights that can guide policymakers, urban planners, and building professionals to leverage RWHS as a transformative tool for achieving Sustainable Development Goal 6 and long-term water security in Sri Lanka.

Keywords: *Policy Implementation; Rainwater Harvesting Systems; Sri Lanka; Urban Planning; Water Security.*

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1. INTRODUCTION

Freshwater scarcity represents a critical and growing global concern, driven by increasing demand across domestic, agricultural, industrial, and environmental sectors. It is estimated that approximately two-thirds of the global population—equivalent to nearly 4 billion individuals—experience significant water scarcity for at least one month each year (Thebuwena et al., 2024). Water scarcity can be broadly classified into physical scarcity, which occurs when natural hydrological conditions cannot meet demand, and economic scarcity, which results from inadequate infrastructure, poor governance, and inequitable resource allocation. Political and socio-economic factors can exacerbate economic scarcity, further restricting access for vulnerable populations.

Sri Lanka exemplifies the paradox of water abundance coexisting with water insecurity. Despite receiving an average annual rainfall of approximately 2000 mm, over 50% of rainfall is lost to the sea due to inefficient capture and management (Sadushan & Neluwala, 2024). The island's bimodal monsoon system, comprising the Maha (Northeast monsoon) and Yala (Southwest monsoon) seasons, creates pronounced temporal and spatial variability in water availability (Sivakumar, 2021). Per capita renewable water resources are estimated at approximately 2400 m^3; however, only 52% of households have access to piped water, while the remainder depend on local sources such as wells and tanks, which are highly susceptible to seasonal fluctuations (Shamsudduha et al., 2025).

Rapid urbanization further compounds these challenges. By 2030, nearly 70% of Sri Lanka's population is projected to reside in urban areas, with significant expansion of impervious surfaces such as high-rise residential and commercial structures (Ranasinghe & Dissanayake, 2018). This urban growth reduces groundwater recharge and, when combined with more intense rainfall due to climate change, increases the risk of urban flooding. Rainwater harvesting systems (RWHS) have emerged as an effective decentralized approach to enhance urban water security, reduce pressure on centralized supply networks, and improve resilience to climate-induced hydrological extremes (Campisano et al., 2017).

Although Sri Lanka's Urban Development Authority mandates RWHS in new buildings, practical implementation remains limited. Existing studies predominantly address the technical feasibility and environmental benefits of RWHS but provide limited analysis of the socio-economic, institutional, and behavioural factors that hinder widespread adoption. The lack of integrated evaluation frameworks to connect design, policy, governance, and stakeholder engagement remains a key research gap.

This study aims to address these gaps by conducting a comprehensive review of RWHS implementation in Sri Lanka's urban context. It critically examines technical performance, institutional barriers, policy effectiveness, and socio-economic drivers influencing adoption. The findings seek to inform evidence-based recommendations to strengthen policy enforcement, stakeholder engagement, and practical integration of RWHS within the built environment, thereby contributing to improved urban water security and climate resilience.

1.1 RESEARCH PROBLEM

Despite Sri Lanka's favourable rainfall and supportive policies promoting rainwater harvesting, practical adoption in urban and built environments remains limited. Many

urban developments have yet to integrate RWH systems effectively, leading to missed opportunities for enhancing water security and reducing stress on centralized water supplies. Barriers include technical knowledge gaps, inconsistent design standards, and insufficient incentives, highlighting the need for targeted research and policy measures to optimize RWH implementation in Sri Lanka's unique social and climatic context.

1.2 RESEARCH OBJECTIVES

This paper aims to evaluate the potential of rainwater harvesting systems as a sustainable water management strategy to address water security challenges in Sri Lanka's built environment by examining the underlying causes of water scarcity, reviewing the types, components, and treatment technologies of RWH systems, analysing relevant policy frameworks and implementation challenges, drawing insights from local and global case studies to identify effective strategies, and proposing recommendations to enhance the adoption and optimization of RWH systems for improved urban water resilience and sustainability.

2. METHODOLOGY

This review was conducted using a systematic and targeted literature search to identify, select, and synthesise relevant research on rainwater harvesting (RWH) systems, water scarcity, and urban water security, with a particular focus on Sri Lanka and comparable contexts. Searches were performed across multiple academic and institutional databases, including Google Scholar, ScienceDirect, and ResearchGate, covering publications from 1999 to 2024 to ensure the inclusion of both foundational studies and recent advancements.

A structured keyword strategy was employed to capture technical, environmental, and governance dimensions of RWH, using terms such as "rainwater harvesting," "rainwater harvesting Sri Lanka," "urban water security Sri Lanka," "water scarcity Sri Lanka," "urban rainwater policy," and "global rainwater regulations." Retrieved records were initially screened by title and abstract to determine relevance. Studies were retained if they addressed technical design, system configurations, or performance aspects, environmental or water quality impacts, or policy frameworks, governance challenges, and stakeholder perspectives relevant to Sri Lanka and similar contexts.

A full-text review was then conducted for 50 shortlisted publications, comprising peer-reviewed journal articles, reputable institutional reports, and national or international policy documents. Following detailed assessment, 5 sources were excluded due to limited relevance, resulting in a final dataset of 45 references incorporated into this review. Key data were extracted on system types, components, water treatment methods, policy frameworks, implementation barriers, and relevant case study outcomes. The findings were then thematically analysed to identify prevailing research trends, effective strategies, knowledge gaps, and context-specific recommendations to inform policy enforcement and the practical uptake of RWH systems within Sri Lanka's built environment.

3. RAINWATER HARVESTING SYSTEM (RWHS)

RWHS can be used for both potable (e.g., drinking, cooking, bathing—with appropriate treatment) and non-potable (e.g., irrigation, toilet flushing, washing) purposes, reducing

pressure on conventional water supplies. These systems can be adapted to suit a variety of building types depending on factors like roof area, water demand, and usage. For instance, individual houses often use simple rooftop harvesting systems to meet household needs, whereas schools and hospitals require larger systems with greater storage capacity to ensure continuous water availability. Commercial and institutional buildings frequently incorporate RWH as part of sustainable design strategies, aiming to reduce reliance on public water supply and enhance resilience during periods of water scarcity. Recognizing this, Sri Lanka's Urban Development Authority mandates RWH installations for new constructions, underlining their strategic role in urban planning (The Gazette, 2009).

RWHs can be broadly divided into two categories such as rooftop rainwater harvesting systems and surface runoff rainwater harvesting systems.

Rooftop rainwater harvesting (RWH) systems are among the simplest and most widely implemented forms of rainwater harvesting, particularly in domestic and institutional buildings. In these systems, the roof functions as the primary catchment area where rainwater is collected and subsequently directed into a storage facility (Kim et al., 2016).

Permeable and impermeable surfaces, such as asphalt and concrete pavements, have been explored for their potential in rainwater harvesting. Recent designs incorporate features such as infiltration openings along sidewalks and streets that direct runoff into subsurface gravel layers, where water is temporarily stored in underground micro-detention systems before reuse or infiltration (Chen et al., 2022). Such methods are commonly known as surface runoff harvesting systems.

3.1 ROOFTOP RAINWATER HARVESTING: KEY COMPONENTS AND TREATMENT

A. This refers to the surface area where rainfall is captured. Common roofing materials include clay tiles, wood, corrugated steel sheets, cement, galvanized iron, concrete, fibre cement, aluminium, and asbestos. Studies have examined the quality of water collected from roofs made of different materials, along with their runoff coefficients, which ultimately influence the volume of water that can be harvested. It was found that steel roofs produced the highest quality water, followed by asphalt tile roofs, galvanized iron roofs, and concrete tile roofs (Shaheed et al., 2017).

B. This is the primary component for storing water in a rainwater harvesting (RWH) system. Storage tanks can be constructed either underground or above ground. The size and design of the tank are determined by factors such as the catchment area, rainfall intensity, duration of dry periods, and daily water demand (Vijitha et al., 2022). Materials commonly used for constructing cisterns include concrete, plastic, galvanized sheet metal, and ferro cement (Kihila, 2014). Ferro cement tanks are often selected due to their cost-effectiveness, durability under extreme weather conditions, and low maintenance requirements (Kihila, 2014). Plastic tanks, on the other hand, are preferred for their ease of cleaning and simple integration with piping systems (Khoury-Nolde, n.d.). To prevent algal growth and mosquito breeding, the tank should be fitted with a tightly sealed cover (Pradhan & Sahoo, 2019). Filter for inlet - a screen filter to remove large contaminants such as debris, branches, and vegetation.

C. First flush diverters - the roofs of the buildings can easily get contaminated with dust, debris, bird and rodent droppings, and vegetation. This mechanism ensures that the first incoming stream of water from the rooftop is sent away from the storage tank.

D. Conveyance system - consists of a set of pipes that direct water from the catchment area to the storage tank. A drain is provided along the edge of the roof and is fixed with a slope to ensure the flow of water to the storage tank.

E. Filtering System – The collected rainwater must be safe and free from contaminants to be suitable for use. Well-designed water filters—such as charcoal filters, sand and gravel filters, and PVC sponge or pipe filters—can be used to achieve this objective (Pradhan & Sahoo, 2019).

F. Outlet pipe and the distribution system - This pipe is installed above the storage tank and is responsible for drawing water from the tank to the point of use. A pump may also be attached to facilitate smooth water extraction and distribution.

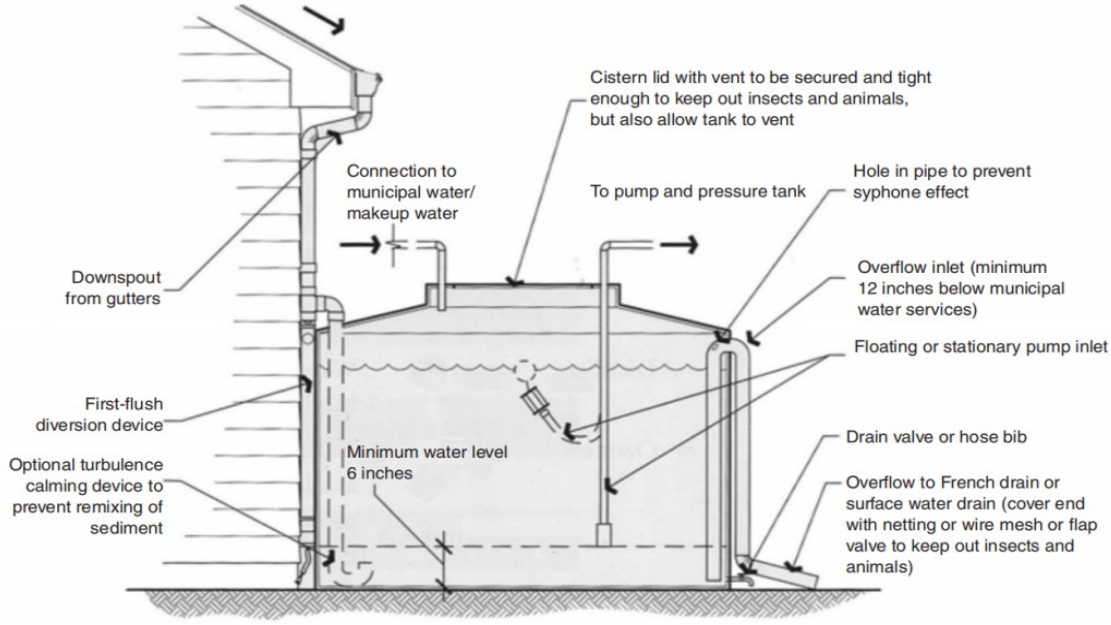


Figure 1: Visual representation of a rooftop rainwater harvesting system
Source: (Kinkade-Levario, 2004)

After the collection of rainwater, the physicochemical and microbiological parameters are assessed to decide how to use the collected rainwater, and they must fall within the range of national and international criteria. Research shows that in Sri Lanka, 68% consume rainwater after boiling without any further treatment. 27% of that population practiced boiling, whereas only 5% of the population practiced filtering (Karthiga & Inoka, 2014).

It has been reported that the first millilitres of precipitation have a significant number of contaminants (Nunes et al., 2020). Higher concentrations of the primary metals discovered include Ca, K, and Na, which might be suspended as both aerosols and fine particulate matter. Escherichia coli, total coliforms, and faecal coliforms are the primary bacteria detected in rainwater (Kim et al., 2016). Microorganisms such as Salmonella spp., Legionella spp., and Pseudomonas spp have been newly discovered to be present in

water (Struk-Sokołowska et al., 2020). Disinfection and appropriate treatment are therefore crucial to be used for potable purposes.

3.2 GROUNDWATER AND SURFACE WATER HARVESTING

Runoff harvesting involves collecting rainwater from surfaces like gardens, driveways, landscapes, open fields, parks, roads, and pavements. This approach is particularly effective in low-rainfall regions and is especially suitable for agricultural applications. In urban settings, it is used to conserve water and facilitate groundwater recharge by directing runoff into infiltration pits. In Sri Lanka, traditional "Pathaha" (unlined runoff ponds) and "Pokuna" (lined runoff tanks) remain prevalent forms of surface runoff harvesting, widely used especially in dry zone agricultural regions (Bandara et al., 2010).

Groundwater recharge is a key method in rainwater harvesting where collected rainwater or treated surface runoff is directed into aquifers through mechanisms such as recharge wells, percolation pits, or infiltration basins (Ariyananda, 2010). This process plays a vital role in replenishing depleted groundwater tables, enhancing water quality through natural filtration, and maintaining the viability of wells during dry periods (De Silva & Ariyananda, 2020). In urban environments, managed aquifer recharge (MAR) techniques are increasingly employed to mitigate the effects of over-extraction and reduce the risk of saline intrusion, offering a sustainable solution to growing water demands (Campisano et al., 2017).

Surface runoff rainwater harvesting involves several key methods tailored for effective groundwater recharge and water storage, particularly in urban and agricultural settings. Traditional surface storage techniques include the use of underground tanks, ponds, and check dams to retain rainwater for later use or gradual infiltration (Radhika & Prasoona, 2021). Recharge structures such as pits, trenches, dug wells, and recharge wells are commonly constructed to direct runoff into shallow or deep aquifers; these are typically backfilled with filter materials like boulders, gravel, and coarse sand to facilitate percolation and reduce clogging. Spreading methods such as check dams, nala bunds, cement plugs, gabion structures, and percolation ponds aid in channelling runoff over permeable ground, encouraging widespread infiltration (Radhika & Prasoona, 2021). Finally, diversion of storm runoff into natural or artificial surface water bodies further assists in augmenting both groundwater and surface water reserves, underscoring the diversity and utility of these approaches in managing water scarcity (Radhika & Prasoona, 2021).

4. GROWTH AND DEVELOPMENT OF RAINWATER HARVESTING

While ancient Sri Lankan civilizations, such as that of King Parakramabahu, pioneered sophisticated water management systems, the country's long-standing heritage of sustainable water use is often underutilized in modern urban planning. The existence of ancient tanks and the intricate distribution systems of sites like the Sigiriya fortress provide concrete evidence of the historical importance and technical ingenuity behind rainwater harvesting (Sayanthan et al., 2017). These ancient tank cascade systems-comprising over 15,000 small tanks supported agriculture, biodiversity, and community drought resilience for centuries (World Bank Group, 2023).

However, despite this rich legacy, contemporary practices often fail to integrate traditional knowledge with modern rainwater harvesting technologies. This disconnect suggests a missed opportunity to leverage time-tested community-based systems to strengthen current policy frameworks and public engagement.

Modern interest in rainwater harvesting re-emerged in the early 1990s, driven largely by severe droughts, declining groundwater quality, and increased salinity in the dry zone. The Community Water Supply and Sanitation Project (CWSSP) provided the initial impetus for institutional support by introducing standardized subsurface brick tanks and above-ground ferrocement tanks for domestic use (Ariyananda, 2010). The establishment of the Lanka Rainwater Harvesting Forum (LRWHF) in 1996 further institutionalized RWH promotion across the island, with support from the National Water Supply and Drainage Board (NWSDB), Sarvodaya, and the Southern Development Authority, along with international partners such as UNICEF and WHO.

While these initiatives helped expand decentralized water access in rural and underserved areas, the literature suggests that their impact in urban contexts remains inconsistent. For example, although policy support has grown — with the Urban Development Authority mandating RWH installations in certain urban developments since 2009 — practical enforcement and monitoring have been notably weak (The Gazette, 2009; Dissanayake & Ranasinghe, 2018). Case studies such as Dematawelihinna in Badulla District and Killinochchi District show that pilot community projects can be highly adaptable and effective in household and institutional settings (De Silva & Ariyananda, 2020; Ariyananda & Aheeyer, 2011). Yet these successes have not translated into widespread replication or scaling, highlighting a persistent implementation gap that previous descriptive studies often overlook.

Despite well-documented benefits of rainwater harvesting systems (RWHS)—such as enhanced drought resilience, reduced labor burden on women and children, and improved public health outcomes (Ariyananda, 2010; Elias, 2015)—their integration into formal urban water management frameworks remains limited. This disparity highlights a critical gap in institutional mechanisms necessary for scaling localized successes into enforceable policies, regulatory standards, or incentive structures that promote broader adoption by urban developers.

Overall, the literature reveals a trend of sporadic adoption driven by donor-funded projects rather than sustained, policy-backed expansion. This inconsistency justifies the need for a more critical synthesis, such as the present study, which examines not only technical aspects but also the governance, institutional, and socio-cultural factors that shape the success or failure of RWHS implementation in Sri Lanka's evolving urban landscape.

4.1 IMPLEMENTATION IN SRI LANKAN BUILDINGS

Several Sri Lankan industries have successfully adopted rainwater harvesting (RWH) systems tailored to their specific operational demands, reducing reliance on municipal water and ensuring continuity during dry periods. For example, Finlays Tea Estate in Haldummulla has implemented a large-scale RWH system to support tea processing activities (Finlays, n.d.). Cargills Quality Dairies harvests over 3,000 cubic meters of rainwater annually, mainly used for cooling processes (Cargills, n.d.). Hayleys Quality Seeds meets approximately 30% of its annual water demand through a system with 7.4

million litres of storage capacity, sufficient to support operations for 7–8 months after the monsoon. MAS Intimates in Thulhiriya, Sri Lanka's first LEED Platinum-certified building, integrates an advanced RWH system used for toilet flushing, landscaping, and cooling, significantly reducing potable water consumption (Aheeyar & Bandara, 2010). The Heritance Kandalama Hotel uses harvested rainwater primarily for irrigation as part of its eco-friendly operations (Aitken Spence Hotels, 2013).

According to Aheeyar and Bandara (2010), projects at David Peiris Motor Company, MillenniumIT Campus, and Brandix Casual Wear met between 15% and 100% of daily non-potable water demands such as cleaning, sanitation, and landscaping. Economic evaluations revealed that the RWH systems at MillenniumIT Campus and David Peiris Motor Company had positive net present values and internal rates of return of 18% and 11% respectively, with acceptable payback periods, confirming their financial viability.

Ranasinghe and Dissanayake (2018) found that residential properties with asbestos, concrete, or tile roofs have adopted RWH systems utilizing roughly half of their rainfall collection potential, retaining about 5% of total rainfall. This contributes meaningfully to stormwater runoff management and reduces urban flash flood risks. If RWH adoption were mandated through effective regulations, over 20% of rainwater could be harvested from residential properties alone, potentially lowering urban flood volumes by a similar margin. Using rainfall data, mass curves were developed to estimate potential storage requirements, revealing that approximately 130 m^3 of rainwater per household per year—equivalent to 53.06% of annual potable water consumption—could be harvested under optimal conditions (Nimalka et al.,2021).

4.2 RWH AS A SUSTAINABLE WATER MANAGEMENT STRATEGY

According to a case study conducted by Thebuwena et al.,2024, connecting rainwater storage to flushing system in an office building has reduced the municipal water usage from 946,444 gallons/year to 574,669 gallons/year. Consequently, establishment of a rainwater harvesting system has improved the overall water efficiency of the building by 72.92%. This case emphasizes the value of rainwater harvesting as a viable strategy for reducing potable water demand in non-potable applications, contributing to resource conservation, cost savings, and climate-resilient infrastructure (Eslamian et al., 2023).

The rainwater harvesting tank served as the community's only supply of clean water during the 2018 floods in the Kilinochchi district, when well water and surface water supplies were contaminated (Ariyananda,2020). People can get water from RWHS constructed in schools, which serve as flood shelters, until government assistance arrives (Ariyananda,2020). Therefore, the implementation of rainwater harvesting systems in flood-prone urban areas is vital, as they offer a reliable alternative water source when conventional potable water supplies are compromised due to contamination or disruption. Furthermore, the widespread adoption of rainwater harvesting in vulnerable urban centres can enhance community resilience, ensure emergency water supply continuity, and support public health during climate-induced disasters.

Rainwater harvesting (RWH) offers crucial environmental benefits, especially in urbanized and water-stressed regions. By reducing demand on groundwater and surface water, RWH helps maintain ecological flows and prevents degradation of wetlands and aquatic ecosystems (Barron, 2009). Urban stormwater pollution has become a major factor contributing to the deterioration of municipal water quality and the environmental

degradation of drinking water catchment areas (Soltaninia et al.,2025). Thereby RWHs decrease the treatment of stream flows in wastewater treatment plants, erosion, and non-point source of pollution of water bodies (Angrill et al.,2017; Campisano et al., 2017).

Moreover, RWH enhances ecosystem services by improving soil moisture, vegetation cover, and groundwater recharge. These effects support biodiversity and reduce landscape degradation, especially in semi-arid zones (Barron, 2009). RWH also strengthens climate resilience by providing a decentralized water source during droughts and floods, mitigating the impact of rainfall variability (Barron, 2009).

Commercial buildings benefit more from RWHS than do homes with small installations since they have larger roof areas, higher water use, and higher water tariffs (Lani et al.,2019). Installing RWHS during the early design and construction phases can significantly reduce retrofitting costs in later stages (Lani et al., 2018).

4.3 IMPLEMENTATION CHALLENGES OF RAINWATER HARVESTING SYSTEMS IN SRI LANKA

Despite progressive policy frameworks promoting the adoption of Rainwater Harvesting Systems (RWHS) in Sri Lanka, several implementation challenges continue to impede widespread uptake, particularly in urban and institutional contexts. According to the Gazette of the Democratic Socialist Republic of Sri Lanka (2009), all industrial and commercial buildings—including car parks—within Municipal and Urban Council jurisdictions are required to submit RWHS plans and obtain prior approval before construction. However, in practice, enforcement remains weak. For instance, in 2017, neither the Dehiwala-Mount Lavinia nor the Kesbewa Municipal Councils approved or rejected any building applications based on RWHS compliance, indicating a disconnect between policy intent and regulatory enforcement (Dissanayake & Ranasinghe, 2018).

Institutional commitment also remains limited. Although the Urban Development Authority (UDA) regulations mandate the inclusion of RWHS in all buildings, including government facilities, no central, provincial, or local authority has independently constructed such systems despite having the financial capacity to do so. Existing installations are largely restricted to a few government offices, particularly schools, and have primarily been funded through donor-driven or NGO-supported initiatives (Dissanayake & Ranasinghe, 2018).

Public awareness constitutes another major barrier to implementation. While national policies highlight awareness-raising as a strategic priority, no formal campaigns or funding allocations have been undertaken by any government institution at the national, provincial, or local level. Consequently, non-governmental organizations (NGOs) have assumed the primary role in conducting outreach efforts, resulting in fragmented and un-sustained public engagement (Dissanayake & Ranasinghe, 2018).

Design optimization and cost considerations further complicate RWHS implementation. A study by Nimalka et al. (2021) identified cylindrical ferro cement tanks as the most structurally efficient and cost-effective option when compared to cuboid and doubly curved alternatives. Life cycle cost analysis confirmed the long-term economic viability of these systems. However, under the current tariff structure provided by the National Water Supply and Drainage Board (NWS&DB), the capital cost recovery period exceeds the typical design life of the system. Notably, when assessed against the actual production

cost of potable water, RWHS becomes significantly more cost-effective, underscoring the need for more realistic valuation methods in economic assessments.

5. WAY FORWAD

While rainwater harvesting (RWH) is acknowledged in Sri Lanka's national building code, its implementation is hindered by vague legal definitions, weak enforcement, and a lack of post-installation oversight. Strengthening regulatory clarity—particularly regarding urban classifications—and introducing standardized verification mechanisms are essential to ensure the consistent application of RWH requirements. Incorporating routine inspections, maintenance standards, and mosquito control measures, as practiced in countries such as Singapore and India, would enhance system reliability and public health safety. Additionally, the absence of financial incentives and government-led installations underscores the need for dedicated funding, subsidies, and policy-backed support to drive adoption, particularly in urban settings. Capacity-building programs for municipal authorities and technical professionals are vital to ensure effective planning and design. Moreover, Sri Lanka must expand research efforts to include system performance, scalability, and urban integration, drawing from global innovations such as smart sensors, infiltration storage, and green infrastructure. A more integrated national approach—combining legal reform, financial incentives, technical training, and innovation—will be essential to establish RWH as a viable tool for sustainable water management and climate resilience in Sri Lankan buildings.

6. CONCLUSION

This review examined rainwater harvesting systems (RWHS) as a sustainable water management strategy to address Sri Lanka's water security challenges. Despite substantial rainfall and historical water management traditions, modern RWHS adoption in urban areas remains sporadic and poorly enforced. Although policies mandate RWHS for new buildings, compliance and monitoring are often weak and symbolic. Technical feasibility alone does not ensure uptake; the gap between policy intentions and enforcement is a major barrier. Most evidence comes from small pilot projects with limited scaling, and few studies assess long-term performance, costs, or social acceptance. While RWHS can reduce municipal water demand and enhance climate resilience, institutional, socio-economic, and behavioural barriers remain underexplored. Limitations include reliance on secondary data with variable methodologies and underrepresentation of grey literature and informal practices. To improve urban water security, an integrated governance approach is needed—combining compliance monitoring, capacity building, financial incentives, and clear guidelines for users and developers. Regular maintenance and health safeguards are critical for system reliability. Future research should focus on multi-disciplinary, long-term studies of RWHS performance in diverse settings and draw lessons from countries with successful implementation. Exploring smart systems and integration with urban green infrastructure can enhance RWHS benefits like flood control and heat reduction. By closing these gaps and strengthening enforcement, RWHS can become a key element of Sri Lanka's resilient, decentralized urban water management.

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READINESS TO IMPLEMENT CONSTRUCTION 4.0 APPLICATIONS IN BUILDING CONSTRUCTION PROJECTS IN SRI LANKA

I.H.G.Y.M.W.U. Yaparathne[1], D.D. Dias[2] and Kavini Guruge[3]

ABSTRACT

The Construction industry is a vital indicator of the country's economic progress and development. Technological advancements play an essential role across various sectors, and their integration boosts both productivity and efficiency. Industry 4.0, a global concept, focuses on digitalising industries through cutting-edge technologies. Construction 4.0, as an application of Industry 4.0, seeks to enhance construction projects' efficiency, effectiveness and profitability. While many countries have begun to adopt Construction 4.0 applications, studies show that the practical use of these technologies is significantly lower than their theoretical potential. This research investigates the readiness of the Sri Lankan building construction industry to implement Construction 4.0 technologies, with a specific focus on assessing the digital literacy of professionals in the sector. A qualitative approach was used, involving interviews with five experts, including academics and industry professionals, to evaluate the current level of digital literacy & awareness. This study followed four main objectives. The research was conducted in two phases: a thorough literature review and semi-structured interviews with five experts using snowball sampling. Data was analysed through coding techniques using NVivo 14 software. The findings revealed that while some technologies are being adopted in Sri Lanka's construction projects, their use remains limited. BIM is the most widely adopted technology, while IoT, VR, AI, big data and cloud computing are only partially implemented. Technologies such as robotics, cobots, digital twins, AR,3D printing, and machine learning are scarcely used. Additionally, the study explored barriers to implementing construction 4.0 applications & strategies to overcome them.

Keywords: *Building construction; Construction 4.0; Implementation; Industry 4.0; Sri Lanka.*

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1. INTRODUCTION

1.1 CONTEXT AND BACKGROUND

The construction industry is one of the major industries playing a pivotal role in fostering economic growth & contributing significantly to the overall global economy. It holds paramount significance and has the potential to impact transportation education & healthcare through the creation of essential infrastructure (Adepoju & Aigbavboa, 2021). According to Perera et al. (2023), construction output represents half of the gross capital and constitutes a range of 3 to 8% of the GDP (Gross Domestic Product) in most countries. Industry 4.0 or the fourth Industrial Revolution has become one of the most discussed subjects among researchers, academicians, and professionals around the world. It represents a new way of organising industrial resources and processes, making them more responsive to an ever-changing environment (Lemstra & de Mesquita, 2023). I4.0 (Industry 4.0) has applications in many sectors like construction, healthcare, agriculture, wood, food, and education. Consequently, Agriculture 4.0, Construction 4.0, Health 4.0, Smart Material 4.0, Smart Operator 4.0, and many more were introduced to improve the efficiency, productivity, and profitability of their industries (Rana & Rathore, 2023). As per (Forcael et al., 2020), the concept of Construction 4.0 is derived from the broader framework of Industry 4.0, often referred to as the "Fourth Industrial Revolution." This emerging paradigm has become prominent in recent years for its transformative impact on major industries, particularly in design and production, shaping the future of efficiency and advancement in the manufacturing sector. However, (van der Heijden, 2023), explained that the construction industry has been slow to adopt new technologies and is often seen as a laggard in innovation. The present research on Construction 4.0 encounters substantial challenges in terms of methodology. Moreover, the existing studies are largely comprised of conceptual studies rather than practical applications, which may create a misleading impression that the Construction 4.0 phenomenon is widely accepted and understood. Therefore, there is an opportunity to revolutionise the sector through the adoption of digitalisation and automation in the field of construction, prioritising practical applications.

1.2 RESEARCH PROBLEM

Despite global interest in Construction 4.0, literature reviews indicate a significant gap between theory and practical implementation in many countries (van der Heijden, 2023). It highlights the need for a thorough investigation into how nations are ready to adopt and maximise the benefits of Construction 4.0 applications in their construction projects. Closing this knowledge gap is essential for the successful integration of advanced principles into the global construction industry. As a major component of the Sri Lankan construction sector, building construction can achieve greater efficiency and profitability through the integration of Construction 4.0 technologies. Through an examination of the current awareness and utilisation of Construction 4.0 applications in building construction projects in Sri Lanka, the research assumes that insights into the industry's current neglect can be obtained, providing a glimpse into its future direction.

1.3 RESEARCH AIM AND OBJECTIVES

The research aims to assess the level of digital literacy and awareness among professionals in the building construction projects of Sri Lanka to implement

Construction 4.0 applications effectively. To achieve the above aim, the following objectives were pursued; [1] Study the concept of Industry 4.0 and Construction 4.0, explore their key technologies, and evaluate the significant benefits they bring to contemporary industrial and construction practices, [2] Check the awareness and digital literacy among professionals in building construction projects in Sri Lanka regarding implementing Construction 4.0 applications, [3] Investigate barriers to implementing Construction 4.0 for building projects in Sri Lanka and [4] Explore strategies to overcome challenges in integrating Construction 4.0 technologies into building construction projects in Sri Lanka.

2. LITERATURE REVIEW

2.1 THE NOTION OF I4.0 AND ITS IMPORTANCE

I4.0 has gained global attention as a key driver of the next generation of industrial development. It represents the fourth Industrial Revolution, bringing advanced technologies to transform industries. The Industrial Revolution began in Britain in the late 1700s and early 1800s, marking a period of significant innovation. The First Industrial Revolution was initiated by the introduction of steam power, which played a vital role in driving industrialisation and quickly expanded to regions across the globe, including the United States (Islam et al., 2022). The Second Industrial Revolution (1900) introduced the internal combustion engine, enabling rapid industrial growth through oil and electricity-powered mass production. The Third Industrial Revolution (1960) integrated electronics and information technology, leading to production automation. These advancements significantly improved industrial efficiency and technological progress (M. Xu et al., 2018). Industry 4.0, also known as the Fourth Industrial Revolution or 4IR, is characterised by the integration of networking, Cyber Physical Systems (CPS), and the Internet of Things (IoT), creating a dynamic and intelligent working environment. This amalgamation of technologies contributes to the enhancement of workplace efficiency and intelligence (Islam et al., 2022). The concept of I4.0 was published by the German government in 2003.

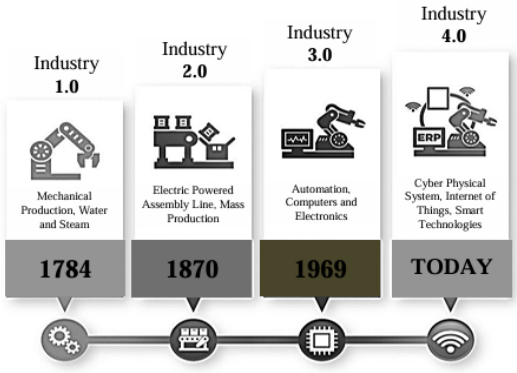


Figure 1: Industrial revolution

Nine primary pillars define the Fourth Industrial Revolution, considered key elements of I4.0. These pillars outline the new technology manufacturers use to enhance all production processes (Singh et al., 2023). I4.0 encompasses IoT, Cloud computing,

Cybersecurity, System integration, big data & analytics, Smart manufacturing, AI (Artificial intelligence), CPS, and Blockchain. I4.0 is crucial in enhancing industrialisation, informatisation, and digitalisation in global business operations and the economy. It aims to improve efficiency, competence, and competitiveness significantly, as evidenced by the research conducted by L. Xu et al. (2018).

2.2 CONSTRUCTION 4.0 AND ITS POTENTIAL BENEFITS TO CONSTRUCTION

The construction industry is a major source of employment in numerous countries and is vital to their economic growth. It is important to highlight that the construction sector represents around 13% of the world's GDP (Karmakar & Delhi, 2021). Construction projects face numerous challenges in timely and budget-compliant delivery. According to Perera et al. (2023), the traditional approach often fails to execute projects within the expected time & budget in the construction industry. Furthermore, their study revealed that the adoption of Construction 4.0 technologies remains relatively low in Sri Lanka. The findings suggest the potential to guide future research aimed at the effective implementation of Industry 4.0 applications within the country's construction sector. Meanwhile, many researchers have identified various issues plaguing the sector. Notably, inadequate consideration of costs and planning in construction projects is a common problem. Additionally, design and execution flaws, budget constraints, contractual scheduling issues, stringent quality requirements, safety and environmental concerns, material logistics problems, sustainability rating system mandates, and stakeholder dissatisfaction due to project delays are significant contributing factors. Authors Mansour et al. (2023) demonstrated that the term Construction 4.0 has recently been utilised by researchers to signify the incorporation of I4.0 technologies into the construction sector. The application of the I4.0 concept can be utilised to address the previously mentioned issues in construction. The study conducted by Forcael et al. (2020), explained that the concept of Construction 4.0 did not emerge independently but was derived from the broader theoretical framework of Industry 4.0. As the concept is relatively new, there is currently no universally accepted definition for it. Instead, several scholars have emphasised the need for a flexible and holistic definition, referring to this fourth industrial revolution as “shift in the manufacturing logic towards an increasingly decentralized, self-regulating approach of value creation, enabled by concepts and technologies such as CPS, IoT, Internet of Services (IoS), cloud computing, or additive manufacturing and smart factories” (Forcael et al., 2020). Moreover, they pointed out that these advancements have also positively impacted the construction sector, giving rise to the term Construction 4.0, which has become increasingly prominent in recent years. This concept is fundamentally driven by construction companies' realisation of the industry's digital shift and is built upon four main pillars: digital data, automation, connectivity, and access to digital technologies (Forcael et al., 2020). Integrating these advanced technologies into the sector can significantly improve efficiency and productivity, helping to resolve common problems and enhance project delivery. However, van der Heijden (2023) argued that the construction industry has hesitated to adopt new technologies and is often viewed as trailing behind in innovation. This hesitance is partly attributed to the industry's complexity, involving multiple stakeholders, intricate supply chains, and large-scale projects with substantial risks. Nonetheless, the rise of Construction 4.0, marking the extensive integration of digitalisation and automation in construction, presents a significant opportunity to revolutionise the sector. The term "Construction 4.0" was introduced in 2016 by the consultancy firm Roland Berger GMBH in their report titled

"Digitisation in the Construction Industry: Building Europe's Road to 'Construction 4.0'. The report highlighted several crucial technologies that could revolutionise the construction industry, such as BIM, IoT, sensors, robotics, and augmented reality. These technologies promise increased efficiency, cost reduction, and improved collaboration and communication among stakeholders in the construction sector (van der Heijden, 2023).

2.3 KEY TECHNOLOGIES INTEGRATED WITH CONSTRUCTION 4.0

2.3.1 BIM

BIM digitally represents a construction project, allowing collaborative design, construction, and operation throughout its lifecycle. BIM goes beyond traditional 2D drawings by integrating 3D models enriched with data. It enables collaborative digital communication and prompts the construction industry to enhance effectiveness and efficiency through data utilisation (van der Heijden, 2023).

2.3.2 IoT

IoT technology significantly improves construction processes, productivity, and safety by collecting and exchanging real-time data. This is evident in construction site management, where IoT devices like servers, computers, tablets, phones, and embedded sensors in equipment generate valuable data. This data is instrumental in optimising operations, enhancing resource management efficiency, and implementing energy-efficient strategies in buildings, such as monitoring energy usage, occupancy, and environmental conditions (van der Heijden, 2023).

2.3.3 Robots, Cobots, and Automation

In Construction 4.0, integrating robots, collaborative robots (cobots), and automation emerges as a pivotal factor in enhancing construction productivity. These technologies play a crucial role by efficiently managing repetitive tasks and addressing both time-consuming and physically demanding aspects of construction work (van der Heijden, 2023).

2.3.4 Digital Twinning and Extended Reality (XR)

Digital twinning is the process of creating a virtual representation of a physical object, system, or process by integrating data from sources such as sensors, BIM, and IoT devices. This creates a real-time digital duplicate that faithfully mirrors the physical entity. The use of digital twins in construction involves simulating processes to allow stakeholders to anticipate and address issues like clashes or inefficiencies before they arise in the physical environment. The integration of XR, including VR (Virtual Reality), AR (Augmented Reality), and MR (Mixed Reality), are commonly employed to support digital twinning initiatives (van der Heijden, 2023).

2.3.5 3D Printing and Additive Manufacturing (AM)

In Construction 4.0, 3D printing and AM emerge as pivotal technologies that bring significant value by revolutionising traditional construction methods. These technologies enable precise and efficient fabrication of complex architectural structures. The key benefits encompass design freedom, allowing for intricate customisation, cost reduction, enhanced sustainability through optimised material usage, and considerable time savings in the construction process. According to van der Heijden (2023), 3D printing and AM

allow for the creation of intricate geometries and complex shapes that are challenging or impossible to achieve with conventional construction methods.

2.3.6 AI, Big Data, Machine Learning (ML), and Analytics

In Construction 4.0, AI, Big Data, ML, and analytics are transformative technologies that reshape traditional construction processes. Their impact is evident in data-driven decision-making, improved project management, increased productivity, and optimised resource allocation. These technologies play a crucial role in efficient resource management by analysing historical data and real-time information, leading to optimized allocation of resources such as labour, equipment, and materials (van der Heijden, 2023).

2.3.7 Cloud Computing and Blockchain

Cloud computing and blockchain are integral to Construction 4.0, ushering in a revolution in the construction industry. Cloud computing empowers the industry by providing scalable and flexible computing resources, storage, and services. Blockchain is a digital record-keeping system that securely stores information in a chain of blocks. Each block contains data and is linked to the previous one, making it difficult to alter past records. Its role in Construction 4.0 is crucial for enhancing communication and collaboration among stakeholders and facilitating the efficient management, analysis, and sharing of extensive project data (van der Heijden, 2023).

Siriwardhana and Moehler (2023), Construction 4.0 offers benefits like cost and time savings, performance improvements, and better collaboration. It has the potential to transform the industry and support development goals. However, adoption remains slow due to skill-related challenges. Recognising its potential, governments worldwide promote Construction 4.0, following Germany’s lead in implementing I4.0 across sectors. Moreover, they pointed out that Many countries, including Australia, China, the UK, the USA, and Malaysia, have strategic plans for Construction 4.0, but a gap exists between theory and practice. Further research is needed to assess readiness and maximise benefits. Closing this gap is vital for global adoption, with Sri Lanka's construction sector being a key economic contributor. Ranasinghe (2022), highlighted that the construction sector is flourishing in Sri Lanka. The impact of the construction industry on society, both socially and economically, is considerable and cannot be overlooked due to its substantial contributions. Integrating digital technologies into the construction industry is crucial for revolutionising the sector by enhancing efficiency, productivity, profitability, and overall sustainability (Wang & Guo, 2022). The study highlights the need for Sri Lankan practitioners, professionals, and academics to understand Construction 4.0 and its enabling technologies. While Construction 4.0 can enhance efficiency, productivity, and sustainability in the construction industry, its effective adoption depends on professionals' digital literacy and awareness. However, findings reveal a knowledge gap, with professionals demonstrating uneven familiarity with Construction 4.0 concepts. Although some are aware of digital technologies, the broader understanding of Construction 4.0 remains low. A thorough assessment of digital literacy levels is essential to bridge this gap and support successful implementation.

3. METHODOLOGY

3.1 RESEARCH PARADIGM

The first research objective was achieved through a comprehensive review of existing literature. A qualitative research methodology was adopted to address objectives [2], [3], and [4]. This approach provided a deeper insight into professionals' awareness and digital literacy, as well as the specific challenges and obstacles they encounter in implementing Construction 4.0. The rich, context-specific data obtained was crucial for examining the complexities of adopting advanced technologies in building construction projects in Sri Lanka. Semi-structured interviews were chosen as the data collection method for these objectives, as they enabled the gathering of detailed, firsthand insights from professionals directly engaged in building construction projects. This approach allowed for open-ended questioning, encouraging participants to share their experiences, perceptions, and opinions on their awareness, digital proficiency, and the challenges associated with implementing Construction 4.0. Additionally, it facilitated an in-depth exploration of both personal and organisational barriers, as well as potential strategies to overcome these challenges.

3.2 POPULATION, SAMPLING FRAME, SAMPLING TECHNIQUE AND SAMPLE SIZE

As Construction 4.0 is a relatively new concept, the study targeted professionals within Sri Lanka's building construction sector, such as civil engineers, project managers, quantity surveyors, architects, and academics, who possess knowledge of Construction 4.0. Given the limited availability of such experts, a snowball sampling technique was employed to recruit participants. This approach aligns with the study's qualitative and exploratory nature, and all data collection and analysis were completed within a constrained four-month timeframe.

4. DATA COLLECTION AND ANALYSIS

This study employed semi-structured interviews to investigate various dimensions of construction 4.0 technologies implemented in building construction projects across Sri Lanka, ensuring that essential topics were thoroughly explored. These interviews featured open-ended questions designed to capture participants' knowledge, experiences, challenges, and perspectives on strategies related to Construction 4.0. Thematic analysis was used to interpret the collected data. Table 1 provides a summary of each participant's position, academic qualifications, and professional background.

Table 1: Demographic profile of participants

Participant's ID	Position	Highest academic qualification achieved	Years of experience
P1	Senior Lecturer	Doctor of Philosophy	More than 10 years
P2	PHD Scholar	Bachelor of Science	2-3 years
P3	Consultant Quantity Surveyor	Bachelor of Science	More than 5 years

Participant's ID	Position	Highest academic qualification achieved	Years of experience
P4	Civil Engineer	Advanced Diploma in Civil Engineering & Advanced Diploma in Supply Chain Management	More than 15 years
P5	Chartered Architect	Bachelor of Architecture	5-10 years

4.1 CURRENT USE OF MODERN TECHNOLOGIES IN SRI LANKAN BUILDING CONSTRUCTION PROJECTS

According to the participants' responses, the Sri Lankan building construction industry is gradually adopting modern technologies, though the overall level of technological integration remains relatively low compared to global standards. BIM is gaining traction, with four out of five participants recognising its value in improving collaboration, efficiency, and project management. AutoCAD and Revit are used for drafting and 3D modelling, though limited references to these tools suggest that traditional methods are still prevalent. Quantity Surveyors are beginning to utilise digital tools like COSTX, Planswift, and Cubicost for accurate quantity take-offs and BOQ (Bill of Quantities) preparation, though manual methods remain common. Primavera, mentioned by an experienced civil engineer (P4), is used for project scheduling and resource management in large projects. Modular construction, noted by P2, is still in its infancy, with adoption hindered by high initial costs, technical barriers, and resistance to change. IoT is being explored in the pre-construction and construction phases, but its implementation is minimal. Similarly, ERP (Enterprise Resource Planning) systems are used by some larger or more progressive companies for data and resource management. While architects have begun using 3D printing for design visualization, its broader application remains rare. Overall, the findings indicate that although technologies like BIM, Revit, and Primavera are gaining traction, more advanced solutions such as modular construction, IoT, ERP, and 3D printing are still underutilised, reflecting the industry's slow pace of technological transformation.

4.2 IMPLEMENTATION OF KEY CONSTRUCTION 4.0 TECHNOLOGIES IN THE SRI LANKAN BUILDING CONSTRUCTION SECTOR

Construction 4.0 incorporates several key enabling technologies such as BIM, IoT, Robotics, Cobots, Digital Twinning, ER, 3D Printing, AI, Big Data, Machine Learning, and Cloud Computing. This research primarily examines the extent to which these technologies are being utilised in building construction projects and aims to determine the level of implementation of Construction 4.0 technologies in Sri Lanka. Participants provided their insights based on their professional experience. The following findings will present the implementation level of each technology within the Sri Lankan context. The following findings will present the implementation level of each technology within the Sri Lankan context.

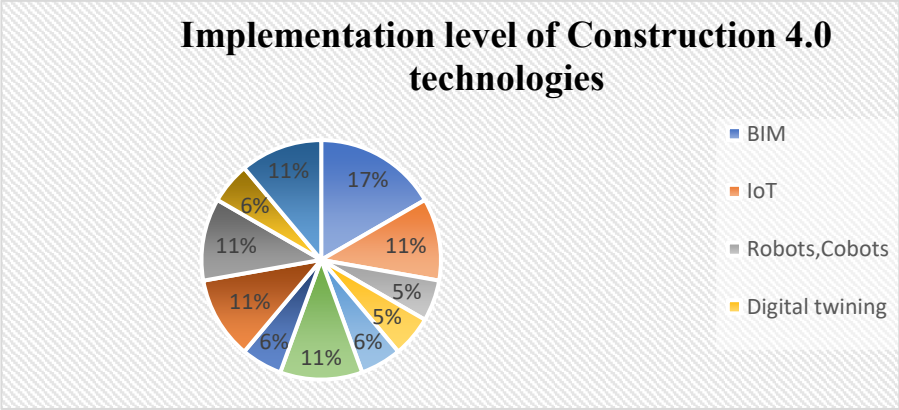


Figure 2: Visual representation of the implementation level of Construction 4.0 technologies

The study revealed that BIM is the most widely implemented Construction 4.0 technology in Sri Lanka's building sector, with all participants confirming its use, and P1 specifically mentioning its robust implementation. IoT integration is progressing well, with architects using digital devices like tablets and mobile phones for on-site efficiency, as noted by P3, P1, P2, P4, and P5 emphasized its growing adoption across the industry. However, advanced technologies like robots, cobots, and digital twinning remain unimplemented, with P2, P4, and P5 pointing out their absence. VR is being tested and partially used, as confirmed by P1, P2, and P5, while AR and 3D printing have minimal to no adoption, with P1, P3, P4, and P5 highlighting their lack of implementation, and P2 stating 3D printing is at a minimal level. AI applications are limited, mostly in design and documentation, with P1 noting its use, P3 indicating its limited application to the design phase, and P5 observing its role in ensuring accuracy during documentation but not in construction. Machine learning is rarely used, as mentioned by P3 and P4. Big data analytics show mixed implementation levels, with P3 and P4 reporting no use, while P2 noted its use and P1 mentioned partial implementation. Cloud computing is widely adopted across most projects, supporting e-tendering and document sharing through platforms like Google Drive, as confirmed by all participants, with P2 highlighting its role in e-tendering and P4 mentioning Google Drive for managing and sharing documents.

4.3 Digital Literacy Level of Professionals in Sri Lanka's Building Construction Sector for Construction 4.0 Implementation

Participants expressed two main viewpoints regarding digital literacy among professionals. One perspective is that digital literacy is very low, while the other suggests that it is at a reasonable level, not low. The findings highlight that digital literacy among Sri Lankan construction professionals remains low, especially in the government sector, and this poses a key barrier to adopting Construction 4.0 technologies. While some awareness exists, particularly among younger professionals and recent graduates, practical implementation and hands-on experience are minimal. P1 and P3 noted that only a few financially capable companies are integrating modern technologies, while the majority lack the necessary infrastructure and resources. P4 and P5 emphasized generational differences, with younger professionals being more tech-aware but lacking opportunities to apply their knowledge. Overall, digital literacy among professionals is

estimated at 40-50%, with the country lagging behind global standards. Enhanced awareness, resources, and practical application are essential for the broader adoption of Construction 4.0 in Sri Lanka.

4.4 CHALLENGES TO IMPLEMENT CONSTRUCTION 4.0 TECHNOLOGIES IN THE SRI LANKAN BUILDING SECTOR

Table 2: Challenges to implement Construction 4.0 technologies in Sri Lanka

Challenges	Overview	References
The labour force is not ready to implement these technologies	P1 mentioned that the industry is not yet prepared to adopt these technologies P2 explained that the workforce is not prepared to adopt these technologies, and their skill level for implementing them is quite low. Additionally, the skilled labour force in Sri Lanka is declining	P1, P2
The government doesn't support to implement of Construction 4.0 technologies	P1 noted that professionals lack adequate support from the government. P2 explained that because the majority of projects are managed by the government, it has not taken any steps to promote or implement Construction 4.0 technologies. Additionally, the government has not established any regulations in this area. P4 noted that most construction projects in Sri Lanka are government driven. participant also pointed out that the government is not aware of the new technologies being adopted in other countries	P1, P2, P4
Implementation cost is high	P1 mentioned that organizations need to invest a significant amount of money for implementation purposes P2 explained that construction firms in Sri Lanka, aside from high-level contractor companies, lack the necessary capital and infrastructure to implement these technologies in the local context. P3 pointed out that when working with modern technologies, professionals need to use certain advanced software. However, purchasing this software can be challenging for professionals due to its potentially high cost. P5 highlighted that implementing Construction 4.0 applications requires a significant financial investment.	P1, P2, P3, P5
Resistance to change	Professionals and labourers are resistant to change and hesitant to adopt or embrace modern technologies	P2
Researchers don't have the proper forum to present their findings	Many academics research how to transform the sector using digital technologies. However, they lack a sufficient platform to present their findings and share them with professionals	P1

Challenges	Overview	References
Professionals need to switch to new software or technology for construction projects, but they require time to learn these tools	Professionals need to switch to new software or technology for construction projects, but they require time to learn these tools while managing their current workload. P5 mentioned that many professionals do not have enough time to adopt new software and continue to rely on older systems.	P5
Knowledge gap of the professionals	P1 highlighted that the lack of knowledge and digital literacy among professionals is a major barrier to progress. P5 mentioned that there is a knowledge gap, with only few professionals understanding how to utilize Construction 4.0 technologies within the industry.	P1, P5
Lack of resources	P3 stated that the lack of resources makes it difficult for professionals to adopt these technologies. They need to purchase software, which can be a challenge due to the high costs involved. P4 also noted that many professionals cannot afford the cost of the software, making it a significant challenge for them. P5 also mentioned that the high cost of software poses challenges for utilizing modern tools within the industry.	P3, P4, P5
Lack of foreign investment	P3 explained that professionals are not engaging with foreign clients. For example, if a client is from Germany and expects the project to be executed using their technologies, the professionals must utilize and implement these technologies to complete the project. P4 shared a similar perspective to P3, highlighting that there is a lack of foreign investors in Sri Lanka's construction projects. The other two job roles (Consultant & Contractor) are contingent on the client's needs, and if the client prefers to utilise modern technologies for their project, professionals are obligated to follow those requirements	P3, P4
Lack of experts in the industry	Professionals in the Sri Lankan context lack sufficient expertise to seek advice, as indicated by Participant P1. P2 identified a challenge in implementing Construction 4.0 applications, nothing that even though there is awareness of Construction 4.0, practical implementation is low. Additionally, it is difficult to find professionals in the industry with experience using this technology or who have been involved in projects utilizing Construction 4.0 in Sri Lanka. P3 also noted that there are only a few experts in Sri Lanka who are knowledgeable about implementing these technologies in projects	P1, P2, P3

4.5 STRATEGIES TO OVERCOME CHALLENGES IN INTEGRATING CONSTRUCTION 4.0 TECHNOLOGIES INTO BUILDING CONSTRUCTION PROJECTS

Considering all the participants' responses, it is evident that the readiness level of professionals and the sector to implement Construction 4.0 is quite low. Participant P4 pointed out that the Sri Lankan construction industry hasn't even fully embraced Construction 3.0 yet. Therefore, significant efforts are needed to promote Construction 4.0, to maximise its potential and enhance the efficiency, effectiveness, and profitability of building construction projects in Sri Lanka. Each participant has provided their recommendations on how to encourage the adoption of Construction 4.0 applications within the industry, and these suggestions will be detailed in the following section. To promote the adoption of modern construction technologies, raising awareness among financially capable individuals through case studies that demonstrate cost savings is essential. CIDA (Construction Industry Development Authority) should take the lead by organising training programs, CPD (Continuous Professional Development) sessions, and bringing in international experts to enhance digital literacy among industry professionals. For instance, countries like Germany, Singapore, and Japan, which are leaders in smart construction, could provide valuable benchmarks, while short-term training programs in digital construction management or BIM could greatly benefit local professionals. Software companies should be encouraged to provide their packages at more affordable prices, making advanced tools more accessible. The government and CIDA must support R&D (Research and Development) by introducing new regulations and encouraging student and professional research projects. Universities should update their curricula to include modern construction technologies, ensuring graduates are well prepared for industry demands. Additionally, professionals must engage in international projects, developing the necessary skills to meet global standards. The government can further accelerate adoption by offering tax incentives and financial support to companies implementing technologies like modular construction. Clients should also be educated on the benefits of modern technologies in improving project efficiency. Moreover, industry professionals and workers need to shift their traditional mindsets and embrace innovation. To gain valuable insights, companies can organise study tours to countries successfully implementing these technologies, allowing professionals to learn from global leaders.

5. METHODOLOGICAL LIMITATIONS

Given that only five participants were involved in this study, the sample size may not sufficiently reflect the broader population's levels of digital literacy and readiness. To gain a more comprehensive understanding, a larger sample, typically around 25 participants or more, would be more appropriate. Data was collected through a virtual platform, with each session lasting approximately 15 to 20 minutes. Furthermore, the study was limited to a qualitative approach due to time constraints and did not incorporate a mixed methods design.

6. CONCLUSION AND RECOMMENDATIONS

The study reveals that while the Sri Lankan building construction industry has begun to embrace modern technologies, the overall adoption of Construction 4.0 is low. Technologies like BIM, AutoCAD, Revit, Primavera, and cloud-based tools are gaining traction, particularly among larger or more progressive firms. However, more advanced

innovations such as IoT, ERP systems, modular construction, AI, machine learning, AR/VR, and 3D printing remain underutilised due to a combination of structural, financial, and educational barriers. A key obstacle is the low level of digital literacy among professionals, particularly in the government sector and among older generations. The readiness of the workforce to adopt Construction 4.0 technologies is low, and the industry has yet to fully transition from Construction 3.0. Challenges such as high implementation costs, lack of government support, resistance to change, limited R&D infrastructure, and a shortage of skilled professionals further hinder progress. Despite these challenges, there is growing awareness, especially among younger professionals, and recognition of the potential benefits these technologies offer. Encouragingly, several participants suggested actionable strategies for fostering wider adoption, including targeted training, curriculum updates, cost reduction for digital tools, and international collaboration. Future studies can be carried out to investigate the impact of governmental policies, incentives, and regulations on either promoting or limiting the adoption of digital technologies in the construction sector.

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REVIEW OF CIRCULARITY ASSESSMENT TOOLS IN THE BUILT ENVIRONMENT

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ABSTRACT

Adopting circular economy in the built environment requires a change in the approach of designing, constructing, operationalizing and deconstructing the buildings. The transition from a conventional building approach towards a circular economy in the built environment requires assessment tools that can evaluate environmental performance and the integration of circular economy (CE) principles across all building lifecycle stages. This study presents a comparative evaluation of 16 circularity assessment tools using two key dimensions: lifecycle coverage and circularity based on CE integration. In order to assess circularity, a standardized scoring system between 1 and 5 was developed, aligned with Ellen MacArthur Foundation's ReSOLVE framework. This study indicates that tools such as BAMB and Madaster offer high levels of CE integration, offering features as varied as material passports, lifecycle tracking, and design-for disassembly. Conventional Life Cycle Assessment (LCA) tools like SimaPro and GaBi, while good in modelling the environment, lack dedicated circularity indicators. Tools such as Circulytics and Level(s) show strength in strategic or organizational-level assessment, but do not provide technical detail regarding material recovery or component reuse. This comparative framework provides valuable insights for academics, practitioners, and policymakers seeking to select or adapt circularity tools. In the Indian context, where sustainable urbanization is a national priority, contextualizing and integrating these tools with existing rating systems like GRIHA and LEED India could accelerate the adoption of circular construction practices.

Keywords: *Circular Design Indicators; Circular Economy; Circularity Assessment Tools; Life Cycle Assessment; Material Passports.*

1. INTRODUCTION

The construction industry is one of the largest contributors to environmental degradation worldwide. There is a great deal of natural resource consumption, and an enormous amount of waste and emissions are produced. The United Nations Environment Programme (UNEP, 2020) estimates that the building and construction sector contributes roughly 39% to global carbon emissions. This data illustrates the unsustainable nature of the current linear economic model, which is based on the "take-make-dispose" economic model. This model places immense pressure on ecosystems and global resources due to

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the growth of urban populations and the growing demands for infrastructure (Pomponi & Moncaster, 2017). Circular economy (CE) concepts have gained global attention as a means of addressing these pressing challenges. Contrary to a linear model, CE emphasizes resource efficiency, material reuse, recycling, waste minimization, and regenerating resources as long as possible, thus reducing the need to extract virgin materials (Kirchherr et al., 2023; European Commission, 2021; Ellen MacArthur Foundation, 2015a). As a result, it promotes the design of buildings that are durable, adaptable, easier to repair, upgradable, extendable, reusable, easy to disassemble or recyclable for their components (Hasani & Riggio, 2025).

Many researchers have emphasized the implementation of R-framework to integrate circular economy in construction sector. The traditional 3R framework including Reduce, Reuse, Recycle has evolved to address complexities in resource use and waste management. Some studies propose extended frameworks of up to 9Rs, including Rethink, Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, and Regenerate (Garusinghe et al., 2023). In the construction sector, these R-principles are increasingly embedded across building lifecycle stages, material flow management, and design practices. (Cimen, 2023) integrated 14 extended R-principles into the Inception-to-Circulation (I2C) framework, encompassing all lifecycle phases from planning to post-use circulation, while Gowsiga et al. (2023) research 17R principles through literature review. Out of these, Reduce and Recycle remain foundational, minimizing material input and enabling secondary material use (Cimen, 2021) while, Repair, Refurbish, and Remanufacture act as a key to longevity of building components, particularly in modular and adaptable systems (Hasani & Riggio, 2025). Rethink and Refuse prompt early-stage shifts in design logic and material selection, integrating system-level innovation (Gowsiga et al., 2023), while Regenerate and Responsible use are the recent additions that emphasize ecosystem restoration and ethical procurement (Garusinghe et al., 2023). While each R-principle is conceptually distinct, many overlap in practice. This entanglement is reflected in integrative models such as Bocken's narrowing, slowing and closing loops framework (Hasani & Riggio, 2025) and the ReSOLVE model (Gowsiga et al., 2023). The evolution from 3Rs to 17Rs in construction thus reflects a growing sophistication in circular economy thinking, which can result in reducing environmental impacts and increasing economic innovation and resilience (Ghisellini et al., 2016). In order to measure how effectively circular practices are being applied, clear, reliable methods are needed. An assessment tool that focuses on circularity plays a crucial role in this process. Architects, designers, engineers, and policymakers can use these tools to assess materials' sustainability, track environmental impacts, and set measurable circularity targets. Based on data on reuse potential, embodied carbon, lifecycle performance, and material recovery, they offer guidance in decision-making.

To support this transition, several circularity assessment tools have been developed. A few of the examples include Madaster, which allows the creation of material passports; Level(s), developed by the European Commission; the Ellen MacArthur Foundation's Material Circularity Indicator (MCI); One Click LCA, a lifecycle assessment software; and Building Circularity Indicator (BCI), which measures circular potential and reusability. A building's lifecycle can be tracked, measured, and evaluated by using tools to assess its circular performance (Pomponi & Moncaster, 2017). It is important to note that each of these tools has unique features and methods of assessment that support sustainable construction techniques (Linder et al., 2017; Morseletto, 2020). While many

of these tools aim to support circular construction, their scope, lifecycle coverage, and specific indicators vary. Therefore, it is important to determine which tools are most appropriate for evaluating circularity in buildings.

Despite their growing use, limited comparative research has been conducted on how these tools align with circular economy principles. To choose the right tool for specific project goals and regional contexts, one must understand their scope, depth, and limitations. A review and comparison of 16 circularity assessment tools are conducted in this paper to fill that gap. This paper examines their lifecycle coverage and circularity integration depth, providing insight into how these tools can help guide the construction industry's transition to a circular economy. However, the study primarily relies on tool documentation and literature reviews rather than empirical data gathered from the stakeholders in the built environment. The scoring framework is qualitative and based on document analysis. Thus, the evaluation lacks performance-based metrics or outcomes from tool implementation by the stakeholders in the construction industry.

Although these limitations are present in the current study, it offers a much-needed starting point for understanding and comparing circularity assessment tools. It provides direction for integrating circular economy principles in Indian urban development thereby supporting national agenda of reducing construction waste and enhance resource efficiency. It offers a comparative framework that can guide policymakers, urban planners, and developers in selecting appropriate tools. This research paper will trigger the discussion on contextualizing these for Indian construction industry by creating a database considering Indian construction material, technology and practices to accelerate India’s transition toward circular construction and sustainable building practices.

2. METHODOLOGY

The purpose of this study is to evaluate various circularity assessment tools applicable to the construction and building sector through a qualitative and comparative method of research. Circular economy principles (CE) are meant to be incorporated and promoted throughout the entire lifecycle of a building, starting with its design, moving on to its construction and operation, and finally ending with its deconstruction or reuse. There are three main components to the methodology. In the first step, a comprehensive literature review was conducted. For this purpose, academic papers, industry reports, and international guidelines were studied to understand the current research and application of CE in the built environment. The study helped identify the key principles and criteria that define circularity in the construction industry.

The study analysed the official documentation and user manuals of selected circularity assessment tools. The documents provide an overview of how each tool works, how it uses indicators, and how it evaluates circularity. Several aspects of the circular economy were considered when selecting the tools, such as resource efficiency, closed material loops, and design for disassembly. A special focus was placed on tools specifically designed for the construction industry, covering lifecycles from design to end-of-life (One Planet Network, 2020). In the review, tools focusing on general sustainability were differentiated from those designed to assess circularity more specifically. Credibility and reliability were ensured by selecting tools developed by well-recognized organizations.

Finally, a comparative framework was developed to assess the tools based on the findings of the literature review and documentation analysis. In addition to covering all lifecycle

stages, this framework also includes evaluating a tool's ability to measure reuse and recovery of materials, its ability to support flexible or adaptable design, and its compliance with circularity principles- R principles discussed in the introduction. By combining these approaches, the study aims to identify which tools are most effective in supporting the transition towards a circular built environment and provide useful insights to stakeholders.

2.1 DATA COLLECTION

Several academic and industry-related sources were reviewed in order to collect data. Science Direct, Scopus, Google Scholar, Springer Link, and Wiley Online Library were used to collect academic research as they cover a wide range of construction and sustainability studies. Also, official documentation available on the websites of the circularity assessment tools such as Madaster, One Click LCA, and eTool LCA, the documents from sustainability rating organizations such as the German Sustainable Building Council (DGNB) and the Green Business Certification Inc. (GBCI) were also included.

Data collection phase involved specific search terms used to find relevant information. It included phrases such as "circular economy in construction," "circularity assessment tools for buildings," "lifecycle assessment in architecture," "material passports" (Open Planet Network, 2020), "BIM and circularity", and "circular design indicators for buildings" (Pomponi & Moncaster, 2017; Geissdoerfer et al., 2017). In addition to providing an overview of a wide range of tools and frameworks, these search terms provided the basis for a comprehensive analysis of the study.

2.2 TOOL SELECTION CRITERIA

To ensure the study was relevant and comprehensive, a set of rules was used to select the right circularity assessment tools. The tools had to meet these conditions: (i) They must emphasize circularity, either directly or indirectly, by using supporting indicators; (ii) They need to be relevant for building projects, construction materials, and architectural design processes; (iii) at least one of these areas should be evaluated: resource reuse, lifecycle impact, design adaptability; R-principles and (iv) They should be discussed in academic studies, recognized by sustainability certifications such as LEED or BREEAM, or backed by policies from institutions such as the European Commission (European Commission, 2021; World Business Council for Sustainable Development, 2022). After applying these rules, 16 tools were selected from an initial list of 20 found during the literature review (See Annexure 1). These 16 tools were chosen because they were technically strong, applied to a variety of situations, and had detailed documentation that made them easy to compare.

2.3 COMPARATIVE FRAMEWORK

A comparative chart was developed in spreadsheet format, with column headers including: tool name, type of tool (e.g., digital or framework), tool developer, key principles and focus areas addressed, type of analysis offered (qualitative or quantitative), practical applications, parameters considered, missing circularity parameters, and the life cycle phases in which the tool is applicable (See Annexure 1). First, the tool type identifies the tools according to categories such as digital platforms (e.g. Madaster), software applications (e.g. SimaPro, One Click LCA), certification systems (DGNB,

GBCI), and conceptual frameworks (e.g., BAMB). Secondly, Quantitative Capabilities assesses the tools' ability to provide measurable results, such as embodied carbon, energy usage during operation, and material flow metrics (Pomponi & Moncaster, 2017). Thirdly, Qualitative Capabilities examine how well the tools support design-based circular strategies, such as flexibility,reuse, reversibility, and design for disassembly including other R-principles (Geissdoerfer et al., 2017). Circularity Focus examines how closely the tool aligns with circular economy (CE) principles, such as maintaining resources in use, adaptability, and recovery after use (Ellen MacArthur Foundation, 2013). It also considers which stages of the building lifecycle each tool covers, namely design, construction, operation, and demolition (European Committee for Standardization, 2012). An evaluation framework was developed to assess 16 circularity tools relevant to the built environment, and each tool was rated on a scale of 1 to 5 for its potential to support circularity, using key characteristics aligned with the Ellen MacArthur Foundation's ReSOLVE framework (Ellen MacArthur Foundation, 2015b) as shown in Table 1. A detailed comparison allows for highlighting the strengths and weaknesses of each tool for supporting CE strategies. This analysis is presented in a comparison table and is accompanied by detailed explanations for the ratings, based on both technical details and literature references (See Table 2).

3. CIRCULARITY EVALUATION CRITERIA AND ANALYSIS

Table 1: Circularity evaluation

Score	Definition	Key Characteristics
1 – Low	Basic sustainability focus, no circularity metrics.	Measures energy use or carbon only; no focus on reuse, adaptability, or material recovery.
2 – Limited	Environmental impact tools without reuse or disassembly support.	Uses LCA to show environmental impact but does not track reusability or circular flows.
3 – Moderate	Some circular ideas at material or product level.	Focuses on recyclability, material health, or reuse at a small scale.
4 – Strong	Covers multiple circular strategies across building phases.	Includes reuse, design for disassembly, and tracks materials through stages.
5 – Comprehensive	Full circular economy integration across lifecycle.	Has material passports, BIM links, reuse scores, and supports circular planning from start to end.

To evaluate life cycle coverage, we analysed how comprehensively each tool addresses different phases of the building life cycle (see Table 2). Tools were assessed for their ability to promote circular strategies such as reuse, recycling, material efficiency, design flexibility, and disassembly and adoption of other R-principles. Ratings were derived from official manuals, scholarly articles, and comparative studies. A bar graph was prepared to visualize the comparative performance of the tools across circularity assessment and life cycle coverage as shown in Figure 1.

Table 2: Tool comparison matrix

Tool Name	Category	Type	Lifecycle Phases Covered	Lifecycle Coverage	Circularity	Strengths	Limitations
BAMB (Buildings As Material Banks)	Framework	EU Research Framework	All Phases	5	5	Holistic CE integration; enables reversible building and material banking	Research-phase; limited adoption
Circulytics	Tool	Organizational Tool	Organizational Operation	1	4	Evaluates CE at organizational level, including resource loops	Not specific to buildings/ materials
Madaster	Tool	Material Passport Platform	Design, Construction, End-of-life	3	4	Tracks reuse and recycling potential of materials	Limited focus on operational energy
Level(s)	Framework	EU Assessment Framework	Design, Construction, Use	3	4	CE indicators include adaptability, durability, resource efficiency	Complex to apply practically
MCI (Material Circularity Indicator)	Framework	Circularity Metric (EMF)	Use, End-of-life	2	4	Measures material reuse and recovery	Limited to product-level assessment
BCI (Building Circularity Indicator)	Tool	Building-Level Assessment Metric	Design, Construction	2	4	Scores circularity at building level	Needs detailed material data
Circularity Assessment for Building Elements	Tool	Research Tool	Design, Demolition	2	4	Evaluates reuse potential of components	Time-intensive; manual process
DGNB	Certification	Certification System	Design, Construction, Operation	3	4	Integrates lifecycle and disassembly metrics	Region-specific (Europe); complex setup

Tool Name	Category	Type	Lifecycle Phases Covered	Lifecycle Coverage	Circularity	Strengths	Limitations
eTool LCA	Software	LCA Software	Design, Construction, Operation	3	3	Robust LCA and energy modelling	No circularity-specific features
One Click LCA	Software	LCA and Carbon Tool	Design, Construction, Operation	3	3	Fast LCA; integrates with BIM and EPDs	Limited direct CE indicators
CTI (Circular Transition Indicators)	Tool	Company-Level Assessment Tool	Production, Use	2	3	Measures global resource flow and efficiency	Not building-specific
GBCI (LEED, TRUE)	Certification	Certification System	Design, Construction, Operation	3	3	Promotes sustainable practices and material reuse	Circularity not directly measured
GaBi	Software	LCA Software	Design, Manufacturing, End-of-life	3	2	Detailed environmental performance analysis	Lacks reuse/ recyclability metrics
SimaPro	Software	LCA Software	Design, Production, Operation	3	2	Detailed environmental impact analysis	Not CE-focused
ICE (Inventory of Carbon & Energy)	Database	Embodied Carbon Database	Design, Procurement	2	2	Provides embodied carbon data	No reuse or circularity indicators
IESVE	Software	Simulation Software	Design, Operation	2	1	Energy and daylight optimization	No material circularity data

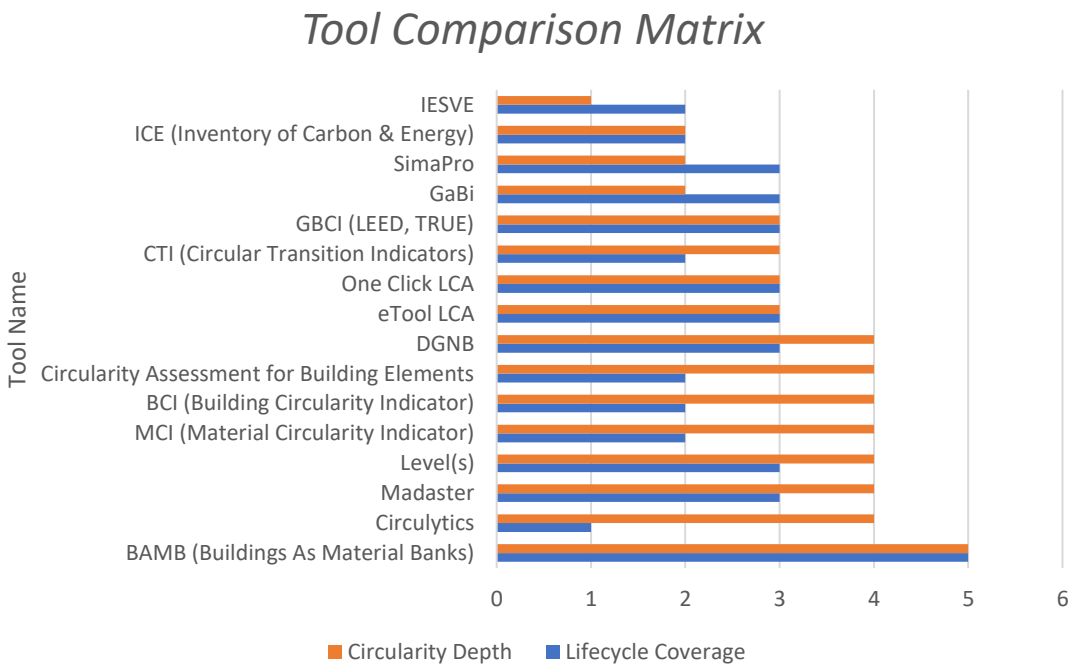


Figure 1: Circularity of assessment tools in built environment

3.1 EVALUATION OF CIRCULARITY ASSESSMENT TOOLS

The following section provides a rationale for evaluating 16 tools and their degree of integration with circular principles.

3.1.1 Highest Circularity Integration

BAMB (Buildings as Material Banks) developed under the EU Horizon 2020 initiative, provides a comprehensive framework for circularity in the built environment. The tool can be applied throughout all design phases, from early concept to end-of-life, and it integrates both qualitative and quantitative analysis through tools such as Material Passports. BAMB aims to facilitate materials recovery, reuse, and flexible adaptation of buildings over time. One of its key strengths lies in enabling future material reuse by documenting product histories and encouraging modular, easy to disassemble design. Compared with tools that address only isolated lifecycle stages, it stands out due to its deep lifecycle integration (Buildings and Materials Bank, 2020; Debacker et al., 2016).

3.1.2 High Circularity Integration

Madaster, developed in the Netherlands, is a digital platform that generates material passports and circularity scores at the building and product level. During the design and operation stages of buildings, it is especially relevant. Despite its strengths in tracking and documenting material data, including embodied value and potential reuse, it lacks the ability to model energy performance, which can be a limitation in full lifecycle sustainability assessments. Among its key differentiators is its integration with building information modelling (BIM) platforms in real time, which promotes transparency in material sourcing and waste reduction (Madaster, 2021).

Level(s) is a voluntary reporting framework initiated by the European Commission that integrates life cycle thinking into building assessments. Performance-based and design-

based indicators such as adaptability, resource efficiency, and life cycle environmental impact are most useful during early design and usage phases. Level(s) does not provide direct circularity metrics, but its structured indicators support long-term circularity (Dodd et al., 2021, European Commission, 2021).

Material Circularity Indicator (MCI), a key advantage of this tool is that it aligns with EU sustainability goals, unlike technical calculators such as MCI or BCI (European Commission, 2021), Material Circularity Indicator (MCI), introduced by the Ellen MacArthur Foundation, measures the degree of circularity in products based on input-output flows, such as the proportion of recycled and reused content. It is primarily used during the design and manufacturing stages of a product. Although MCI provides clear, quantifiable metrics for circularity, its limitations include its limited application to whole-building assessments. In addition to its numerical simplicity, it has a wide range of industry application and serves as a useful tool for quantifying closed-loop material flows (Ellen MacArthur Foundation, 2015b).

Building Circularity Indicator (BCI) offers a building-scale score based on criteria like disassembly potential and modularity. The tool is most useful during the design and refurbishment phases of a project. However, BCI does not consider energy or a lifecycle's impact when identifying reuse potential. The main benefit of this tool is that it provides architectural planning for deconstruction and flexible design, which makes it stand out from more general LCA tools (Honic et al., 2019).

Circularity Assessment for Building Elements (CABE) Circularity Assessment for Building Elements (CABE) is focused on assessing individual building components, particularly in design and renovation contexts. In addition to considering disassembly potential, recyclability, and reusability of materials, it does not consider the system-level operations of buildings. Its strength is enabling component-level reuse strategies, and it differs from building-scale tools in its granular focus (One Planet Network, 2024).

DGNB (German Sustainable Building Council) DGNB (German Sustainable Building Council) certification incorporates circular economy concepts within a broader sustainability framework. This method applies to all phases of construction, but it focuses on the design and operational phases. Although DGNB is not solely focused on circularity, it promotes resource conservation, modular construction, and material efficiency. In addition to its integrative, performance-based approach, it is included in one of the most respected green certification schemes in Europe (Deutsche Gesellschaft für Nachhaltiges Bauen, 2020).

Circulytics, by the Ellen MacArthur Foundation, measures an organization's circularity performance, focusing on strategy, operations, and enabling factors rather than specific buildings or materials. Instead of being used during design or construction phases, it is useful during strategic planning or portfolio management. A key strength of this tool is its ability to evaluate corporate circular readiness, and its unique contribution is that it focuses on macro-level circular performance, making it unique among building-specific tools (Ellen MacArthur Foundation, 2020).

3.1.3 Moderate Circularity Integration

One Click LCA integrates Life Cycle Assessment (LCA) with BIM workflows and supports early to mid-design phases. The tool enables the evaluation of carbon, material, and circular impacts. Although it includes circular economy modules, its primary focus

remains on environmental impact assessment rather than circularity. The key strength of One Click LCA is that it is compatible with numerous databases and software platforms (One Click LCA, 2023).

eTool LCA is another LCA-based platform with some circularity features, especially useful in the concept and construction documentation stages. Although it supports environmental impact assessments, it is not equipped to evaluate reuse or design-for-disassembly strategies. In addition to its detailed energy and carbon modelling, it can model multiple design scenarios over the lifecycle of a building (eTool, 2022).

GBCI (Green Business Certification Inc.) administers rating systems such as LEED and WELL. Material reuse, lifecycle impact, and adaptive reuse are included in these certifications, especially during the design and refurbishment phases. Their primary focus is on sustainability performance, rather than directly measuring circularity. One of GBCI's strengths is its market recognition, and its unique role is to set standardized benchmarks for green building practices (U.S. Green Building Council, 2020).

Circular Transition Indicators (CTI), developed by the World Business Council for Sustainable Development, helps organizations measure material flows and identify circular opportunities. It is useful for managing corporate resources and construction supply chains, although it is not specific to buildings. One of its limitations is that it lacks spatial or structural specificity. The main advantage of this tool is that it enables you to track your progress toward circular procurement and materials management (World Business Council for Sustainable Development, 2022).

3.1.4 Low Circularity Integration

GaBi is a robust LCA tool widely used for assessing the environmental impacts of products and systems. In addition to the design and procurement phases, it does not include modules for assessing circular strategies such as reuse or disassembly. It offers detailed impact analysis across many sectors, but it differs from circularity tools by focusing solely on environmental impacts without reuse metrics (Burhan, 2018; Sphera, 2023).

SimaPro offers similar capabilities to GaBi, emphasizing in-depth lifecycle environmental assessments. Despite its suitability for early-stage design and specification, it lacks features that support circular design decisions. Because of its depth and transparency, it is useful for academics and consultants, but unlike circularity tools, it does not integrate feedback on material reversibility or modularity (PRé Sustainability, 2023).

ICE (Inventory of Carbon and Energy) is a dataset rather than a tool, providing embodied energy and carbon values for various building materials. While it applies to design and procurement, it does not assess circularity indicators. The advantage of this tool lies in its ability to select materials based on their carbon footprint quickly. What makes ICE different is its focus on static embodied energy values without lifecycle modelling or reuse potential (Hammond & Jones, 2011; Inventory of Carbon & Energy, 2024).

3.1.5 Very Low Circularity Integration

IESVE (Integrated Environmental Solutions Virtual Environment) is a simulation platform used for modelling energy performance, thermal comfort, and daylight. Despite its effectiveness in optimizing building performance, it does not address circularity

features such as material reuse, modularity, or lifecycle adaptability. The strength of the tool lies in energy and comfort modelling, and it stands out more as an energy efficiency tool than as a circularity tool (Integrated Environmental Solutions, 2022).

4. CONCLUSION

The study analysed and compared 16 tools for measuring circularity in the built environments. Tools were evaluated based on how well they support circular economy strategies like reuse, recycling, disassembly, and adaptability and how many stages of a building's life they cover. Due to their focus on circular design and full lifecycle coverage, tools like BAMB and Madaster scored the highest. IESVE and Simapro, although useful for environmental assessments, showed limited circularity support. Each tool serves a different purpose - some are best suited for building-level evaluations, while others focus on specific products, organizations, or materials. The ratings were based on the ReSOLVE framework, and comparison studies. In general, circular construction goals were better supported by tools that included both detailed data and practical design strategies. Most of the tools evaluated are developed for international contexts and may not completely align with the local materials, construction practices, or regulatory frameworks prevalent in India. This limits insights into actual usability and adoption in Indian contexts. As India continues to grow and build at a rapid pace, circular economy strategies become increasingly important. Therefore, adapting or creating tools suited to India’s unique materials, methods, and challenges is necessary. In addition to supporting long-term environmental goals, this will help make buildings more sustainable and reduce waste. The current evaluation of circularity assessment tools is theoretical and comparative in nature. The future research may involve field validation or pilot testing of tools in actual building projects, which can offer practical validation of their effectiveness. Also, the future research can emphasize on the operationalization of integration of these tools with Indian rating systems like GRIHA and LEED India and the challenges it might present. The awareness of these tools in the community of academicians, architects and developers in India is unknown. Future research should focus on the evaluation of the awareness of circularity tools among the stakeholders of the built environment in India and on making these tools more accessible and relevant to the Indian construction industry.

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7. **ANNEXURE 1:** Comparative chart for circularity assessment tools

RESOURCE	TOOL NAMES	TYPE OF TOOLS	INVENTOR OF TOOL	QUANTITATIVE ANALYSIS	QUALITATIVE ANALYSIS	KEY PRINCIPALS
https://madaster.com/	Madaster	Digital tool for Material Tracking and Management	Thomas Rau, a Dutch architect	Embodied Carbon Calculation, Material Composition Analysis,Life Cycle Assessment (LCA), Material Circularity Index (MCI), Resource Scarcity Assessment, Financial Valuation of Materials	Material Reusability Potential, Compliance with Sustainability Standards, Design for Disassembly, Health & Toxicity of Materials, Transparency & Documentation, Supply Chain Traceability	Circular Economy, Sustainability, Transparency
https://www.dgnb.de/en/certification/important-facts-about-dgnb-certification/about-the-dgnb-system	DGNB Certification System (Deutsche Gesellschaft für Nachhaltiges Bauen)	Framework for Planning and Optimization Tools for Sustainable Construction	Founded by the German Sustainable Building Council (DGNB) in 2007	Life Cycle Assessment (LCA)	Design and architectural quality	Holistic Sustainability, Life-Cycle Orientation, Performance-Based Assessment
https://oneclicklca.com/	One Click LCA	Digital tool for Carbon Designing	Bionova Ltd (Finland)	Global Warming Potential (kg CO_2e), Embodied Carbon, Energy Consumption (MJ/m².), Water Consumption (m³), Waste Generation (kg/m².),	Design Optimization, BIM Integration, Lifecycle Thinking, Circular Economy Insights,Regulatory Compliance (EU Taxonomy, Carbon Neutrality goals, and National Regulations)	Whole-life carbon assessment
https://www.iesve.com/software	IES Virtual Environment (IESVE)	Digital tool for Building performance simulation software	Integrated Environmental Solutions (IES)	Energy consumption, thermal comfort levels, daylight factor, CO_2 emissions, HVAC efficiency	Design strategies for sustainability, building usability, climate adaptability	Energy modeling, thermal comfort, daylight analysis, HVAC analysis, carbon impact assessment
https://c2ccertified.org/	Cradle to Cradle Certified	Calculation tool for Sustainability certification	McDonough Braungart Design Chemistry (MBDC)	Material composition, recyclability %, renewable energy use, water efficiency	Social fairness, material health, design for circularity	Material health, material reutilization, renewable energy, water stewardship, social fairness
https://bregroup.com/about/bre-trust	BRE Trust Design for Deconstruction	Framework for sustainable building deconstruction	BRE Trust (Building Research Establishment)	Material reuse potential, embodied carbon reduction, waste diversion rates	Ease of disassembly, adaptability of design, long-term sustainability	Circular economy, ease of disassembly, reuse potential, embodied carbon reduction
https://environment.ec.europa.eu/topics/circular-economy/levels_en	Circular Footprint Formula	Calculation tool for Life Cycle Assessment (LCA) methodology	European Commission, PEF/OEF Initiative	Carbon footprint (kg CO_2e), resource depletion %, recyclability rates	Environmental impact reduction strategies, eco-design principles	Carbon footprint, material resource efficiency, environmental impact, recyclability
https://weathershift.com/	WeatherShift	Digital tool for Climate scenario analysis	Arup	Temperature variations, precipitation changes, extreme weather probability	Climate resilience strategies, adaptation measures	Future climate projections, temperature shifts, precipitation changes, resilience planning
https://rheaply.com/	Rheaply	Digital tool for marketplace for material reuse	Rheaply Inc.	Quantity of materials diverted from landfills, cost savings from reuse	Circular economy participation, collaboration between stakeholders	Circular economy, resource sharing, material tracking, waste reduction
https://www.athenasmi.org/	Athena Impact Estimator	Calculation tool for Life Cycle Assessment (LCA) software	Athena Sustainable Materials Institute	Embodied carbon (kg CO_2e), energy consumption, material lifecycle impact	Sustainable material selection strategies, ecological benefits	Embodied carbon, material lifecycle impact, energy use, emissions calculation
https://go.materialsmarketplace.org/	Materials Marketplace	Digital Tool exchange platform for material reuse	U.S. Business Council for Sustainable Development (US BCSD)	Waste reduction metrics, material exchange rates, CO_2 impact	Industrial symbiosis, corporate sustainability initiatives	Circular economy, material repurposing, industrial symbiosis, carbon footprint reduction
https://act.speckle.arup.com/login	Arup Carbon Digital Tool	Digital tool for Carbon assessment and design tool	Arup	Operational and embodied carbon (kg CO_2e), energy intensity	Carbon reduction strategies, sustainable design optimization	Embodied carbon calculation, operational carbon analysis, carbon reduction strategies
https://environment.ec.europa.eu/levels_en	Level(s)	Sustainability framework for buildings	European Commission	Life cycle carbon footprint, energy use, water consumption, indoor air quality	Circular economy principles, eco-design strategies, social impact	Sustainable building performance, EU policy compliance
https://ecorglobal.com/circularity/	ECOR Circularity Platform	Circular material innovation	ECOR	Waste upcycling %, circularity index	Material innovation, waste repurposing	
https://planonsoftware.com/uk/news/building-circularity-index-bci-partner/	Building Circularity Index (BCI)	Circularity performance indicator	BCI Initiative	Circularity score, material reusability	Circular economy in buildings	
https://simapro.com/	Sima Pro	Life Cycle Assessment (LCA) software	PRé Sustainability	Carbon footprint, toxicity impact	Circular product design	
https://sphera.com/product-stewardship/life-cycle-assessment-software-and-data/?nab=0	Gabi LCA	Life Cycle Assessment (LCA) software	Sphera	Resource depletion, environmental impacts	Product sustainability strategies	
https://cerclos.com/products/etool/	eTool LCA	Whole-building LCA tool	eTool Global	Embodied energy, operational carbon	Carbon reduction strategies	
nepfi.org/wordpress/wp-content/uploads/2021/12/PRB-Guidance-Resource-Efficiency.pdf	PREP (Product Resource Efficiency Principles)	Circular economy guideline for product design	European Commission	Resource efficiency tracking, embodied energy, material recoverability	Sustainable design guidance, eco-design principles	Product longevity, material efficiency, end-of-life recovery
https://zwia.org/zwh/	Zero waste Hierarchy (ZWIA)	Zero-waste design and policy framework	Zero Waste International Alliance (ZWIA)	Waste diversion %, landfill reduction impact, material reuse potential	Waste prevention strategies, sustainable consumption	Waste hierarchy, landfill reduction, closed-loop material flow

FOCUS AREA	Application	PARAMETERS	MISSING PARAMETER	Phase of building
Real Estate and Infrastructure	Material Passports, Circularity Insights, Life Cycle Assessments	Embodied Carbon, Material Composition, Reusability	no real-time prediction model for reuse feasibility.	Design, Construction, End-of-Life
Buildings and Districts in Various Life Cycle Phases	New Construction, Renovations, Buildings in Use, Urban Districts	Carbon footprint, resource efficiency, indoor air quality, thermal comfort, economic viability, recyclability	do not actively influence procurement strategies for cities, governments, and developers.	Design, Construction, End-of-Life
Building construction	BREEAM, LEED, DGNB, and other green building certifications	Global Warming Potential (GWP)	track carbon & energy impacts but lack detailed insights on material adaptability & reuse potential.	Design, Construction, End-of-Life
Building energy modeling, HVAC efficiency, daylight analysis	Green building design, net-zero energy projects, LEED certification support	Solar gain, ventilation rates, building envelope efficiency, indoor air temperature	No direct circularity scoring for building materials.	Design, Operation
Product sustainability, material health, circular economy	Certified products (textiles, packaging, furniture), Apple's material innovation	Material toxicity, biodegradability, carbon footprint, closed-loop design potential	do not actively influence procurement strategies for cities, governments, and developers.	Material Selection, Construction, End-of-Life
Circular construction, modular building	Adaptive reuse projects, prefabricated buildings	Component reusability, ease of dismantling, structural longevity, carbon savings	no real-time prediction model for reuse feasibility.	Design, Construction, End-of-Life
Life cycle assessment, carbon emissions tracking	Eco-friendly product manufacturing, EU environmental impact assessments	Material efficiency, energy consumption, waste generation, transportation emissions	Lacks a clear material circularity indicator (focuses mostly on emissions). No real-time tracking of waste diversion or reuse potential.	Material Selection, Operation, End-of-Life
Climate impact prediction, extreme weather adaptation	Future-proofing cities, flood mitigation planning, sustainable urban development	Temperature rise, humidity levels, precipitation trends, sea-level rise risk	No material or waste tracking integration (purely focused on climate adaptation). Lacks direct connection with LCA tools to measure long-term material impact.	Design, Operation
Waste reduction, resource-sharing economy	University surplus materials, corporate asset reuse programs	Material tracking, cost savings, CO_2 reduction from reuse, resource circularity	do not quantify the embodied carbon or energy savings from reuse	Construction, End-of-Life
Life cycle impact of buildings and infrastructure	LCA for LEED projects, net-zero carbon developments, sustainable retrofits	Embodied carbon, transportation impact, operational energy, end-of-life impact	track carbon & energy impacts but lack detailed insights on material adaptability & reuse potential.	Material Selection, Construction, Operation
Circular economy, material repurposing	Manufacturing waste reuse, industrial material exchanges	Waste diversion rate, lifecycle savings, carbon emissions avoided, material lifespan	do not quantify the embodied carbon or energy savings from reuse	Construction, End-of-Life
Low-carbon building design, net-zero strategies	Carbon footprint analysis for infrastructure, green building projects	Material impact, operational energy use, decarbonization pathways, emission hotspots	no real-time prediction model for reuse feasibility.	Design, Construction, Operation
Sustainable building performance, EU policy compliance, whole-life impact assessment	Green public procurement, sustainable residential & commercial buildings	Life cycle carbon assessment, energy efficiency, resource efficiency, indoor comfort	No policy enforcement tool that tracks how much circularity is being implemented in a project compared to regulations.	Design, Construction, Operation, End-of-Life
Circular economy, material reuse	Packaging, interior panels, furniture	Recycled content, energy-efficient processing	do not quantify the embodied carbon or energy savings from reuse	Material Selection, End-of-Life
Building reuse, circular design	Renovations, adaptive reuse projects	Material lifespans, adaptability	No post-occupancy tracking of circular performance over time.	Design, Construction
LCA, environmental impact	Sustainable product development	Carbon emissions, material toxicity	No detailed tracking of material reusability & adaptability.	Material Selection, Construction
LCA, eco-design	Sustainable supply chain optimization	Water use, emissions impact	track **carbon & energy impacts** but lack **detailed insights on material adaptability & reuse potential**.	Material Selection, Manufacturing
Whole-building lifecycle sustainability	Net-zero buildings, carbon accounting	Operational energy, material impacts	track **carbon & energy impacts** but lack **detailed insights on material adaptability & reuse potential**.	Design, Construction, End-of-Life
Product longevity, material efficiency, end-of-life recovery	Industrial product manufacturing, sustainable procurement	Product lifespan, recyclability index, energy efficiency, **remanufacturing feasibility, modular component recovery, repairability score**	Lacks quantitative weightage for circularity in decision-making.	Material Selection, Manufacturing, End-of-Life
Waste hierarchy, landfill reduction, closed-loop material flow	City-wide zero-waste initiatives, circular economy businesses	Resource recovery, composting efficiency, landfill diversion rate, **toxicity elimination, extended producer responsibility (EPR), redesign for reuse**	No carbon footprint analysis linked to waste reduction.	Construction, Operation, End-of-Life

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REVIEW ON TECHNOLOGICAL INTERVENTIONS TO ENHANCE FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

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ABSTRACT

Floods are among the most common and destructive natural disasters worldwide, posing a substantial threat to the built environment and its socioeconomic stability. As climate change contributes to flood hazards, improving disaster resilience through technical means has become increasingly important. This paper aims to investigate the technological interventions that improve flood resilience in the built environment. Using a comprehensive literature review, the study investigates cutting-edge technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), the Internet of Things (IoT), Smart Sensors, Artificial Intelligence (AI), and Digital Twin (DT) highlighting their contribution to flood resilience in the built environment by improving risk assessment, enhancing early warning systems, facilitating real time monitoring, and supporting resilient planning and design strategies that enhance flood resilience in the built environment. To create a more resilient built environment, the paper concludes with recommendations for combining technology adoption with practice and policy.

Keywords: *Built Environment; Disaster; Flood; Resilience; Technologies.*

1. INTRODUCTION

Disasters significantly affect the built environment (BE) and the failure of the built environment can have substantial effects on economic and social activities. Thus, as we move toward safer cities, it is critical to design the built environment to withstand natural disasters (Malalgoda & Amaratunga, 2015). The rising intensity and frequency of natural disasters pose a growing threat to the built environment, making the built environment vulnerable to natural disasters (Li et al., 2023; Rus et al., 2018; Zięba et al., 2020). Floods are among the most frequent natural disasters, and they create one of the most severe impacts worldwide (Dutta et al., 2023; Islam et al., 2016). Floods drastically disrupt the functioning of built assets, and the impact caused by floods on property devastation, disruptions to water, power, and utility supplies, and a halt to routine community operations hinder sustainable development targets for assets (Rathnasiri et al., 2023).

According to the Academy of Disaster Reduction and Emergency Management et al. (2024), flooding has been the most common disaster in the last 30 years, accounting for 46.63% of the total frequency of all the disasters, where a population of 3239.28 million

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was affected causing 7763 deaths along with 10.05% of the total direct economic loss. The resilience of the BE and its community relies on activities taken to prepare for disasters (Mannucci et al., 2022). In recent years, the notion of resilience has drawn significant interest from the scientific community, possessing considerable potential to manage and synthesize general perspectives by integrating many components to assess issues comprehensively (Tayyab et al., 2021). Technology is one such component that improves the ability to analyze natural disaster risks and build disaster relief strategies and risk management policies (Munawar et al., 2022). Flood resilience technologies possess the capacity to reduce damage related to and caused by flooding (Ebekozien et al., 2024; White et al., 2018).

The aim of this paper is to investigate the technological interventions to improve flood resilience in the built environment. In achieving this aim, a comprehensive literature review was conducted focusing on the key areas of study such as flood, disaster, resilience, technologies and the built environment. Integration of state-of-the-art technological developments, examining current practices, identifying the barriers to adoption of technologies, and proposing strategies to address such barriers were the main objectives of the literature review. The paper derived a conceptual framework incorporating the key technologies that can be used to enhance flood resilience in the context of built environment. The scope is limited to flood resilience and does not extend to other types of disasters or to non-technological approaches. As such, the next section reviews the flood resilience in the built environments, followed by the technological intervention to achieve flood resilience in the built environment.

2. FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

2.1 IMPACT OF FLOOD ON THE BUILT ENVIRONMENT

Floods are one of the most devastating natural disasters, causing substantial loss of life, assets, and fortune (Dutta et al., 2023). The built environment consists of man-made building and infrastructure stocks that represent physical, natural, economic, social, and cultural capital (Hassler & Kohler, 2014). The built environment plays a vital role in societies as it serves to safeguard people and infrastructure from natural disasters (Wei et al., 2021). The built environment is significantly affected by flood disaster (Li et al., 2024). The occurrence of floods causes significant losses to ecology, flora and fauna, assets, and human lives. Economic repercussions include household damage, industry loss, and crop devastation. At the public level, economic consequences include the breakdown of power plants, water and sewerage systems, and damage to roads and bridges (Dube et al., 2018; Rathnasiri et al., 2023; Yereseme et al., 2022). Flooding can significantly damage the functionality, safety, and sustainability of the built environment, especially where urban development gets in with flood-prone areas (Alabbad & Demir, 2024). As such, floods are having a significant influence on the built environment because they compromise structural integrity and interrupt essential services, reflecting the vulnerability of the built environment.

2.2 FLOOD RESILIENCE

The term "resilience" refers to a system, community, or society's ability to tolerate, absorb, accommodate, adapt to, transform, and recover from the consequences of a danger in a timely and effective manner (Sarker et al., 2020). Resilient methods foster quicker

recovery for individuals, communities, and buildings (White et al., 2018). Resilient construction involves planning and constructing buildings and infrastructure that can quickly recover from natural disasters, climate change, and other risks (Chmutina & Rose, 2018). Flood resilience measures may allow water intrusion but aim to reduce damage and improve recovery (White et al., 2018). In the flood domain, resilience is constantly characterized by the interplay of people (e.g., financial level, health status, past experience, and the physical environment) (Zevenbergen et al., 2020).

Reducing the vulnerability of the system or community while increasing its capacity would help to achieve resilience (Lanlan et al., 2024). The United Nations Office for Disaster Risk Reduction (UNDRR) has defined vulnerability as "the conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards". The degree of vulnerability is determined by the design, predisposition, fragilities, inborn capacity, or weakness of the exposed elements, whereas the capacity is the integration of all the assets, attributes, and capacities that a community, organization, or society has to manage and lower the risk of disaster (Chaudhary & Piracha, 2021). According to Lanlan et al. (2024), vulnerability often decreases with increased resilience, and identifying the weakest points in social-ecological systems is the focus of vulnerability.

Flood risks for vulnerable urban areas are being further increased by inadequate drainage systems and heavy runoff from impermeable surfaces in developing country urban settlements (Rana et al., 2021). Strengthening flood resilience in the built environment needs proactive planning and the combination of adaptive measures during planning and construction stages (Mannucci et al., 2022). Investing in physical infrastructure is critical for enhancing flood resilience technology (Ebekozien et al., 2024). Reducing vulnerability and increasing the capacity would therefore increase resilience, and vice versa (Graveline & Germain, 2022).

2.3 ROLE OF TECHNOLOGY IN ENHANCING FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

Technology plays a vital role in enhancing disaster resilience and reducing vulnerability (Akinosho et al., 2020). Creating resilient technologies is essential for reducing threats to the built environment. However, a common emphasis is on designing these technologies to be responsive to the socio-economic conditions of the environment in which they will be applied (Bosher & Dainty, 2011). While other industries use technology to stay ahead, the construction industry's productivity is often unstable or declining due to underinvestment in technology, and the use of technology is showing potential to assist the pre- and post-event stages of disaster management (Akinosho et al., 2020; Galera-Zarco & Floros, 2024). With the global impacts of climate change intensifying, it is essential for stakeholders to adopt innovative approaches to strengthen climate resilience within the built environment (Ebirim et al., 2024).

Innovative technologies can significantly reduce risks both before and after disasters and they are expected to play an important role when it comes to the enhancement of resilience in the built environment (Galera-Zarco et al., 2024). Flood-resilient technologies have the capacity to reduce damage caused by flooding (White et al., 2018). Digital innovations related to Industry 4.0 have emerged as essential instruments for this purpose. As a result, technologies and digital transformation have become crucial options

for disaster risk management (Ariyachandra & Wedawatta, 2023). In this regard the next section further reviews the technological interventions in flood disaster resilience in the built environment.

3. TECHNOLOGICAL INTERVENTIONS IN FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

The use of cutting-edge technologies will result in notable successes in terms of risk reduction both before and after the disaster (Arabameri et al., 2022). Improving assessment methodologies and understanding of flood risk vulnerability can help decision-makers reduce damage and fatalities (Nasiri et al., 2016). Technologies such as Geo-visualisation, Geographical Information Systems (GIS), Remote Sensing (RS), Internet of Things (IoT) and smart sensors, Artificial Intelligence (AI) and Digital Twins (DT) have significant potential in reducing the vulnerability to flood disasters and intensifying resilience (Ge & Qin, 2025; Hussain et al., 2021; Liu et al., 2025; Munawar et al., 2022; Rehman et al., 2019; Sengupta, 2025; Samarakkody et al., 2023).

Okem et al. (2024) highlighted that the combination of early warning systems and smart technologies has emerged as a factor that is revolutionizing disaster resilience. By enabling real-time monitoring, precise flood prediction, and prompt notifications, these innovations enhance disaster preparedness and lessen the negative impact of floods on infrastructure and communities (Sengupta, 2025). Buildings can be outfitted with IoT sensors that monitor flood levels in real time. These devices transmit alarms to building occupants, prompting them to take action (Jan et al., 2022; Kamal et al., 2025). As a result, incorporating these technologies into the built environment enhances protection and safety while also encouraging adaptive solutions that improve flood resilience.

3.1 KEY TECHNOLOGIES USED FOR FLOOD RESILIENCE

This section elaborates on the key technologies that can be used to improve flood resilience by analyzing the features of each technology.

3.1.1 Internet of Things (IoT) and Smart Sensors

The Internet of Things (IoT) has become an essential tool for disaster management, helping to create resilient and sustainable cities and promoting the collection and analysis of real-time data, offering prospects for urban catastrophe management and enabling inter-device communication through the internet (Zeng et al., 2023). The incorporation of sensors and monitoring systems into critical infrastructure is the foundation of smart technologies in disaster resilience. Real-time data on the performance of buildings, bridges, dams, and other infrastructure elements is obtained through the deployment of sensors, which allows engineers to identify early indications of distress or vulnerabilities (Okem et al., 2024). Sensor systems can continuously observe and analyze certain occurrences, including their geospatial distribution and temporal evolution. The combination of sensor data, GIS, and the Internet has become the primary mode of operation for disaster response systems. It is commonly used for data processing, spatial analysis, and visual representation of disasters. Real-time observations from sensor systems should be continuously updated and interpreted accurately for their intended purposes (Hong & Shi, 2023).

3.1.2 Geographical Information Systems (GIS) and Remote Sensing (RS)

GIS and RS are used for assessing and mapping flood vulnerability (Hussain et al., 2021). According to Leeonis et al. (2025), GIS is a useful tool for assessing flood impacts after they have occurred, assisting with recovery planning, and updating risk assessments going forward. Remote sensing technologies have become essential for flood management, offering prompt and comprehensive information vital for disaster response and damage evaluation (Sengupta, 2025).

Post-flood damage assessments use GIS technology to compare pre- and post-disaster images, identifying affected areas and calculating recovery costs. GIS maps are commonly used in community awareness campaigns to educate residents about flood preparedness and evacuation routes (Leeonis et al., 2025). Sengupta (2025) further stated that GIS enables complete flood risk assessments by combining varied information, including topography, bathymetry, and flood defense infrastructure. Nakhapakorn et al. (2022) explored the application of geospatial technologies such as GIS to assess the physical vulnerability of buildings to the risk of urban floods, and the study was focused on Warin Chamrap municipality in Thailand, which is a region vulnerable to frequent flooding. This demonstrates that the availability and utilization of technology has the potential to reduce the physical vulnerability of building structures to floods.

3.1.3 Artificial Intelligence (AI)

Artificial intelligence techniques utilize algorithms for the examination of extensive datasets, encompassing machine learning techniques (algorithms capable of learning from data without dependence on rule-based programming) and deep learning techniques (a subset of machine learning consisting of algorithms that enable software to execute tasks, such as image recognition, by exposing multilayered neural networks to substantial volumes of data) and these technologies are capable of providing four main analytics types namely, (1) descriptive analysis; analysis of past and current situations, (2) diagnostic analysis; casual factor analysis for a given event, (3) predictive analysis; analysis of the potential future scenarios (4) prescriptive analysis; analysis of the actions which has to be taken (Asian Development Bank, 2020). With respect to design specifications, understanding the nature of potential floods permits engineers to include appropriate flood resistant features into the design of the buildings, such as reinforced materials and elevated structures. This reflects that the application of AI in flood resilience for planning and construction is a game changer, and decision-makers will be able to design, construct, and maintain infrastructure that is well prepared for severe flood events by leveraging AI-driven data analysis, predictive modelling, and real-time monitoring, which would significantly reduce the vulnerabilities in the built environment (Saravi et al., 2019).

The study carried out by Saravi et al. (2019), explores innovative applications of AI, specifically Machine Learning (ML) to strengthen flood resilience and preparedness. Moreover, the study elaborated on how hydrological patterns, historical flood data, and climate variables can be analyzed by the application of AI driven models to notify on the development of flood-resilient infrastructure, and regarding risk assessment, precise flood classification informs planners regarding potential flood risks in specific areas, accompanying decisions on site selection and zoning to keep away from high-risk zones. Furthermore, Liu et al., (2025) have highlighted that machine learning models can be applied in flood vulnerability assessment.

3.1.4 Digital Twin (DT)

A digital twin is a digital replica of a real-world physical asset that includes a time dimension for all of its features. This model adapts to changes over time and represents various virtual instances at a particular time point. Digital twins evolve with the physical item throughout its life cycle, allowing for real-time bidirectional mappings between physical and virtual assets (Ariyachandra & Wedawatta, 2023). To improve urban flood resilience, digital twin-based resilience management systems have become essential because they allow lifecycle-oriented emergency management to be implemented continuously rather than in discrete phases (Ge & Qin, 2025). Wang et al. (2024) elaborated on the application of digital twin technology during design and construction phases to prevent flooding and to enhance urban resilience.

Amidst severe flooding caused by Hurricanes Irene (2011) and Ida (2021), the town of Manville, New Jersey, encountered major challenges in recovering from flood damage. To support successful and resilient recovery, researchers developed an Urban Digital Twin, a virtual, data-rich replica of the built environment that can be used to guide rebuilding decisions, prioritize actions, and increase community resilience to future floods (Josephs et al., 2024). During the design phase, DT assists in planning of flood mitigation infrastructure such as flood gates, levees and drainage networks, whereas during the construction phase DT could be used for real-time monitoring of the construction activities with regard to material selection for flood resilience. Digital twins not only help to improve the speed and quality of management decisions by visualizing complex data in a simple and accessible way during a disaster, but they can also simulate the evolution of a disaster while taking into account the unique characteristics and conditions of a city, thus acting as a critical element of an early warning system (Josipovic & Viergutz, 2023).

3.1.5 Summary

Table 1 highlights the technological interventions in improving flood resilience, and the corresponding disaster management stage these are applied.

Table 1:Technological interventions for flood resilience

Technology	Interventions	Disaster Stage
Internet of Things & Smart Sensors	Real time monitoring of flood levels, Alerts to building occupants, Monitoring of infrastructure performance	Pre-disaster and post-disaster
Geographical Information Systems and Remote Sensing	Public awareness, Damage assessment, Evacuation route planning	Pre-disaster and post-disaster
Artificial Intelligence	Vulnerability assessment, Predictive flood modelling, Risk informed design and planning	Pre-disaster
Digital Twin	Real time monitoring, Flood mitigating infrastructure design, Simulation of disaster evolution	Pre-disaster and post-disaster

3.2 BARRIERS AND STRATEGIES IN IMPLEMENTING TECHNOLOGIES TO ENHANCE FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

The above sections discussed the key technologies that can help to improve the flood resilience in the built environment while reducing the vulnerability of the built environment against floods. However, there are practical barriers to the implantations of such technologies. Lack of awareness, lack of finances, resistance to adopt resilient measures, lack of reliable information, and absence of clear policies and regulatory frameworks to integrate flood-resilient technologies were identified as the key barriers hindering the implementation of flood-resilient technologies (White et al., 2018; Müller et al., 2024; Asian Development Bank, 2020; McBean & Rodgers, 2010). Collaborative approaches, enhancing awareness, developing the strategies and policies, and encouraging community engagement are some of the measures that can be taken to address these challenges (White et al., 2018; Müller et al., 2024; Nakhapakorn et al., 2022; Nasiri et al., 2016; Okem et al., 2024). Further research is needed to clearly identify the right measures to minimize the implementation of technologies to achieve flood disaster resilience in the built environments (Nakhapakorn et al., 2022).

As per these barriers, it is clear that technology alone is insufficient in order to achieve flood resilience in the built environment. Stakeholder cooperation, institutional preparedness, and strategic planning are also equally important. Hence, construction professionals, urban planners, and developers need to work together in order to bridge the gap between technological interventions and real-world implementation. Construction and urban planning stakeholders should include flood-resilient technologies in design and planning rules, backed up by financial incentives, trustworthy data, and clear regulatory frameworks. Strengthening stakeholder collaboration, creating awareness, and engaging communities are all necessary to overcome opposition and ensure effective implementation.

3.3 A CONCEPTUAL FRAMEWORK TO INTEGRATE TECHNOLOGICAL INTERVENTIONS TO IMPROVE FLOOD RESILIENCE IN THE BUILT ENVIRONMENT

The literature explored the key technologies that can be used to improve the flood resilience in the built environment. It also briefly revealed the barriers in implementing such technologies along with a few high-level strategies. Based on this review, a conceptual framework has been developed, as shown in Figure 1, which will act as a guide to inform this research to further explore the key features of these technologies in reducing the level of vulnerability and increasing the level of capacity of the built environment against flood disaster, while also trying to propose practical strategies to overcome the barriers in implementing such technologies in the context. It maps the relationship between flood resilience in the built environment, vulnerability, and capacity, and identifies essential technological interventions.

In this regard, the framework intends to improve the resilience of built environment, which is the context, against the flood disaster, which is the main disturbance, as stipulated in the focus of this study. As per the theoretical understanding, resilience can be increased by reducing vulnerability and increasing the capacity of the built environment. In doing so, the identified essential technological interventions such as IoT, GIS, AI, and DT play a key role in reducing vulnerability while increasing the capacity

of the built environment. However, the barriers for implementation of these technologies mainly in terms of lack of knowledge and understanding, lack of funding and lack of policies or regulatory frameworks are also incorporated in the framework as it helps to make informed decisions in effectively adopting such technologies. Higher level strategies are proposed which will need to be further translated into actions to effectively implement the technological intervention to improve flood resilience in the built environment.

In this context, this conceptual framework provides a basis for expanding this study in terms of exploring the key features of the identified technological interventions to clearly show how such features and technologies would help to enhance flood resilience in the built environment, while also proposing actionable strategies to address the barriers to effectively implement the technological interventions in the context of the built environment.

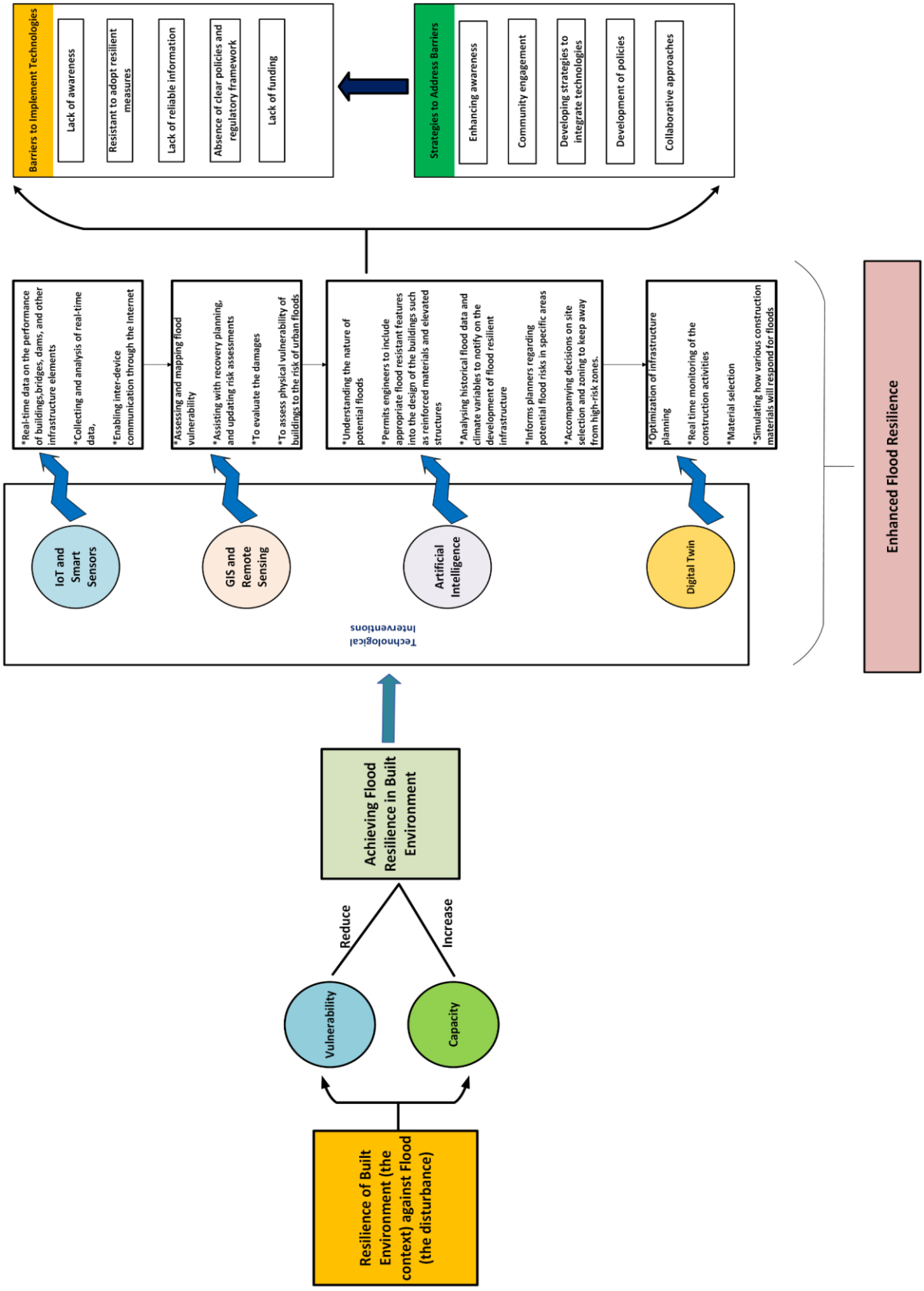


Figure 1: Conceptual framework to increase flood resilience in the built environment

4. CONCLUSIONS

The rising frequency and intensity of floods require a dramatic change in disaster-resilient strategies. This study reviews the key technologies, such as IoT and Smart Sensors, GIS and Remote Sensing, Artificial Intelligence and Digital Twin to enhance flood disaster resilience in the built environment. These technological interventions provide predictive analysis, real-time monitoring, climate-adaptive infrastructure, and advanced simulation modeling in order to enhance flood disaster resilience in the built environment. Integrating these technologies has the potential to provide proactive, more efficient, well as sustainable practices for flood disaster resilience in the built environment. Importantly, to maximize the effectiveness of these technologies, it is recommended that the policymakers integrate them into disaster management frameworks, urban planning regulations, and infrastructure development guidelines. Practical adoption can also be fostered by focused professional training and incentives that encourage technological integration in the built environment. The paper also highlights the barriers in implementing such technologies along with high-level strategies to address such barriers. This paper is based on an ongoing research degree that is at its initial stage. The conceptual framework developed in this paper will be used to further investigate the technologies, barriers, and strategies in detail to improve the flood resilience of the built environment.

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SERIOUS GAMES FOR DISASTER RISK REDUCTION: ENHANCING COMMUNITY PREPAREDNESS FOR SUSTAINABLE FUTURES

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ABSTRACT

Disaster-resilient communities are essential to ensure sustainable futures, particularly in regions vulnerable to disasters. Traditional disaster risk reduction training methods often struggle to engage communities effectively, limiting their ability to apply knowledge in real-world scenarios. This study explores the potential of Serious Games as an innovative educational tool for enhancing disaster risk reduction, particularly in developing countries where such approaches remain underutilised. Through game-based workshops, participants engaged in immersive, scenario-driven learning experiences that integrated global and local disaster risk reduction knowledge, expert insights, and peer learning. Nine games were played during the workshops with community members and university students in the Eastern Province in Sri Lanka. A pre- and post-evaluation questionnaire, focus groups, and observations were used for data collection, analysed through statistical comparison and content analysis. Findings indicate that Serious Games not only improve risk awareness and strategic thinking but also improve collaborative learning and social responsibility. The study also highlights the ability of Serious Games to convey sensitive information in an engaging manner, making disaster education more accessible and impactful. Additionally, it highlights the importance of gender-sensitive approaches, emphasising the role of women in strengthening community-driven disaster risk reduction strategies. By offering an interactive learning approach, Serious Games contribute to effective disaster risk reduction and ultimately create sustainable futures.

Keywords: *Awareness; Collaborative Decision Making; Interactive Learning; Disaster risk reduction; Serious Games.*

1. INTRODUCTION

In recent years, disastrous incidents have been increasing drastically, resulting in extensive damage, disruption, and possible fatalities, leaving people unable to function (Inoguchi et al., 2021; Wang & Taylor, 2014). Disasters can impact lives in multiple ways, including fatalities, injuries, diseases, and adverse effects on physical, mental, and social well-being (Perry & Lindell, 2003). Additionally, disasters create property damage, asset destruction, service disruptions, socio-cultural and economic instability, and

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environmental degradation (Ali & Mannakkara, 2024). Given these far-reaching consequences, effective disaster preparedness strategies are essential to mitigate the risks associated with future disasters (Wells et al., 2013), as they can significantly reduce the impact of disasters by ensuring that communities, emergency responders, and relevant institutions are ready to respond effectively (Herstein et al., 2021).

It is widely recognised that regular training sessions and simulation exercises are crucial in enhancing disaster preparedness among professional responders and the public. Through continuous practice, individuals can develop critical skills, improve decision-making under pressure, and gain familiarity with emergency protocols (Alexander, 2000). Such training also ensures that communities are better prepared to protect themselves and minimise risks when faced with real-life disaster scenarios (Perry & Lindell, 2003).

Disaster management practitioners have increasingly recognised the potential of 'Serious Games' as an innovative and effective tool for disaster preparedness training (Kankanamge et al., 2020; Solinska-Nowak et al., 2018). Serious Games are designed not only for entertainment but also to facilitate learning by engaging users in immersive and interactive experiences (Gee, 2003; Wouters et al., 2013). Therefore, Marsh (2011) asserted that Serious Games have the fundamental principle of 'playing for a purpose' beyond entertainment. These digital or physical simulation-based games provide an opportunity for players to acquire, test, and reinforce critical disaster-related knowledge in a risk-free environment, enhancing their ability to respond effectively in real-life emergency situations (Chittaro & Ranon, 2009). Serious Games can influence the player (disaster responder) to achieve a common goal (rescue and relief of the affected community) while facing the disruptions of the disaster. Therefore, Serious Games can improve decision-making, problem-solving skills, and situational awareness, making them a valuable supplement to traditional disaster preparedness programs (Fleming et al., 2020).

While Serious Games have proven to be an effective tool in enhancing disaster preparedness and risk management in developed nations, their adoption in developing countries faces several barriers that hinder their widespread success due to socio-economic, infrastructural, and cultural challenges (Solinska-Nowak et al., 2018). This is due to the unfamiliarity with the concept of using 'games for learning', particularly for serious topics like disaster preparedness (Mahamood et al., 2024;). Further, in many developing countries, disaster management is traditionally viewed as a highly formalised and hierarchical process led by government agencies or international bodies. Serious Games, which typically require a more interactive, collaborative, and individualised approach, may not be aligned with such formalised approaches (Popescu et al., 2011). This gap in understanding can reduce the acceptance and uptake of Serious Games among both policymakers and the target populations who might benefit from them (Fleming et al., 2020).

Accordingly, this study examines the role of Serious Games in disaster risk reduction in a South Asian developing country, Sri Lanka. Among the developing countries, Sri Lanka has gained significant attention due to its vulnerability to various disasters, including high winds, floods, landslides, tsunamis, and droughts, which have caused widespread devastation throughout its history (Ali & Mannakkara, 2024; Weerasekara et al., 2021). These disasters pose severe threats to the population, infrastructure, and economy, highlighting the critical need for effective disaster risk management and preparedness to create a sustainable future in the country. The study seeks to assess the effectiveness of

Serious Games in improving disaster education, raising awareness, and strengthening crisis response capabilities in multi-cultural settings. Further, drawing insights from the global experiences on how Serious Games can be tailored and integrated into existing disaster risk management practices will also be investigated.

2. CHARACTERISTICS OF SERIOUS GAMES

The modern history of Serious Games initiated in the late 1950s, which emerged as an effect of 'war gaming' and developed into an active contribution of learning to improve active participation in learning (Kolb, 1984; Wilkinson, 2016). Salen & Zimmerman (2004) claimed that Serious Games are different from general games designed previously focused on enjoyment or competition, whereas Serious Games aim to offer their users the opportunity to learn actively. The idea of 'purposing play' has been resonating with the use of Serious Games (Ardley, 1967). Accordingly, Serious Games have been used to cultivate cultural and social values and to communicate desired behaviours.

Serious Games provide the opportunity for the players to practice the skills and lessons learnt during the game to improve their performance within the game (Vlachopoulos & Makri, 2017). This training would be helpful to enhance the social dimensions of players while planning for the next disaster (Solinska-Nowak et al., 2018). Further, a positive emotional response can be established in players' minds through Serious Games, which provide them with a challenging, memorable, and fun learning experience (Mahamood et al, 2024). In this way, people can enhance the process of remembering information regarding each disaster, and they may get excited about the new social situation due to the disaster without having negative emotions. Moreover, serious games emphasise creating a safe learning environment where individuals can engage in 'experiential learning, i.e., learning through mistakes without experiencing the devastating consequences that would occur in real-life scenarios (Chittaro & Ranon, 2009). According to Babu et al. (2016), Serious Games provide the players with situational awareness, making them aware of the disaster's type, scope, impact, and complexity. Collaborative learning through collective playing is another feature of Serious Games, which offers more space for building relationships, practising negotiations and conflict resolution, and exchanging information or sharing experiences that are important in community handling during challenging scenarios (Wilkinson, 2016).

Further, Serious Games often include adaptive learning pathways, where the difficulty or content adjusts in response to players' choices and performance, supporting personalised learning experiences that match diverse needs and skill levels (Gee, 2003). They also facilitate reflective learning by prompting players to evaluate their decisions, discuss alternative strategies, and consider the ethical or social implications of their actions, and deepen critical thinking and preparedness (Perera et al., 2015). Narrative and storytelling elements embedded in Serious Games create engaging, context-rich scenarios that help players to retain the knowledge they gained from the game (Popescu et al., 2011). Moreover, Serious Games support assessment and feedback mechanisms, enabling trainers and learners to monitor progress, identify gaps, and tailor future learning efforts (Wouters et al., 2013). Serious Games can be deployed widely, reaching diverse and remote populations with limited resources. Further, Serious Games can promote intercultural understanding and empathy by exposing players to different perspectives and community needs (Salen & Zimmerman, 2004). Therefore, it can be argued that Serious Games provide a powerful and innovative approach to learning and problem-solving, bridging the gap between knowledge and practice in an engaging, impactful way.

3. RESEARCH METHODOLOGY

The study's main aim was to investigate the role of Serious Games in enhancing disaster risk reduction in developing countries by assessing their effectiveness in improving disaster education, raising awareness, and strengthening crisis response capabilities in multicultural settings. Accordingly, this study adopted a mixed-methods research approach, employing pre and post-evaluation questionnaires, focus groups, and observations as data collection techniques The primary reason for selecting a mixed-methods research approach was to gain an in-depth understanding of various communities' and stakeholders' perceptions, experiences, and attitudes towards using game-based learning for disaster preparedness, while quantitatively assessing the knowledge gain after playing the game. In developing countries like Sri Lanka, integrating Serious Games into disaster risk reduction is a relatively novel concept, and there is a need to understand how local communities, policymakers, and disaster management professionals perceive and adapt to the use of games for disaster awareness and preparedness. Within this context, the mixed-methods research approach enabled the exploration of key issues such as cultural readiness, technological accessibility, and educational preferences (Creswell, 2013; Denzin & Lincoln, 2011; Saunders, 2019), which may impact the effectiveness and acceptance of Serious Games as a tool for disaster risk reduction. The research design of this study consisted of 4 phases, as described below.

3.1 PHASE 1: DESK STUDY

A desk study was carried out to review the Serious Games currently available for disaster risk reduction. The primary purpose of the desk study was to identify the characteristics of Serious Games for disaster risk reduction in general and to investigate the criteria that must be considered in developing an interactive board game within the context of Sri Lanka, concerning cultural, social, economic, and technological dimensions. Accordingly, Serious Games such as Disaster Mitigation Action Card Game (Kaneko et al., 2018), RISKLand board game (UNICEF/Red Cross), Games4Sustainability, HAZAGORA (Michellier et al., 2019; Mossoux et al., 2016) and STOP Disasters online game (UNISDR) were reviewed. The review criteria used during the desk study included the disasters represented in the game and their relevance to Sri Lanka, simplicity and ease of understanding of the game for the public, relevance of the game characteristics/characters to the Sri Lankan community and availability of facilities/resources to run the game. Following the above review, the HAZAGORA game (Michellier et al., 2019; Mossoux et al., 2016) was selected as the basis for developing a suitable board game for the Sri Lankan context.

3.2 PHASE 2: CONTEXTUALIZING THE GAME TO THE SRI LANKAN CONTEXT

To adapt the Hazagora board game for Sri Lanka, modifications were made to reflect local contexts and increase relevance. To support this contextualisation, a documentary review identified relevant disasters, and two expert consultations with local authorities helped confirm the disasters to include and the location for the game's test run. Accordingly, floods, tsunamis and droughts were chosen as the disasters to include in the game by considering their severity (ACAPS, 2024). The Northeast region of Sri Lanka was chosen as the location to test-run the game, as this region was severely hit by the Tsunami in 2004, as well as the presence of floods and droughts.

Next, the original Hazagora materials were reviewed and customised. Some of the character roles were adapted to represent typical livelihoods found in Sri Lankan villages, such as fishermen, carpenters, and community leaders. In consultation with local experts and drawing on resources published by the Disaster Management Center of Sri Lanka, locally relevant disaster risk reduction strategies and guidelines were integrated into the gameplay. To ensure accessibility, all game materials were translated into Sinhala and Tamil. The format and layout of the adapted game are given below (refer Figure 1):

- The game can be played for a set duration or a fixed number of rounds, with 5–8 players in one group.
- At the start, players are assigned roles representing rural community members (e.g., fisherman, carpenter, village leader) along with resource and protection cards
- In the first round, players collect additional resources by rolling a dice; in subsequent rounds, they develop assets, build infrastructure and/or take measures to protect families from hazards
- The 'game master' introduces a disaster scenario with specific magnitude and impact that affects the players according to their preparedness measures (e.g., safer construction, insurance).
- After the disaster event, the village leader convenes a meeting where a 'notice' is read, summarising key disaster risk reduction lessons and future preparedness strategies.



Figure 1: Layout of the game

3.3 PHASE 3: PILOTING THE GAME

Two (02) pilot games were conducted with people from different ethnic groups and subject disciplines, such as gaming, disaster, and built environment to ensure the context and game rules are applicable to Sri Lanka. Following the pilot games, some of the game rules were changed to simplify and reduce the overall time of the game.

3.4 PHASE 4: CARRYING OUT WORKSHOPS IN SRI LANKA

Nine (9) games were played in the North-Eastern province of Sri Lanka, as shown in Table 1 below. Following the game, participants' opinions about knowledge enhancement were explored through focus group discussions. These discussions were analysed using content analysis to investigate the knowledge gains and their views regarding the game. Both deductive and inductive coding were applied to identify the key themes from the focus group discussions (refer to Figure 2 for the cognitive map prepared

based on these themes). Additionally, during the gameplay, the research team recorded evidence of knowledge enhancement (e.g. players choosing to build homes in safer, less disaster-prone areas) using observation forms. Pre- and post-evaluation questionnaires with structured questions were also administered to quantitatively assess changes in participants' disaster preparedness knowledge.

Table 1: Profiles of the games played

No	Location	Participants
Game 1, 2 and 3	Trincomalee	Community Leaders and members
Game 4 and 5	Trincomalee	University students
Game 6 and 7	Batticaloa	University students
Game 8 and 9	Batticaloa	Community Leaders and members

4. DATA ANALYSIS AND DISCUSSION

The following section presents observations made and feedback received from different members who participated in the game.

4.1 IMPROVEMENT OF KNOWLEDGE AND UNDERSTANDING

Participants showed a clear improvement in their knowledge and understanding of disaster mitigation as they progressed through the game, particularly evident in their active sharing of personal disaster experiences. For example, one participant noted, "*As I am originally from the middle of the country, I have never experienced floods, but after listening to my fellow community members today, I learned many aspects regarding floods and the methods we need to follow*." This aligns with Ronan et al (2001), who highlight the value of community-based learning in disaster education.

The game structure simulated real-life disaster scenarios and encouraged collaborative decision-making. After each disaster event, a community meeting was held where a Village Leader read a 'notice' outlining best practices before, during, and after disasters. Grounded in global guidelines but tailored to the Sri Lankan context, this approach mirrors effective community-driven disaster preparedness (Gautam, 2010). Participants acknowledged the practical knowledge gained, such as safeguarding essential documents and medicine for quick evacuation, as reflected in participant feedback. Serious games reinforced critical disaster mitigation practices often overlooked in real-world planning (Lindell & Perry, 2004). Overall, participant feedback indicated successful knowledge transfer, consistent with literature emphasising serious games' role in fostering practical skills (such as identifying alternative evacuation routes).

Experiential learning emerged as a key outcome, with participants learning through gameplay and mistakes, for example, relocating homes to safer areas after experiencing simulated disasters. This aligns with Kolb's (1984) experiential learning theory and Kiili's (2005) emphasis on learning through safe experimentation and immediate feedback. Following Gee's (2003) idea of 'pleasantly frustrating' experiences and Vygotsky's (1978) theory of learning through challenge, participants refined their strategies, considering measures like purchasing insurance and building hospitals in safer locations.

4.2 GOAL ORIENTED

Unlike casual games, which aim primarily to entertain, Serious Games are purposefully designed to achieve specific learning outcomes or behavioural changes (Chittaro & Ranon, 2009). The game in this study was structured to promote engagement in disaster risk reduction activities by mimicking real-life scenarios. For example, players navigated emergency response situations by selecting evacuation routes and prioritised preparedness actions such as following building codes and avoiding hazard-prone areas. As they progressed, players met performance targets such as implementing effective mitigation measures, optimising resource management, and demonstrating collaborative decision-making during crises.

4.3 LEARNING IN AN ENJOYABLE WAY

Even though the term Serious Games suggests a serious nature, these games incorporate an element of fun while facilitating learning (Michael & Chen, 2006). This enjoyable approach to learning was evident during the project. For instance, one university student remarked, *"We thought we would come for a three-hour session on disaster risk management, but this turned out to be completely different—we learned about disasters in a much more enjoyable way."* Similarly, a disaster management field worker observed that in traditional disaster risk reduction events, facilitators typically engage in continuous lecturing. However, within the game environment, facilitators introduce the game and its rules, after which the players take ownership of the experience, making learning more interactive and engaging.

4.4 COMMUNICATING SENSITIVE MESSAGES WHILE BEING IN A SAFER ENVIRONMENT

Simulating disasters can be sensitive due to participants' past experiences (Crookall, 2010). Participants may have had distressing experiences related to past disasters, which could affect their emotional well-being. However, incorporating disaster simulations within a board game creates a safe and controlled environment for learning. This aligns with the findings of Gee (2003), who argues that games provide 'psychological safety', allowing players to experiment, make mistakes, and reflect without real-world consequences.

The role of serious games in fostering emotional resilience and preparedness has been widely discussed in disaster education literature. For example, Wouters et al. (2013) found that Serious Games enhance both cognitive and emotional engagement, helping learners process complex or distressing topics in a more manageable way. Similarly, game-based learning can support emotional regulation by enabling players to interact with risk scenarios at a comfortable pace, reducing anxiety while still reinforcing critical decision-making skills (Tsai et al., 2020). This was evident in participant feedback from this study. One participant remarked, *"I was able to practice real-world disaster scenarios while being in a safe, risk-free environment. This game enabled me to better prepare for challenges I may encounter in my personal life."* This supports Backlund & Hendrix's (2013) view that serious games offer an immersive yet emotionally safe environment, helping players build confidence in real-world scenarios. One participant, previously reluctant to discuss their tsunami trauma, felt secure enough during the game to share their experiences openly.

4.5 KNOWLEDGE TRANSFERRING

One of the primary objectives of this game was to enhance public awareness of disaster risk reduction. To achieve this, a diverse group of participants was selected, including community leaders, disaster management field workers, university students, community members from various livelihoods and ethnic backgrounds, and schoolteachers. This diverse representation aimed to facilitate the continuous transfer of disaster risk reduction knowledge across different sectors of society. For instance, university students could share their learnings with their families, disaster management field workers could integrate insights into their ongoing work, and schoolteachers could educate their students. A schoolteacher commented, *"I am definitely going to use this in my teaching to educate school children about disaster risk reduction."* This reflects the concept of social learning, as Tsai et al. (2020) described, where individuals acquire and spread knowledge through observation, interaction, and shared experiences. Further, the disaster management field offices and community leaders suggested developing similar Serious Games for other critical issues in Sri Lanka, such as Dengue control, to improve the awareness of the community regarding such diseases.

4.6 GENDER PERSPECTIVES

During the game, an interesting trend emerged among the women participants: stockpiling essential supplies using their game cards. They actively stored food, water, and other critical commodities necessary for an effective disaster response. This behaviour aligns with real-world disaster preparedness patterns, where women often take on key roles in household and community resilience-building. Research shows that women, due to their caregiving roles and responsibility for the well-being of families (Enarson, 2000), are more likely to stockpile supplies and adopt proactive risk reduction behaviours (Cvetković et al., 2024), a pattern reflected in the game.

This observation in the game also reflects the concept of *anticipatory adaptation*, where individuals and communities take proactive actions to mitigate disaster impacts (Kelman & Gaillard, 2010). By stockpiling resources, the women participants demonstrated an understanding of disaster cycles and the importance of preparedness, reinforcing findings from previous research that women play a crucial role in ensuring food security and resource management in times of crisis.

4.7 INNOVATIVE IDEAS

As the game progressed, a clear transformation in the participants' decision-making patterns was observed. Initially, players focused on individual survival strategies, making decisions primarily aimed at securing their safety and resources. However, as the game unfolded, players began to adopt a more collective approach, prioritising the entire community's well-being. This shift toward community-oriented thinking was particularly evident in their collaborative efforts to establish shared resources for disaster response. This was evident in their creation of an “insurance pot,” a communal fund to aid vulnerable members after disasters, reflecting real-world resilience strategies that pool resources to reduce individual impacts. Players also discussed long-term preparedness, such as building a hospital on safer land, demonstrating an understanding of disaster risk reduction principles, such as locating critical infrastructure away from high-risk areas and the importance of building community-level resilience.

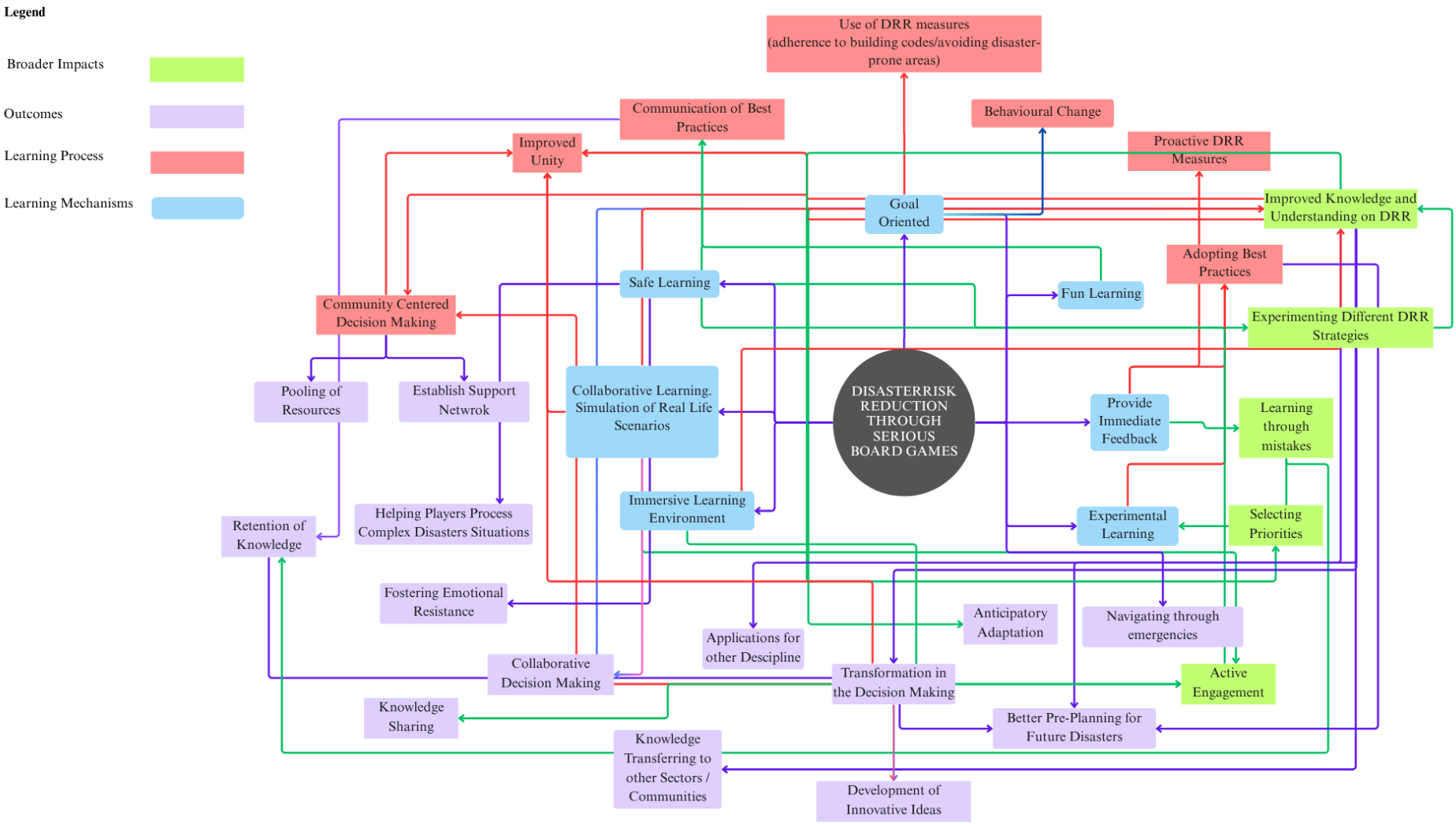


Figure 2: Influence of Serious Games for disaster risk reduction

4.8 VISUALISING SERIOUS GAMES FOR DISASTER RISK REDUCTION

Considering the above discussions, Figure 2 has been added to visualise how Serious Games could influence disaster risk reduction. Figure 2 illustrates how Serious Games can enhance disaster risk reduction by linking learning mechanisms, processes, outcomes, and broader societal impacts. At its core, the model highlights the characteristics of Serious Games such as immersive and experimental learning, goal-oriented nature, fun learning, etc., as key mechanisms that foster engagement, collaboration, and feedback within the simulated disaster scenarios. These learning experiences facilitate safe environments for users to process complex situations, adopt best practices, and develop emotional readiness for real-life disasters.

Through this process, it shows a pathway from individual learning to collective action. Outcomes such as improved decision-making, emotional resilience, and community collaboration are connected to long-term impacts like the development of proactive disaster risk reduction measures, behavioural change, and better pre-disaster planning. The diagram effectively captures the cyclical and interconnected nature of learning in disaster risk reduction, emphasising that serious games not only transfer knowledge but also shape attitudes, foster innovation, and support adaptive capacities in disaster-prone communities.

5. CONCLUSION

This study was carried out to investigate the role of Serious Games in enhancing disaster risk reduction in developing countries by considering Sri Lanka as a case study. The findings reaffirm the established understanding that Serious Games are powerful educational tools, providing experiential learning opportunities, immediate feedback, and a safe environment for trial and error. By immersing participants in realistic disaster scenarios, these tools enhance decision-making, strategic thinking, and behavioural change, key competencies for building sustainable and disaster-resilient communities. Additionally, this study highlights the unique ability of Serious Games to balance emotional sensitivity with experiential learning, peer interaction, and long-term knowledge retention, surpassing traditional disaster risk reduction awareness methods.

One of the study's insights is the significance of integrating gender-sensitive approaches into disaster education and preparedness initiatives. Recognising and strengthening the role of women in disaster response and preparedness can lead to more inclusive and equitable risk reduction strategies, ensuring that sustainability efforts are socially justified and community-driven. Moreover, the observed shift from individualistic to community-oriented decision-making underlines the potential of Serious Games to foster collective action and social responsibility, core principles of sustainable futures. Sustainable resilience is not only about reducing disaster risks but also about strengthening social cohesion, resource-sharing, and proactive community participation, which were evident and strengthened through this study.

This study demonstrates the feasibility of using Serious Games for disaster risk reduction awareness, particularly in developing countries where such approaches are not yet widely recognised. The findings align with global research supporting the use of Serious Games to motivate behavioural change and enhance disaster preparedness, all essential for creating sustainable, resilient, and adaptive communities. One of the study's limitations is its focus on only three prevalent disasters in Sri Lanka, leaving room for future research

to explore the applicability of Serious Games across a broader range of disaster scenarios, healthcare challenges, such as dengue and sustainability challenges.

This study contributes to theory by expanding the conceptual understanding of Serious Games as tools, not only for individual learning but also for cultivating collective, community-based disaster preparedness in developing country contexts. It advances theoretical models of experiential learning in disaster risk reduction by integrating social dimensions such as gender sensitivity and community participation, demonstrating that effective risk reduction education requires addressing social equity and inclusivity. From a practical perspective, the study demonstrates how games can deliver cost-effective, engaging, and inclusive training that enhances decision-making and community preparedness. By highlighting gender-sensitive approaches and collective action, it provides a model for designing disaster risk reduction interventions that are locally relevant, equitable, and sustainable.

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SHAPING REGENERATIVE STORMWATER MANAGEMENT: A CONCEPTUAL FRAMEWORK FOR BLUE-GREEN INFRASTRUCTURE

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ABSTRACT

Urbanisation and infrastructure development have intensified stormwater-related challenges such as increased runoff, flooding, and ecological degradation. Blue-green infrastructure (BGI) has emerged as a sustainable solution for stormwater management by integrating natural and engineered systems to mimic the natural water cycle. Although the environmental and social benefits of BGI are widely acknowledged, its implementation remains limited due to barriers, including a lack of awareness, funding constraints, fragmented responsibilities, and regulatory uncertainties. Existing literature lacks a comprehensive framework specifically addressing the use of BGI in stormwater management. This study aims to fill that gap by developing a conceptual framework to promote BGI adoption for stormwater systems. A systematic literature review was conducted using databases including Scopus, Web of Science, Engineering Village, and Google Scholar. Manual content analysis was used to explore the benefits, barriers, and strategies related to BGI implementation. Findings reveal that community engagement, inter-agency collaboration, knowledge sharing, and policy integration are essential to overcoming adoption barriers. Based on these insights, a conceptual framework was proposed to guide planners, policymakers, and practitioners in promoting BGI within urban water management. This framework supports the strategic integration of BGI to enhance resilience, sustainability, and multifunctionality in stormwater infrastructure.

Keywords: *Barriers; Benefits; Blue-green Infrastructure; Stormwater Management; Strategies.*

1. INTRODUCTION

The construction industry, a key driver of urban development, has significantly contributed to the rapid urbanisation seen across the globe (Scaroni, 2021; Ahmad et al., 2019). As cities expand, natural landscapes are increasingly replaced with impermeable infrastructure such as roads, pavements, and buildings. This transformation alters land

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use patterns, disrupts natural hydrological cycles, and intensifies surface runoff, leading to increased incidences of flooding, erosion, and environmental degradation (Barbosa et al., 2012; Kvamsås, 2023; Scaroni, 2021). Traditional stormwater management systems, which prioritise rapid drainage via underground pipes and channels, often fail to adequately address pollution control, source reduction, and ecological sustainability (Gogate et al., 2017; Prudencio & Null, 2018). Consequently, there is a growing need for sustainable, integrated stormwater solutions that can effectively respond to the environmental challenges associated with urbanisation.

In response to these limitations, Blue-Green Infrastructure (BGI) has emerged as a resilient and sustainable approach to urban stormwater management. BGI refers to an interconnected system of natural and semi-natural landscape elements, such as green spaces, wetlands, and water bodies, that serve multiple purposes, including flood control, biodiversity conservation, and water purification (Ghofrani et al., 2017). It represents an ecosystem-based method for managing stormwater quantity and quality through biophysical processes like infiltration, storage, detention, and biological uptake of pollutants (Liao et al., 2017). Among the most commonly implemented BGI systems are rain gardens, bioswales, green roofs, artificial wetlands, and retention or detention basins, all of which integrate environmental and urban design principles to deliver multifunctional benefits.

The potential benefits of BGI extend beyond stormwater control. These systems contribute to improved water quality, enhanced biodiversity, urban cooling, and the creation of recreational and aesthetically pleasing environments (Hamann et al., 2020). One of the primary objectives of BGI is to mitigate urban flooding and reduce Combined Sewer Overflows (CSOs), offering direct economic and environmental advantages (Wilbers et al., 2022). Furthermore, BGI solutions can be more adaptive and cost-effective in the long term compared to conventional grey infrastructure, while delivering co-benefits that support human health, well-being, and urban resilience.

Despite its many advantages, the widespread adoption of BGI in urban stormwater management remains limited. Numerous studies have highlighted institutional, technical, and socio-political barriers to its implementation (Frantzeskaki et al., 2017; O'Donnell et al., 2017;). These include a lack of stakeholder coordination, unclear maintenance responsibilities, insufficient commitment from water professionals, and limited technical knowledge (Suleiman, 2021). Additionally, the absence of standardised guidelines, performance metrics, and long-term monitoring mechanisms hinders confidence in BGI's reliability and cost-effectiveness when compared to traditional stormwater systems (Qiao et al., 2018; Davis et al., 2015). Uncertainty over long-term performance and the lack of institutional capacity to manage BGI facilities further exacerbate resistance to its integration into mainstream infrastructure planning.

Even though many studies have emphasised the importance of BGI, there remains a significant gap in its application, specifically for stormwater management. While the broader environmental and social benefits of BGI are widely recognised, there is a lack of comprehensive frameworks that address its implementation within the context of stormwater systems. Therefore, a comprehensive conceptual model is necessary to promote the effective utilisation of BGI for urban stormwater management. Such a model must incorporate the technical and ecological functions of BGI but also address institutional arrangements, governance structures, public awareness, and long-term

maintenance strategies. Without such a framework, efforts to mainstream BGI into urban development processes are likely to remain fragmented and ineffective. Accordingly, this study aims to fill this gap in both academic literature and practical implementation by developing a conceptual framework to promote BGI adoption for stormwater system. The research has two objectives, 1) investigate the role of BGI in stormwater management with benefits and 2) examine the strategies to overcome identified barriers.

2. RESEARCH METHOD

This study was conducted through a comprehensive literature review focusing on BGI and stormwater management to develop a conceptual framework to promote BGI for sustainable stormwater solutions. The review process explored key theories, concepts, benefits, barriers, and strategic approaches relevant to BGI implementation. A similar methodological approach was adopted by Kavamas (2023) and Kaur and Gupta (2022), who also utilized structured literature reviews for framework development.

To retrieve relevant literature, a set of keywords was formulated, including: *"Blue-green infrastructure*" AND *"management*" AND (*"enabler*" OR *"benefit*" OR *"advantage*" OR *"barrier*" OR *"limitation*" OR *"disadvantage*") * AND (*"stormwater*" OR *"storm drainage*" OR *"runoff*" OR *"rainwater*") *. These search terms were applied across several academic databases such as Web of Science, Scopus, Engineering Village, and Google Scholar to ensure a comprehensive and diverse selection of sources. The study involves a few rounds of screening to reduce the initial pool of 163 articles to a final selection of 87 documents consisting of 73 journal papers and 6 conference papers.

Due to the limited number of studies that collectively address these interconnected areas, both combined and separate keyword searches were used. The initial search results were filtered by reviewing titles, abstracts, and keywords, after which a purposive sampling method was applied to select the most relevant and high-impact articles. The final pool of literature included seminal works on BGI benefits and barriers, as well as key contributions to stormwater management practices.

Manual content analysis was conducted on the selected articles, allowing the author to extract critical themes, patterns, and strategies related to BGI implementation. Especially, a three-phase coding approach was employed creating open, axial, and selective codes to systematically identify, organize, and interpret codes within the data. The insights gained from this analysis formed the foundation for the development of the conceptual framework.

3. LITERATURE REVIEW

3.1 CONVENTIONAL STORMWATER MANAGEMENT

Conventional stormwater management typically relies on engineered systems designed to rapidly collect and discharge runoff from urban areas into nearby water bodies (Prudencio & Null, 2018). These systems primarily focus on flood control and public safety, with limited attention to environmental sustainability. Historically, surface runoff was considered a nuisance or waste product rather than a resource, leading to the development of extensive grey infrastructure, networks of drains, pipes, culverts, and channels constructed with impermeable materials such as concrete, asphalt, and steel (Gallo et al., 2020). While effective in reducing urban flooding, such systems increase

impervious surface coverage, limiting infiltration and intensifying runoff volume and pollution (Tsegaye et al., 2019).

Grey infrastructure tends to prioritise rapid conveyance of stormwater, often without treating or retaining it, which contributes to water quality degradation and urban heat effects. These systems are usually centralised and space-intensive, making them unsuitable for compact urban settings where green elements are limited (Gallo et al., 2020). Moreover, they fail to replicate natural hydrological processes such as infiltration, filtration, and evapotranspiration (Szeląg et al., 2019). Traditionally, stormwater systems have been managed by sanitation and water departments in a siloed, top-down manner, focusing on quick removal rather than ecological integration (Jean et al., 2021).

Even though urban stormwater management is essential for addressing environmental, economic, and social challenges, such approaches are increasingly seen as inadequate and modern technologies are needed to cope with the increasing demands of urban growth, climate change, and financial limitations (Bohman et al., 2020; Fletcher et al., 2015). In fact, conventional stormwater management systems primarily rely on grey infrastructure, such as pipes and culverts, which effectively control flooding however pose environmental and spatial limitations (Zhou, 2014). In contrast, BGI offers a multifunctional, sustainable alternative that integrates ecological principles, providing benefits such as water quality enhancement, biodiversity, and resilience, while addressing the shortcomings of traditional systems (Kaur & Gupta, 2022; Pochwat et al., 2019).

3.2 BLUE-GREEN INFRASTRUCTURE (BGI)

Blue-green solutions are frequently recommended as a sustainable, multifunctional approach that can help counteract the negative impacts of urbanisation while responding to climate change by regulating water and heat, purifying air and water, and enhancing recreational aspects and biodiversity (Voskamp & Van de Ven, 2015). The multifunctional nature of nature-based solutions such as BGI aligns with a systemic, or "integrated" water management approach, which combines various aspects to enhance resilience against water-related hazards (Fletcher et al., 2015). Integrated blue aspects into the green environment focus on protecting landscapes through a network of blue and green areas, including features such as permeable pavements, rain gardens, bioswales, wetlands and other blue-green aspects (Kaur & Gupta, 2022). Accordingly, there is a requirement in urban planning, design, and management to enhance resilience and sustainable development in BGI (Schewenius & Wallhagen, 2024).

BGI development management is frequently associated with the specialised roles of various professionals, including water engineers, landscape architects, and urban planners, to provide for successful design (Pochwat et al., 2019). Combining specialised professional knowledge with community involvement can improve the long-term effectiveness and flexibility of BGI (Keeler et al., 2019). It is essential to facilitate decision-making, promote enhanced democratic engagement, ensure community satisfaction, and enhance people's interest in blue-green aspects to the long-term viability of BGI projects (Rahtz et al., 2023). Therefore, community involvement is essential for the successful implementation of BGI and for creating more sustainable solutions (Everett et al., 2023).

BGI can be classified into several types, such as rain gardens, bioswales, green roofs, retention ponds, constructed wetlands, green cover, and sponge city (Hamel & Tan,

2022). Further, BGI types can be categorised into micro-scale, meso-scale, and macro-scale (Ahmad et al., 2019). Interventions in BGI can be implemented at various scales, each with unique advantages and challenges (Everett et al., 2023). Micro-scale measures, such as urban parks and green roofs, offer localized benefits and community engagement but may have limited overall impact (Hamel & Tan, 2022). Meso-scale projects can collectively improve urban resilience but require coordinated planning. Macro-scale initiatives, like sponge cities and urban green corridors, afford significant flood mitigation and environmental benefits, though they demand substantial investment and institutional coordination (Sehrawat & Shekhar, 2024).

3.3 BENEFITS OF BLUE-GREEN INFRASTRUCTURE

The integration of water elements into green spaces enhances the functionality of the whole stormwater management system by creating new experiences for people (Pauleit et al., 2020). Therefore, there are some combined advantages of this holistic approach duo to integration (Pauleit et al., 2020). Accordingly, the implementation of BGI strategies to traditional stormwater management systems has gained environmental, social, and health benefits in recent years (Sharma et al., 2021). Mainly, these are done due to huge environmental and health impacts associated with stormwater in the world (Singh et al., 2023). Therefore, the best stormwater management techniques aim to reproduce natural water cycles by reducing stormwater runoff volume and increasing infiltration (Bell et al., 2018).

Table 1: Benefits of BGI

Benefits	Citations
Carbon sequestration	[1], [8], [9], [14], [16], [17], [4], [14], [18]
Enhance biodiversity	[1], [8], [9]
Climate regulation	[4], [14], [13], [18], [19], [20]
Air quality improvement	[1], [20], [1], [13], [19], [8], [7]
Water quality improvement	[1], [3], [8], [9], [11], [15], [17], [20], [22], [24]
Soil quality improvement	[20], [29], [8]
Water saving	[20], [1], [13], [19], [12], [9], [17], [22]
Reduce flood risk	[8], [9], [17], [5]
Provide recreational activities	[1], [10], [21], [2], [4], [14], [18]
Energy savings	[13], [19],
Aesthetic appearance	[7], [4], [14], [18]
Cost efficient	[23], [11]

[1] (Alves et al., 2019) [2] (Bell et al., 2018) [3] (Brears, 2018) [4] (Depietri & McPhearson, 2017) [5] (Dreiseitl, 2015) [6] (Dushkova et al., 2021) [7] (Everett et al., 2023) [8] (Everett et al., 2023) [9] (Fletcher et al., 2015) [10] (Gascon et al., 2015) [11] (Ghofrani et al., 2017) [12] (Hamel & Tan, 2022) [13] (Haase et al., 2017) [14] (Keeler et al., 2019) [15] (Krivtsov et al., 2022) [16] (Li & Trivic, 2024) [17] (Liao et al., 2017) [18] (Lourdes et al., 2021) [19] (Lund, 2018) [20] (Markevych et al., 2017) [21] (McDougall et al., 2022) [22] (Mguni et al., 2015) [23] (Moreno et al., 2017) [24] (O'Donnell et al., 2017)

As per the benefits identified in Table 1 by referring to the 25 research papers, 13 emphasised that BGI provides water quality improvement by mitigating stormwater and

reducing flood through filtration, retention and evaporation of water. Further, through recreational activities, people strengthen their psychological and physical well-being. There is considerable research and literature in many countries with multiple benefits of BGI for improving urban ecosystems (Kim & Song, 2019). This can shift stormwater infrastructure from invisible underground pipeline systems to blue-green stormwater measures, with new opportunities for sustainable urban areas (Sharma et al., 2021). However, there are barriers to the implementation of this approach. Blue-green solutions may be able to address some issues by improving green spaces for the benefit of both people and wildlife (Voskamp & Van de Ven, 2015).

3.4 BARRIERS TO BLUE-GREEN INFRASTRUCTURE

Although BGI systems are gaining recognition and are being adopted in various countries in the world, still, there are many barriers remaining (Raška et al., 2022). A significant issue concerning BGI is that most BGI theories and implementations have been developed in developed countries such as the USA (Meerow, 2020), Sweden (Suleiman, 2021), Norway (Wilbers et al., 2022), Portland (Dlugonski & Szumanski, 2015) and other developed countries. Moreover, the expansion of informal settlements can worsen water management problems through their impacts on ecosystem services in the form of water purification and retention (Harriden, 2012). Although current stormwater research addresses various technical, institutional, and financial barriers to adopting alternative stormwater management strategies, these barriers still prevail (Kvamsås, 2021).

Table 2: Barriers of BGI

Barriers	Citations
Lack of funding	[1], [2], [4], [9], [13], [16], [17], [18], [20], [22]
Uncertainty about the cost	[1], [4], [9], [13], [14], [16], [19], [20]
Lack of awareness	[1], [2], [4], [6], [7], [16], [20], [21]
Reluctant to support new practices	[1], [4], [8], [10], [13], [16], [17], [18], [21], [22]
Legal regulations	[1], [8], [16], [17], [18], [22]
Fragmented roles and responsibilities	[8], [10], [16], [20]
Weather uncertainty	[3], [15], [21]
Implemented on a small scale	[7], [8]
Lack of space	[1], [4], [8], [13], [16], [17], [18], [22]

[1] (Almaaitah et al., 2021) [2] (Ashley et al., 2011) [3] (Caruzzo et al., 2018) [4] (Dhakal & Chevalier, 2017) [5] (Drosou et al., 2019) [6] (Hysa, 2021) [7] (Kaur & Gupta, 2022) [8] (Kordana, 2018) [9] (Kordana & Słyś, 2020) [10] (Mell, 2008) [11] (Neumann et al., 2017) [12] (O'Donnell et al., 2017) [13] (Pregnolato et al., 2016) [14] (Roy et al., 2008) [15] (Sarabi et al., 2019) [16] (Sarabi et al., 2020) [17] (Stec & Mazur, 2019) [18] (Tchórzewska-Cieślak, Rak, et al., 2019) [19] (Thorne et al., 2018) [20] (Wamsler et al., 2020) [21] (Wihlborg et al., 2019) [22] (Zawilski et al., 2014)

Table 2 depicts the barriers to implementing the BGI approach in the world. It indicates that among 22 studies, 50% of the studies identified a lack of awareness and knowledge of BGI practices as the most prevailing barrier. Accordingly, other barriers are raised, including lack of funding, the uncertainty of costs, reluctance to support BGI projects, fragmented roles and responsibilities and legal issues. Therefore, the practitioners are

required to identify the financial, knowledge, social, and legal barriers in BGI implementation (Wamsler et al., 2020). For this reason, professionals have to recognise and resolve the new planning issues and change causes, as well as adopt new methods of planning, executing, and collaborating (Kvamsås, 2021).

3.5 STRATEGIES TO OVERCOME THE BARRIERS OF BGI

As discussed earlier, the transition from conventional stormwater systems to BGI is hindered by numerous institutional, technical, and social challenges (Liu & Jensen, 2018). Therefore, it is essential to adopt targeted strategies that can facilitate this transition and accelerate the adoption of BGI. A key strategy involves implementing inclusive flood risk management approaches that promote bottom-up community engagement. This participatory model empowers local stakeholders, residents, planners, and property owners, to actively contribute to BGI planning and implementation (Drosou et al., 2019; Staddon et al., 2018). It also enhances visibility through media and public support, rather than relying solely on political momentum (Cettner et al., 2014).

Incorporating public-private collaborations is crucial, as it bridges the gap between privately and publicly owned land, enabling more integrated and extensive BGI solutions (Wihlborg et al., 2019). Additionally, knowledge sharing and organisational learning are vital for overcoming the widespread lack of awareness about BGI practices. Furthermore, knowledge transfer frameworks can ensure that learning from pilot programs and successful case studies is embedded into routine municipal operations (McCormick et al., 2013; Wihlborg et al., 2019). Countries like Sweden have demonstrated success by facilitating knowledge exchange networks among municipalities, political bodies, and professionals, fostering innovation and regulatory development (Geels, 2011; Wihlborg et al.., 2019).

For emerging economies, similar collaborative models should be established to promote innovation and adaptability. To support long-term implementation, multi-stakeholder collaboration involving community members, water professionals, urban planners, and policymakers is essential throughout the planning, construction, and maintenance phases (Cheshmehzangi et al., 2024; Drosou et al., 2019). Overcoming institutional fragmentation and encouraging interdisciplinary approaches can enhance coordination and sustainability. Furthermore, technological innovation and governance reform should be integrated into existing frameworks to improve stormwater management and foster intelligent, resilient urban development (Cousins, 2018; Holtz et al., 2008). Finally, systematic monitoring and evaluation of BGI systems, including their design, operation, and cost-effectiveness, is needed to generate evidence-based improvements and support future scalability (Read, 2016; Wihlborg et al., 2019).

Additionally, effective BGI implementation requires tailoring strategies by scale. Because micro-scale efforts focus on community engagement and flexible design while meso-scale involve collaboration and stewardship (Hamel & Tan, 2022). Further, macro-scale use master plans, policies, and technology (Wihlborg et al., 2019). Across all levels, aligning with sustainability goals, securing funding, and promoting education and coordination are essential for success and long-term impact (Sehrawat & Shekhar, 2024).

3.6 CONCEPTUAL FRAMEWORK

This section outlines the conceptual framework developed to promote BG infrastructure for stormwater management, emphasising the associated benefits, barriers, and strategies to overcome those barriers. Figure 1 provides the developed conceptual framework. The framework initially presents the existing conventional stormwater management systems, which primarily rely on structures such as culverts, drains, and outfalls to manage stormwater. Transitioning to BGI involves understanding its infrastructure including diverse elements such as rain gardens, bioswales, green roofs, retention ponds, constructed wetlands, green cover, and sponge cities as more sustainable alternative.

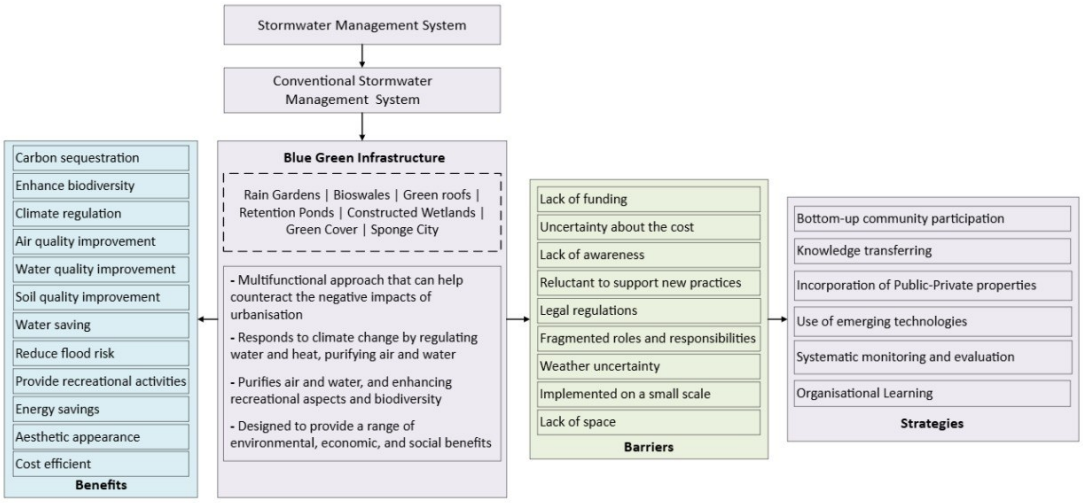


Figure 1: Conceptual framework for implementing BG infrastructure for stormwater management

The framework defines BG infrastructure in terms of its physical components and elaborates on its multifunctional nature, highlighting its role in regulating climate, purifying air and water, and enhancing urban biodiversity and recreational spaces.

Subsequently, the framework highlights key benefits of BGI, including environmental improvements, resilience against climate extremes, and social advantages like recreation and aesthetic value, which are visually represented in the blue-shaded section. These benefits range from carbon sequestration and air quality improvement to reducing flood risks, saving water, enhancing biodiversity, and providing cost-effective solutions.

In parallel, the green-shaded section of the framework captures the barriers that hinder the adoption of BG infrastructure. Critical barriers include lack of funding, uncertainty about costs, lack of public awareness, legal and regulatory challenges, fragmented responsibilities among stakeholders, and spatial constraints, which are critical for planning. Recognising these challenges, the framework proposes strategies for promoting BG infrastructure, including bottom-up community participation, incorporation of public-private properties, knowledge transfer, use of emerging technologies, organisational learning, and systematic monitoring and evaluation.

While prior studies have developed conceptual models for BG infrastructure, proposing a data management framework for strategic urban planning, and adapting to climate change, specific frameworks targeting BG infrastructure for stormwater management remain limited (Almaaintah et al., 2021; Sorensen et al., 2021). The interactions among components form a dynamic process in this framework, understanding barriers informs

the development of targeted strategies, which are facilitated by stakeholder collaboration and technology. The continuous cycle of implementation, assessment, and adaptation ensures the framework remains responsive to changing urban contexts. Therefore, this framework offers a valuable contribution to the existing body of knowledge by providing a targeted and practical approach for BG infrastructure implementation in stormwater management.

4. CONCLUSION AND RECOMMENDATIONS

In conclusion, conventional stormwater management systems are seen as inadequate, prompting a shift toward nature-based BGI solutions that integrate ecological design to manage runoff, enhance resilience, and restore water quality and flow restoration. BGI offers a sustainable, multifunctional approach to urban resilience by integrating stormwater management with green spaces, combining expert knowledge with community engagement. Further, it provides key benefits such as carbon sequestration, increased biodiversity, improved air, water and soil quality, water and energy saving, and enhanced recreational spaces. However, several barriers hinder the widespread implementation of BGI in stormwater management, including lack of funding and awareness, cost and weather uncertainties, reluctance to adopt new approaches, and stiffness of legal requirements. Overcoming these challenges requires integrated strategies such as bottom-up community participation, incorporation of public-private properties, organisational learning, knowledge transferring, utilisation of emerging technologies, and systematic monitoring and evaluation. To advance the effective implementation of BGI, future research should evaluate adaptive strategies across the diverse urban contexts to address current barriers and propose models for integrated governance and sustainable financing.

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SHAPING SUCCESSFUL PROCUREMENT FUTURES: THE EVOLVING LANDSCAPE OF PUBLIC-PRIVATE PARTNERSHIP IN SRI LANKA

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ABSTRACT

Public Private Partnership (PPP) is a long-term arrangement wherein a government agency and a private sector consortium work together to supply public asset or service, with the private sector bearing considerable risk and administrative burden. In the modern world, PPP is a strategic approach that many governments use to manage their public obligations while additionally earning the benefits of the private sector's engagement in the development of infrastructure. In practice, there are two approaches that PPP initiatives can begin: by solicitation or un-solicitation. For both approaches, the ultimate product's delivery is influenced by the performance of the procurement process. One important factor in the success of PPP projects is seen to be a fair and transparent procurement procedure. The authors conducted a comprehensive study on the evolution of Sri Lanka's PPP procurement process. The results of the comprehensive analysis revealed that the PPP procurement process in Sri Lanka has been evolving for more than 25 years, utilising both unsolicited and solicited approaches. Finally, it was noted that the evolution of the PPP procurement process can be utilised to guide future developments and reforms to shape a fair and transparent PPP procurement process.

Keywords: *Circulars; Guidelines; Procurement Process; Public Private Partnership.*

1. INTRODUCTION

Governments all over the world have been enlisting the private sector to assist with the development of modernised sustainable infrastructure since the late 1990s (Hettige et al., 2021; Osei-Kyei et al., 2018). In this sense, the quantity of Public Private Partnership (PPP) initiatives has grown significantly over time, especially in lower and middle-income countries (World Bank, 2021). As per the opinion of many countries around the world, PPP is a crucial tool for executing major and sophisticated infrastructure projects (Yu et al., 2018). In the industrialised world, the United States, Canada, Australia, and the United Kingdom have all consistently drawn significant amounts of private

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investment into their PPP markets, while notably, PPP investments are rising rapidly among the leading developing nations, including China, India, Brazil, and South Africa (Fernando et al., 2023).

PPP is a long-term contractual arrangement whereby a public sector organisation and a private company share resources and risks for the development of public facilities (European Investment Bank, 2023; World Bank, 2021). Governments all over the world preferred to use PPP over traditional public procurement since it offered the advantages of having the private sector (Keers & Fenema, 2018). In practice, PPP projects can be initiated through two main approaches: solicitation and un-solicitation (Fernando, 2020; World Bank, 2021). The solicited approach is where the government identifies a project and invites private investors to bid and develop the project (World Bank, 2021). In contrast, under the unsolicited approach, a private investor proposes a project to the government without an open invitation by private sector organisations seeking business opportunities (Public-Private Infrastructure Advisory Facility, 2017). Since PPP is a cooperation between the public and private sectors to accomplish a common goal and its tremendous benefits, PPPs are favoured by governments in both solicited and unsolicited approaches (Fernando et al., 2022). Osei-Kyei et al. (2018) stated that a clear procurement process leads to the success of PPP projects and attracts the benefits of having PPP to the government. The establishment of a fair and transparent procurement process necessitates the identification of gaps in the existing process and the implementation of appropriate reformations to address them (Fernando & Chandanie, 2018; Fernando et al., 2025). It is highly beneficial to observe the evolution of the PPP procurement process over time in order to identify the gaps and propose reforms to close such gaps (European Investment Bank, 2023; Osei-Kyei et al., 2018). In addition, the evolution of the PPP procurement process provides us insight into the impact of past modifications, alterations, and reformations made to the current procedure, which assists in selecting the best reformations to fill the gaps in the process (European Investment Bank, 2023; Zawawi, et al., 2016).

Therefore, this paper aims to explore the evolution of PPP procurement process in Sri Lanka. Accordingly, the paper begins with a brief outline of the study, followed by the adopted research method. Then, the data collected from the literature are presented and analysed to visualise the evolution of PPP procurement process. Further, this study was limited to the evolution of the procurement process of PPP in Sri Lanka.

2. METHODOLOGY

A thorough literature review assists the researcher in obtaining current information about the research area and allows the study's foundation to be strengthened (Khallaf et al., 2018). Saunders et al. (2019) viewed that a strong body of literature may help researchers ensure that the information already known about their field of study is up to date and that they are creating new, original knowledge that does not already exist in the literature. Thus, a thorough literature review was conducted to investigate how the PPP procurement process evolved over the years in Sri Lanka. Accordingly, an in-depth investigation was carried out studying 15 documented records which include amendments to the constitution, circulars, regulations, guidelines and supplements to guidelines, as indicated in Table 1.

From the inception of PPP in Sri Lanka, every document pertaining to PPP procurement that legally constituted entities have issued, have been selected for this study. For selecting the listed documents in Table 01, the National Procurement Commission, the legal entity currently in charge of regulating PPP procurement in Sri Lanka, and the Department of Public Finance, the legal body in charge of overseeing PPP procurement in Sri Lanka prior to the establishment of the National Procurement Commission, were consulted.

Table 1: Details of reviewed documents

No.	Name of Source	Published Year	Nature of the source
01	Financial regulations	1966	Regulation
02	Financial regulations – revised	1992	Regulation
03	Guidelines on Government Tender Procedure – Part I and II	1996	Guideline
04	Guidelines on Government Tender Procedure – Part I (Revised)	1997	Guideline
05	Guidelines on Government Tender Procedure – Part II (Revised)	1998	Guideline
06	Government Procurement Guidelines for Goods and Works	2006	Guideline
07	Public Finance Department Circular No. 444	2010	Circular
08	Supplement No. 23 to Guidelines on Government Tender Procedure – Part II	2011	Supplement to Guideline
09	19th Amendment to Constitution	2015	Amendment to Constitution
10	Supplement No. 30 to Guidelines on Government Tender Procedure – Part II	2016	Supplement to Guideline
11	Public Finance Department Circular No. 2/2019	2019	Circular
12	Ministry of Finance Circular No. PFD/PPP/Guidelines/2019	2019	Circular
13	20th Amendment to Constitution	2020	Amendment to Constitution
14	21st Amendment to Constitution	2022	Amendment to Constitution
15	Government Procurement Guidelines for Goods, Works and Non-consulting Services	2024	Guideline

Finally, the evolution of the PPP procurement process was investigated for both solicited and unsolicited approaches based on a synthesis of the literature. This helps to visualise future development and reformations that are essential for achieving a fair and transparent procurement process for PPP.

3. PPP PROCUREMENT PROCESS IN SRI LANKA

Public Property Act (1992) mandated that government employees are required to make sure that public resources are used in a way that safeguards the interests of the public. In

the Premchandra v. Jayawickreme [1994] case, the Supreme Court held that there is no absolute or unrestricted authority in public law, that competent public officials are granted discretion to be used for the public good, and that the objective of exercising that discretion must be considered in relation to the reasons it was granted. Considering this, the state assumes the role of trustee for the use of natural and national resources for the benefit of the public as a party to the PPP, and all public agencies are obligated to act impartially, honestly, and transparently while implementing PPPs.

In Sri Lanka, there is no explicit legislation pertaining to PPP procurement, and neither the general contract law nor any of its sections particularly address PPP procurement (Fernando et al., 2023; United States Agency for International Development, 2016). However, it deals with general branches of law such as the Unfair Contract Terms Act, Employment, Taxes, Customs, Insurance, Banking, and Foreign Exchange Regulation (United States Agency for International Development, 2016). In the 1997 case of Smithkline Beecham Biological S. A. and Others v. State Pharmaceutical Corporation, Honourable Justice Dr. Amerasinghe of the Supreme Court rendered a judgement on a procurement case, declaring that "*In my view, law includes regulations, rules, directions, instructions, guidelines and schemes that are designed to guide public authorities"*. Accordingly, there is no uncertainty that in absence of specific provision in the basic contract law or specific act to deal with PPP procurement, procurement guidelines and regulations related to PPP are set forth for PPP procurement law.

In accordance with Article 43 (1) of the Constitution, the President had delegated authority to the Minister of Finance on *"Government Financial Regulations, Interpretation and Amendments"* (Fernando et al., 2023). The financial regulations were first published in 1966 (Ministry of Finance and Planning, 1966) and updated in 1992 (Ministry of Finance and Planning, 1992). Chapter XIII of the financial regulations in 1966 and its updated version in 1992 outlined the procedures to be followed when procuring works, goods, and services. Whereas it does not deal with the procurement of PPP.

Later, Guidelines on Government Tender Procedure have been issued in two sections in 1996: Part I: Projects financed by public funds, including donor funds; and Part II: Private sector financed infrastructure projects also known as Part II Guidelines (Ministry of Finance and Planning, 1996). Part I Guidelines were revised in 1997 (Ministry of Finance and Planning, 1997), and Part II Guidelines were revised in 1998 (Ministry of Finance and Planning, 1998). Part II Guidelines provide spaces for both solicited and unsolicited and describe the procurement process in detail (Ministry of Finance and Planning, 1998). Guidelines on Government Tender Procedure - Part I, was replaced by the Government Procurement Guidelines for Goods and Works – 2006 (National Procurement Agency, 2006) and later, Government Procurement Guidelines for Goods and Works (2006) was replaced by Government Procurement Guidelines for Goods, Works and Non-Consulting Services -2024 (National Procurement Commission, 2024). Further, National Procurement Commission (2024) stated that Guidelines on Government Tender Procedure - Part II - 1998, remain in effect. By Public Finance Circular No. 2/2019, Part II Guidelines was renamed as Guidelines for private sector infrastructure projects on PPP basis in 2019 (Ministry of Finance, 2019b). In light of the above, the Government Tender Procedure - Part II is the first to establish the legal framework for PPP procurement in Sri Lanka by providing space to both solicited and unsolicited PPP approaches.

3.1 PROCUREMENT PROCESS FOR SOLICITED PPPS

PPP concepts are relatively new to the country (Ministry of Finance and Planning, 1998). Reference 225 of the Part II Guidelines sets forth the procedure for infrastructure projects that have not been identified as eligible for funding from the Consolidated Fund. As per Part II Guidelines, the procedure for procurement of solicited PPP includes identifying PPPs, preparing an expression of interest, evaluating pre-qualification, preparing request for proposal documents, evaluating proposals, negotiating submitted offers, preparing an implementation agreement and signing the implementation agreement. As outlined in Part II Guidelines, Figure 1 depicts the main steps in the procurement process of solicited PPPs.

According to the set forth procedure in Part II Guidelines, the priority project should be identified by the line ministry, and its feasibility is verified along with the Bureau of Infrastructure Investment (BII), a specially dedicated unit established under the Board of Investment (BOI). Later, the Bureau of Infrastructure Investment was inactive, and its power was granted to the National Agency for PPP by Public Finance Circular No. 2/2019 (Ministry of Finance, 2019b). Once it is determined as a feasible project, then it is forwarded to the cabinet for its approval with the line ministry recommendations.

Cabinet Appointed Negotiation Committee: a special committee set forth under Part II Guidelines, issue Expression of Interests jointly with the Project Committee: special technical committee appointed under Part II Guidelines. The Project Committee evaluates Expression of Interests and prepares a shortlist for Cabinet Appointed Negotiation Committee approval. Afterwards, Request for Proposal documents are issued to all shortlisted applicants.

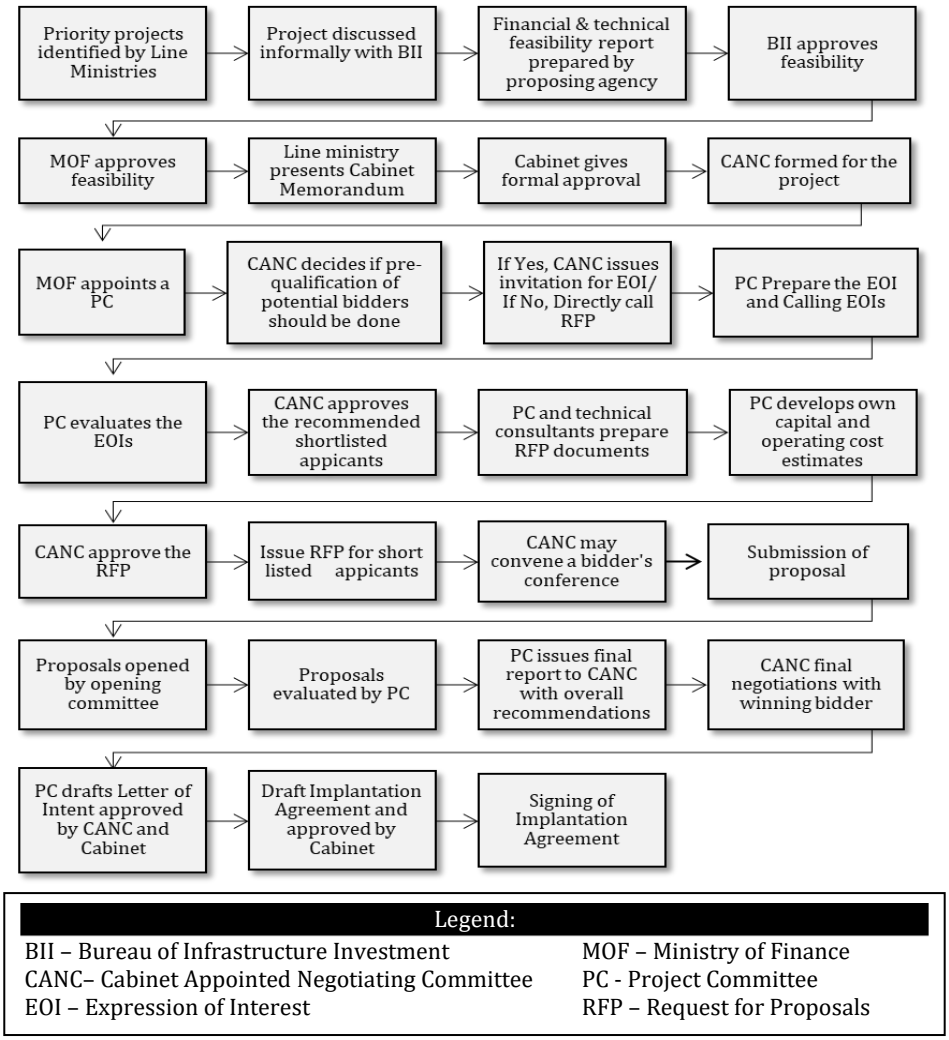


Figure 1: Procurement process for solicited PPPs as per Part II Guidelines – 1998

Once the proposal is received from applicants, the Project Committee shall verify during the first screening that all proposals are (i) technically sound in relation to the project's functional objectives, (ii) environmentally acceptable, and (iii) financially feasible. In the detail evaluation, (i) compliance with the major technical performance criteria, (ii) compliance within the key environmental standards, and (iii) compliance with health and safety standards are taken into consideration for the technical proposal assessment while financial proposal is assessed under (i) proposal's financial acceptability, (ii) the high financial standing and reputation of the private proponent and their financial partners, (iii) the soundness of the financing plan, (iv) projections of all pertinent capital and operating costs of the project, (v) the basis for the tariff. Later, the Cabinet Appointed Negotiation Committee negotiates with the winner on the terms of the contract. Then implement agreement is drafted and forwarded to the cabinet for its approval. Once the implementation agreement is approved, the contract is signed to implement PPP. Accordingly, as shown in Figure 1, it is required to follow a lengthy process to procure solicited PPPs. Ministry of Finance and Bureau of Infrastructure Investment play a major role in PPP procurement, and two special committees appointed by the cabinet and the Ministry of Finance: Cabinet Appointed Negotiation Committee and the Project

Committee respectively, play a role similar to the Procurement Committee and Technical Evaluation Committee in traditional public procurement.

3.2 PROCUREMENT PROCESS FOR UNSOLICITED PPPS

Reference 237 (a) of Part II Guidelines states, "Line ministries, agencies and BOI/BII receiving unsolicited proposals should have them processed according to the procedures applicable to solicited proposals". Further, as stated in reference 237(b), it was recommended that open competitive proposals be called for before making the decision based only on unsolicited proposals. In addition, Reference 237 (b) of Part II Guidelines states "When owing to urgent and exceptional circumstances, it becomes necessary to deviate from the above-prescribed procedure, specific Cabinet approval should be obtained for such deviation". As per the provisions of the Part II Guidelines, solely unsolicited PPPs should not be entertained and only in urgent and exceptional circumstances such unsolicited PPPs can be launched with a specific Cabinet approval.

Thus, the processes that must be taken to implement unsolicited PPPs formally are identical to those for solicited PPPs, as shown in Figure 1, except for the first step. Instead of identifying the priority projects by line ministry or coordinating agency, the first step in processing unsolicited PPPs is, receipt of the proposal by the private proponent. However, the Part II Guidelines are silent about the procedure that needs to be followed in unsolicited PPPs that are launched because of a specific Cabinet decision.

In August 2010, the Public Finance Department issued Circular No. 444, and it was highlighted that various government units misused the provision of Part II Guidelines to entertain unsolicited PPP in urgent and exceptional circumstances that are to be launched with a specific Cabinet approval (Ministry of Finance, 2010). Due to that backdrop, a Standing Cabinet Appointed Review Committee (SCARC) was established to make assessment of such unsolicited PPP as per Public Finance Circular No. 444 and set forth procedure to procure unsolicited PPPs is as given in Figure 2.

Accordingly, the Standing Cabinet Appointed Review Committee decides the suitable procedure to way forward the unsolicited PPP and such process is not specifically mentioned in the Public Finance Circular No. 444, and it remains a question on the transparency of such procedure.

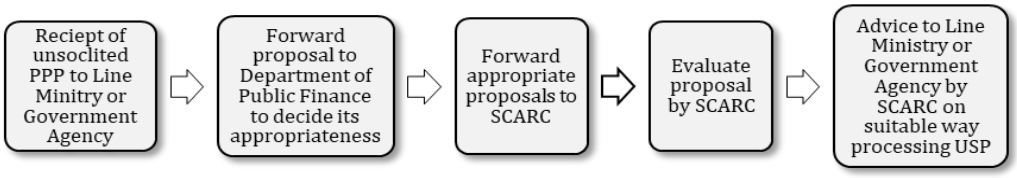


Figure 2: Procurement process of unsolicited PPPs as per public finance circular No. 444

Supplement 23 to Part II Guidelines was released in 2011, and it permits handling of all unsolicited PPPs without following the standard procurement process, according to the Standing Cabinet Appointed Review Committee's recommendations and with the assistance of a supporting committee through the "Direct Negotiation" method (Ministry of Finance, 2011). It is an improvement for the set-forth procedure in Public Finance Circular No. 444, to access unsolicited PPPs. As outlined in Supplement No. 23, Figure 3 depicts the main steps involved in the process of procuring USPs.

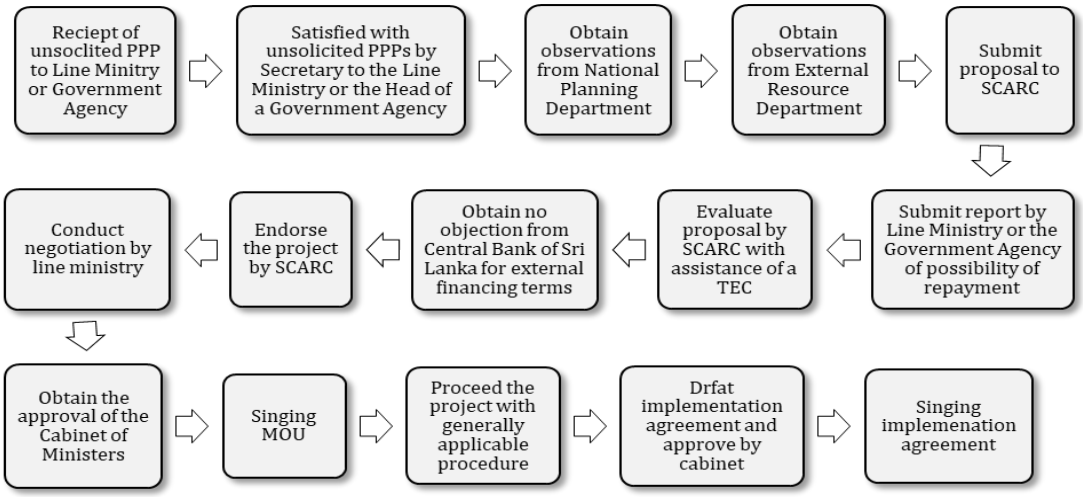


Figure 3: Procurement process of unsolicited PPPs as per supplement No. 23

The Secretary to the Line Ministry or the Head of a Government Agency must first be satisfied with the submissions by determining whether the unsolicited PPPs are relevant to the Public Investment Plan of the relevant line Ministry or the Government Agency, within the overall policy strategies of the Government, and when compared to the funding arrangements that are currently in place. Subsequently, unsolicited PPPs must be presented to the Standing Cabinet Appointed Review Committee together with a report verifying the possibility of repayment and the remarks of the Departments of External Resources and National Planning.

Afterwards, with the assistance of the Project Committee, the Standing Cabinet Appointed Review Committee performs unsolicited PPPs evaluation by taking into account the proposed project's strategic importance. If the Standing Cabinet Appointed Review Committee accepts the proposal, the line ministry will proceed with project negotiations with the potential investor, consulting the Standing Cabinet Appointed Review Committee, over technical concerns, project costs, contract terms, etc. After the completion of successful negotiations, approval from the Cabinet of Ministers should be required before finalising the contract or agreement. A memorandum of understanding should be signed with considering the project's nature and the level of commitments expected from the government or a government agency. Afterwards, the project is proceeding with the acceptable procedure to get development approvals and finally an implementation agreement is signed by the private proponent and the government.

Later, Supplement 30 to Part II Guidelines were issued in 2016 to supersede the Supplement 23 that leads to corruptive practices arisen from Direct Negotiation method. Supplement 30 introduces the "Swiss Challenge" procurement process to deal with unsolicited PPPs (Ministry of Finance, 2016). The procedure of Swiss challenge approach as stipulated in Supplement 30 to Part II Guideline, is shown in Figure 4.

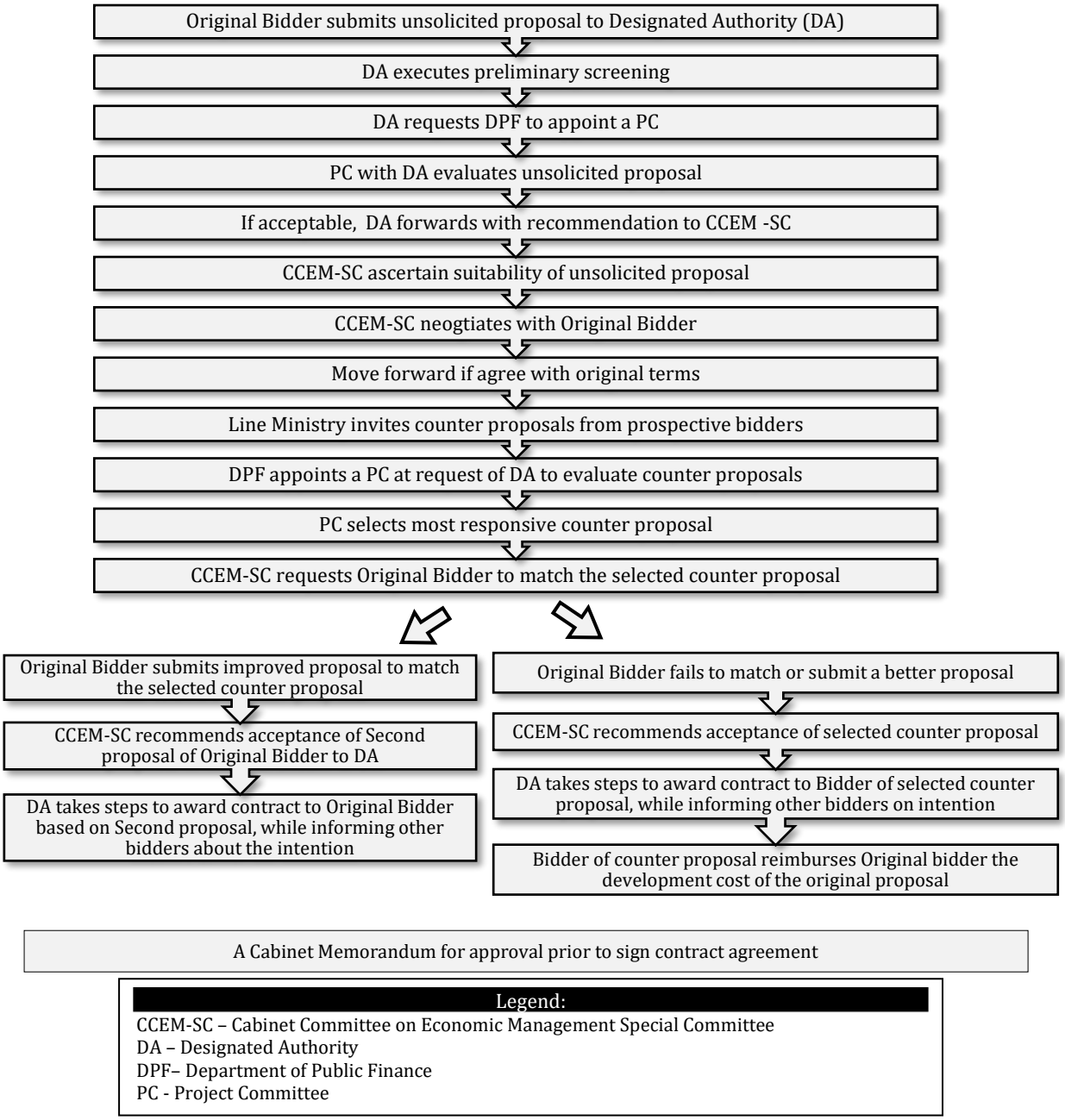


Figure 4: Procurement process of unsolicited PPPs as per supplement No. 30

First, the original proponent submits proposal to Designated Authority (DA): Line Ministry or Government Agency. Designated Authority executes preliminary screening of such unsolicited PPP and afterwards, the Department of Public Finance appoints a Project Committee to evaluate unsolicited PPP in detail if it is sound. Accordingly, Project Committee evaluate unsolicited PPP in detail giving due consideration for: (i) significance and relevance of the proposal in terms of sectorial priority within government overall policy priorities, (ii) alternative delivery options, (iii) merits of the proposed project and its conformity with the existing legal, regulatory and environmental policy of the country, (iv) reputation, and experience possessed by the original proponent in the sector, (v) industry and/or field of the proposed project, (vi) experience and proven track

record and financial capability of the original proponent, (vii) acceptability and feasibility of the implementation plan.

If it is determined by the Project Committee that proposal is acceptable, it forwards to the Cabinet Committee on Economic Management Special Committee (CCEM –SC) to assess its suitability and negotiate with the original proponent. The Cabinet Committee on Economic Management Special Committee is empowered to negotiate with the original proponent to agree upon the terms of the proposal giving due consideration to the above matters. Then the Designated Authority calls counter proposals from prospective bidders and forwards them to the Project Committee to evaluate. The Project Committee selects the most responsive counter proposal and the Cabinet Committee on Economic Management Special Committee requests original bidder to match the selected counter proposal.

If the original proponent submits an improved proposal (Second proposal) to match the selected counter proposal, the Designated Authority takes steps to award contract to the original proponent unless the bidder of selected counter proposal. However, project is awarded to bidder of selected counter proposal, cost of original proposal should be compensated. Finally, Cabinet approval is obtained to award the contract to selected proponent.

The Swiss Challenge procurement method, which was introduced by Supplement 30 to Part II Guidelines, was declared to be ineffective in September 2019 by the Ministry of Finance circular No. PFD/PPP/Guidelines/2019 due to its inherent issues. The Ministry of Finance (2019a) instructed that the methodology recommended in Part II Guideline in 1998 be used again instead of the Swiss Challenge procurement method until suitable mode is suggested. With the ratification of the 19th Amendment to the Constitution, the National Procurement Commission was established pursuant to Section 156(B) of the Constitution to develop sound public procurement procedures and policies (Nineteenth Amendment to the Constitution, 2015). The National Procurement Commission was subsequently abolished with the introduction of the 20th Amendment to the Constitution (Twentieth Amendment to the Constitution, 2020) and then re-established under the 21st Amendment (Twenty-First Amendment to the Constitution, 2022). Nevertheless, the National Procurement Commission has not yet introduced comprehensive PPP guidelines or procedure to entertain USP.

4. ANALYSIS AND DISCUSSION

In Sri Lanka, there is no explicit legislation governing PPP procurement, instead unique PPP procurement laws exist in some countries having developed PPP environment, such as Chile, Jordan, and Mexico (Economic Intelligence Unit, 2017; Economic Intelligence Unit, 2019). The President of Sri Lanka assigned the responsibility of Financial Regulations to the Minister of Finance in accordance with Article 43 (1) of the Constitution. Accordingly, the Financial Regulations were first published in 1966 and were later revised in 1992. Though, the Chapter XIII of Finance Regulations address public procurement, PPP procurement is not specifically covered from it. The Ministry of Finance published two parts of guidelines on government tender procedures in 1996. Part I that were revised in 1997, deals with projects financed by public funds, including donor funds while Part II that were revised in 1998, uses for PPP projects. Government Procurement Guidelines for Goods and Works - 2006 replaced the Government Tender

Procedure - Part I - 1997, and later Government Procurement Guidelines for Goods, Works and Non-Consulting Services - 2024 replaced Government Procurement Guidelines for Goods and Works - 2006. However, Guidelines on Government Tender Procedure - Part II -1998 are still in force. Accordingly, the first legislative framework addressing PPP procurement was Guidelines on Government Tender Procedure - Part II, which was originated in 1996 and revised in 1998.

Both solicited and unsolicited proposals are encouraged in Part II of the Government Tender Procedure. It sets forth the procedure for procurement of solicited PPP including identification of PPPs, project feasibility studies, project development, prepare expression of interest, evaluate pre-qualification, prepare request for proposal documents, evaluate proposals, negotiate submitted offers, prepare implementation agreement and sign implementation agreements. Economic Intelligence Unit (2017) highlighted that Chile and Mexico also followed similar steps for procurement of solicited PPP.

Unsolicited PPPs should not be accepted on their own and procured as a solicited proposal in line with the Government Tender Procedure - Part II; instead, it should only be begun with special Cabinet approval in circumstances of exceptional and urgent. In August 2010, Circular No. 444 of the Public Finance Department disclosed the process that needs to be followed in unsolicited PPPs that are launched because of a specific Cabinet decision, since the Government Tender Procedure - Part II was silent on that. To embrace unsolicited PPPs, the "Direct Negotiation" method was introduced in 2011 by Supplement 23. Afterwards, Supplement 23 was superseded by Supplement 30 in 2016, introducing with it the "Swiss Challenge" method for managing unsolicited PPPs. Peru successfully uses the Swiss Challenge method and Chile utilises the Bonus approach to convert USP into competition (Economic Intelligence Unit, 2017), while South Africa uses the Best and Final Offer method (Economic Intelligence Unit, 2015).

The Ministry of Finance announced in September 2019 that the Swiss Challenge procurement method was no longer in use due to its inherent flaws and further instructed to follow the procedure outlined in Government Tender Procedure - Part II for unsolicited PPPs until a proper procedure is introduced. Even though the National Procurement Commission was set up to provide appropriate public procurement regulations and processes, no comprehensive PPP guidelines or process to deal with USP has yet been implemented.

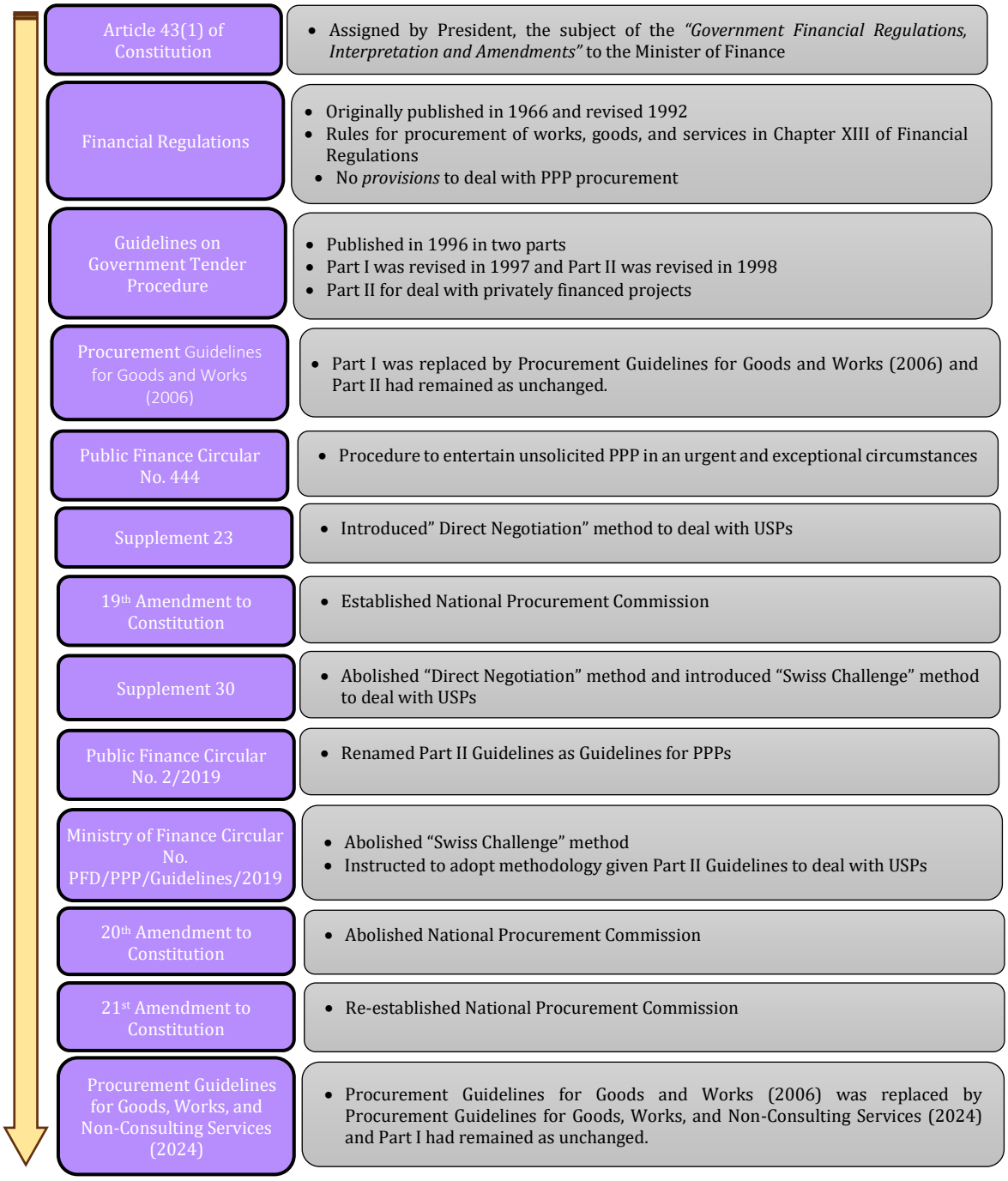


Figure 5: Evaluation of PPP procurement process in Sri Lanka

In a nutshell, Figure 5 offers a summary and visual representation of the PPP evolution for both unsolicited and solicited approaches in Sri Lanka. According to Figure 5, the PPP procurement procedure has been evaluated for over 25 years and allows for both unsolicited and solicited offers. Furthermore, it shows that formal procedure reformed and develop to ensure a fair and transparent procurement process for PPP, even while several approaches were considered to embrace unsolicited PPPs while providing lengthy process for solicited PPPs.

5. CONCLUSION

This study presents the findings of a literature review based on amendments to the constitution, regulations, guidelines and circulars related to PPP procurement in Sri Lanka. The results indicate that although the Financial Regulations of 1966 marked the beginning of formal public procurement, the Government Tender Procedure - Part II in 1996, was the initial regulation that governed PPP procurement.

Government Tender Procedure - Part II, revised in 1998, is the present guideline for PPP procurement, with some revisions. Part II Guidelines are open for both solicited and unsolicited PPPs. It provides a lengthy process to entertain solicited PPPs. Initially, unsolicited PPPs have been entertained with full competition, and later Direct Negotiation method and the Swiss Challenge approach were introduced for initiating unsolicited PPPs. Subsequently, the Swiss Challenge and Direct Negotiation procurement methods were eliminated due to inherent problems. In order to create fair and transparent procurement for Sri Lanka in the future, this study highlights the necessity for a thorough and simplified PPP procurement process and offers improved methods for accepting unsolicited PPPs.

A comprehensive review of 15 documents led to the development of Figure No. 05, which visualises in detail the evolution of PPP procurement for both solicited and unsolicited approaches from its inception. It was observed that a lengthy procedure must be followed in the circumstance of the procurement of solicited PPPs. Even though various strategies have been considered, no procedure has been firmly established for the procurement of unsolicited PPPs. Accordingly, the diagram shown in Figure 5 can be utilised to collect primary data for future developments and reformations that are required for a successful PPP procurement process as a future research direction. Although the study's primary focus is on the development of the PPP procurement process in Sri Lanka, it is expected that the article's findings and discussion will inspire policymakers and government officials in other countries to shape suitable PPP procurement processes in their own nations, adding global significance of this study.

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SHORT-TERM ELECTRICITY DEMAND FORECASTING IN SRI LANKA USING STATISTICAL AND DEEP LEARNING MODELS

Ranju Kumari Shiwakoti[1], Piya Limcharoen[2] and D.N.L.S. Uduwage[3]

ABSTRACT

Electricity plays a critical role in energy sustainability. Accurate electricity demand forecasting supports achieving energy sustainability in Sri Lanka by enabling more effective planning and management of both renewable and non-renewable energy sources, which are required to generate the electricity. Thus, this study determines the best statistical and deep learning models for short-term electricity demand forecasting using a 4-year time series dataset, provided by the Ceylon Electricity Board of Sri Lanka (Jan 2020–Mar 2024). Initially, the Linear Regression, Polynomial Regression, and Fast Fourier Transform methods used to develop a baseline model by comparing the error rates of their predictions across different sequence lengths. Subsequently, the study proposes the use of Multilayer Perceptron and Long Short-Term Memory (LSTM) as deep learning methods to develop better predictive models for next-day electricity demand. The prediction accuracy of these two models was assessed using key performance metrics, including Mean Absolute Percentage Error, Mean Absolute Error, and Root Mean Square Error. Finally, the performance metrics of each deep learning model were compared against those of the baseline model. The findings show that the LSTM method is very effective for predicting electricity demand. It works well with the dataset and gives the lowest error values for all performance metrics. The final demand forecasting model contributes to smarter grid development, enhances renewable energy integration, and supports energy sustainability by enabling a more energy-efficient future.

Keywords: *Deep Learning; Demand Forecasting; Electricity; Energy Sustainability; Renewable Energy.*

1. INTRODUCTION

Energy sustainability is one of the Sustainable Development Goals (SDGs) (SDG 7), due to the broad and growing nature of energy use, the numerous environmental impacts associated with energy systems, and the significance of energy in living standards and economic development (Kufeoglu, 2022). Many countries, regions, and cities are

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working toward energy sustainability by reassessing their energy consumption, which at present is below the required threshold (Kufeoglu, 2022). Sustainability consists of environmental, economic, and social dimensions, all of which are closely connected to energy (Kabeyi & Olanrewaju, 2023). This connection makes energy sustainability a crucial part of overall sustainability (Konara & Tokai, 2022). Extracting energy resources from the environment and releasing the energy waste back to the environment (Kabeyi & Olanrewaju, 2023) is one good example of the aforementioned connection. Since energy is essential for most activities, achieving energy sustainability is key to reaching broader sustainability goals.

Electricity, produced from various energy sources such as thermal, nuclear, and renewables, is fundamental to modern life and technology. Figure 1 illustrates seven common sources used for electricity generation. Accurate forecasting of electricity demand is essential for energy sustainability, as it helps estimate future power needs from both renewable and non-renewable sources. Such predictions support efficient system operation, strategic planning, and decisions related to infrastructure, maintenance, and management (Zhang et al., 2018). Furthermore, an accurate electricity forecasting model can assist in various aspects, such as ensuring the efficient operation of daily activities, strategic planning of power systems, and addressing areas like management, maintenance, and infrastructure expansion.

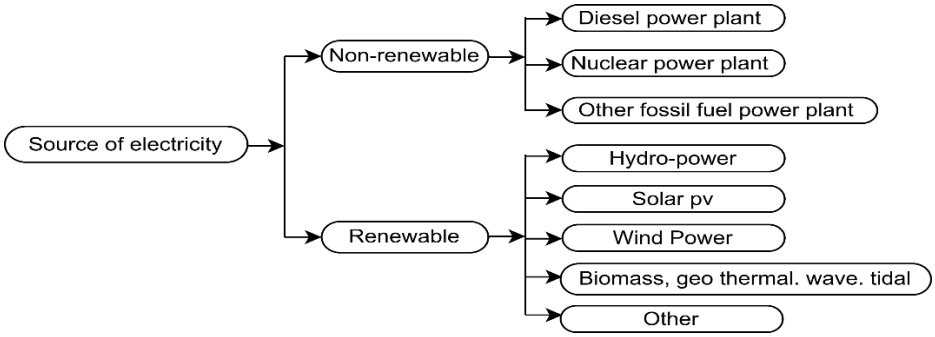


Figure 1: Common energy sources generate electricity

A key goal of electricity forecasting is to ensure an adequate and efficient electricity supply that meets future demand. Electricity forecasting (Also known as "Electricity load forecasting"), which outputs predicted the total electricity demand for the corresponding duration, is classified into short-term (hours to a week), medium-term (weeks to a year), and long-term (over a year) (Somarathne et al., 2022). Short Term Load Forecasting (STLF) aids in electricity distribution and maintenance, handling short-term management and preventing short-term shortages, Mid-Term Load Forecasting (MTLF) supports power planning and market stability, while Long-Term Load Forecasting (LTLF) focuses on long-term infrastructure and technological growth (Shiwakoti et al., 2023). Among the aforementioned three forecasts, SLTF captures the impact of human behaviour on electricity consumption over various time frames, including hourly, daily, weekly, and monthly. Thus, SLTF is crucial in the energy sector, as accurate predictions of future electricity demand are necessary to ensure the reliable and efficient functioning of power systems (Zhang et al., 2018) as well as determine the requirements and help manage the balancing of renewable and non-renewable energy sources, which is part of energy sustainability.

As a developing country, Sri Lanka is no stranger to blackouts and power cuts, with the energy sector struggling for decades due to twin crises: a capacity crisis and a financial crisis. One of the main causes of these blackouts is the decline in rainfall, a recurring issue each year when rainfall is below average. According to the Dailymirror (2022)Sri Lanka experienced its worst power cuts in March and September 2022 due to the country's failure to secure sufficient coal stocks for thermal power generation. However, it was severely impacted by inadequate hydro power generation due to below-average rainfall in 2022 (Dailymirror, 2022). This indicates that having an accurate STLF model to forecast electricity demand at least one day in advance has become crucial for maintaining the supply-demand balance in Sri Lanka. STLF models typically generate point forecasts for future load values, but there is an increasing demand for models that can provide probabilistic forecasts, such as those based on quantile regression (Chen & Ran, 2019). Probabilistic forecasting, unlike deterministic forecasting (point forecasting), acknowledges uncertainty by providing a range of possible outcomes with assigned probabilities, rather than a single point forecast. Two recent studies related to STLF in Sri Lanka have been conducted by Somarathne et al. (2022) and Abeysingha et al. (2021). Both studies used a maximum of 48 data points per day, representing half-hourly electricity demand for forecasting. However, the aforementioned studies did not mention any hyperparameter tuning during the training of their models. The performance of the model is based on the training dataset and its related hyperparameters. As a result, improving data points, selecting the appropriate model, and tuning related model hyperparameters such as input sequence length for predicting the output, network architecture, etc., can significantly enhance the accuracy of STLF.

To address this gap, this study focuses on short-term electricity demand forecasting using a quarter-hourly (15-minutes) recorded demand dataset from Sri Lanka, providing more accurate STLF predictions. The study utilizes an extensive dataset spanning approximately four years (January 1, 2020, to March 31, 2024). As deep learning has shown its capability to capture more complex patterns, the aim of this study is to determine the most effective deep learning model to predict next-day electricity demand by comparing its accuracy with statistical models. Furthermore, this study considers fine-tuning two important hyperparameter, namely, sequence length in order to optimize the model's predictive performance during the training phase.

Below objectives are covered in this study to achieve the aim of this study:

- To analyse and understand electricity demand patterns in the Ceylon Electricity Board (CEB) dataset from 2020 to 2024.
- To identify key temporal trends and factors influencing energy demand for improved forecasting accuracy.
- To evaluate and compare the predictive performance of different modelling approaches in order to determine the most effective model for future energy demand forecasting.

2. LITERATURE REVIEW

Statistical STLF models use past data like electricity load, weather, and calendar information. Statistical approaches encompass a variety of regression models, including linear regression, multiple regression, stepwise regression, logistic regression, and polynomial regression (Sudan, 2024). Additionally, methods such as Moving Average

(MA), Autoregressive Moving Average (ARMA), Autoregressive Integrated Moving Average (ARIMA), Autoregressive Integrative Moving Average Exogenous (ARIMAX), and Seasonal Autoregressive Integrated Moving Average (SARIMA) are well-known in the field of statistical prediction (Yadav, 2024). The models based on the aforementioned methods work well for patterns with statistical cycles in predictions, but they are less accurate for real-time load forecasting that includes non-cyclical data with dynamic fluctuations. They also struggle to handle the complex and non-linear nature of load consumption (Zuo et al., 2023). To address the limitations of statistical models in capturing the non-linear and complex patterns in electricity consumption, Artificial Intelligence (AI) techniques have been introduced. These AI techniques include Machine Learning (ML) and Deep Learning (DL) methods, which improve the accuracy of short-term electricity demand forecasting.

DL is a subset of ML that emerged to address more complex patterns in input data. Deep Neural Networks (DNNs) is a method in DL. It is based on artificial neural networks (ANNs), particularly a type known as Feedforward Neural Networks (FNNs), which process information in a unidirectional flow without any feedback loops. DNNs are neural network architectures that consist of multiple layers of ANNs. Multilayer Perceptron (MLP) is one of the simplest DL models, built on the structure of FNN using Backpropagation to learn patterns through hidden layers. Another important type of DNN is the Recurrent Neural Network (RNN), which processes information using feedback loops, allowing the network to retain information from previous inputs. This makes RNNs particularly well-suited for capturing patterns in sequential data. RNN-based architectures are commonly applied in tasks such as text processing, speech recognition, and video analysis. Variants like standard RNNs, Long Short-Term Memory networks (LSTMs), and Gated Recurrent Units (GRUs) have been developed to capture patterns better. LSTM, introduced by Hochreiter and Schmidhuber (1997) was designed to address limitations in RNNs, such as forgetting past data and the issues of vanishing and exploding gradients. GRUs were later developed as a simpler alternative to LSTMs, with fewer parameters but comparable performance (Rivas et al., 2025). LSTM makes it uniquely powerful for sequential data (Malashin et al., 2024), outperforming DNNs (no memory), RNNs (short-term memory), and even GRUs (less precise control).

Both statistical and deep learning models can be effective for learning patterns in time-based data, such as electricity demand. Another aspect of the SLTF models is high dependency on the calendar parameters such as year, month, day of the week, and hour, along with seasonal factors like holidays and special days. These are classified as deterministic variables. Weekday demand is generally higher and more stable due to industrial activities, while weekends and holidays experience lower consumption. To account for these variations, dummy variables are assigned to differentiate between weekdays, weekends, and holidays in predictive models (Ramanathan et al., 1997). In addition to the aforementioned areas, SLTF models can be further fine-tuned using the hyperparameters. A hyperparameter is a parameter whose value is set before the learning process begins, and these values influence the learning process itself (Abeysingha et al., 2021). A hyperparameter can be a sequence length, number of layers, etc., which directly influences the speed and performance of the learning process when training SLTF models.

3. RESEARCH METHODOLOGY

This section provides a visualization of the electricity demand dataset, outlines the methods used to develop the forecast models, and provides a detailed explanation of the proposed electricity demand forecasting model.

3.1 ELECTRICITY DEMAND DATASET

The dataset, sourced from the CEB, contains electricity demand records spanning four years and three months, from January 1, 2020, to March 31, 2024. Figure 2 shows the overall electricity demand profile over four years and three months, illustrating the use of a 365-day rolling moving average to smooth annual trends. The blue line represents the actual recorded energy demand. The data is plotted every 15 minutes (a total of 96 data points per day), representing fluctuations throughout the day. The green line, representing the day-mean, an average of the 96 daily values, highlights seasonal (daily) trends by minimizing short-term day-to-day variations.

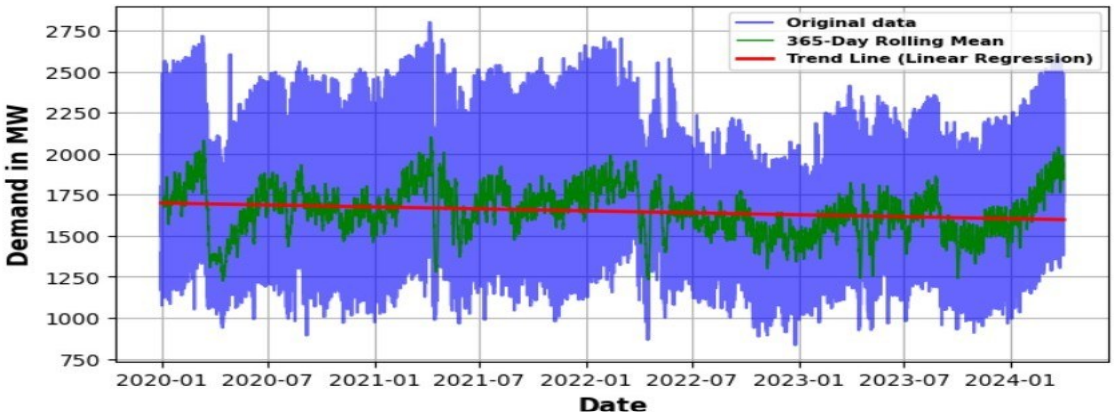


Figure 2: Four years and three months overall demand profile

The red line illustrates the linear regression trend, based on daily mean indicating the overall direction of energy demand over the 4 years period. Notably, from July 2022 to January 2024, a declining trend of demand is observed, primarily due to prolonged power cuts and political instability in Sri Lanka. During this period, the country faced an economic crisis, fuel shortages, and disruptions in electricity generation, all of which contributed to reduce energy consumption.

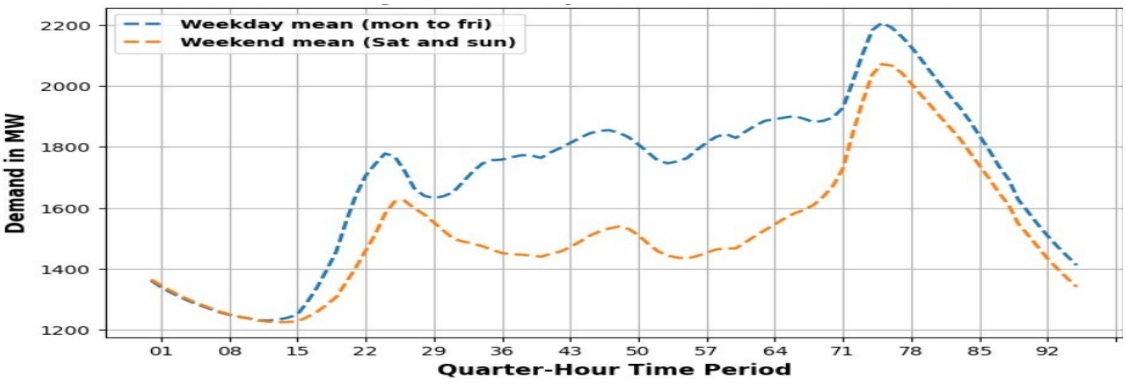


Figure 3: Average demand profile for weekday and weekend patterns

On weekends, residential electricity demand exhibits unpredictable fluctuations due to varying human activities, posing challenges for accurate forecasting. In contrast, weekdays demonstrate more stable demand patterns, particularly during midday and evening hours. Despite these variations, electricity consumption during late-night and early-morning hours remains relatively consistent across both weekdays and weekends, as illustrated in Figure 3. The details in Figure 3 infer the demand fluctuations, peak usage periods, and potential differences in energy consumption trends between regular working days and weekends.

3.2 MODELS

This subsection outlines the methods employed in the study to develop an effective deep learning framework for predicting next-day electricity demand. It begins with a brief overview of three statistical methods, followed by detailed descriptions of two selected deep learning methods, including an explanation of their underlying operating principles. The statistical methods, includes Linear regression, Polynomial regression, and Fast Fourier Transform. These methods help in analysing the trends and seasonality in the electricity demand data. The deep learning methods includes Multilayer Perceptron and Long Short-Term Memory which are known for their ability to capture complex patterns and long-term dependencies in time-series data, making them highly effective for accurate forecasting.

3.2.1 Fast Fourier Transform (FFT)

In frequency analysis, the FFT is employed to identify common frequency components between two time series. As an optimized form of the discrete Fourier transform, FFT detects periodic patterns and their relative strengths within the data. It decomposes input signals into smaller frequency components, making it easier to recognize similarities in the frequency domain. The Fourier transform, a mathematical approach, converts time-domain signals into their frequency-domain equivalents, representing complex signals as a sum of simpler harmonic frequencies (Yemets et al., 2025).

3.2.2 Linear Regression (LR)

Regression analysis is a key statistical method for understanding the relationship between a dependent variable and independent variables. Widely used across scientific fields, it is especially valuable in business and economics for identifying causal links. This method involves modelling relationships and estimating parameters to develop a predictive equation. Simple linear regression focuses on how one independent variable influences a dependent variable, aiding in trend analysis and prediction (Patil & Patil, 2021). The formula for linear regression is as follows (see *Equation 1*),

$y=\beta_0 + \beta_1 x + \varepsilon$ *(Equation 1)*

3.2.3 Polynomial Regression (PR)

Polynomial regression is a form of regression analysis that uses an nth degree polynomial to model the relationship between dependent and independent variables. It is a specific variation of Multiple Linear Regression (MLR) where the polynomial equation captures the curved interactions between these variables (Patil & Patil, 2021). The number of degrees represents the curve's flexibility. It is useful when the data has a non-linear relationship but can be approximated by polynomial function. The model of polynomial is given below (see *Equation 2*):

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \cdots + \beta_h x^h + \varepsilon \qquad \textit{(Equation 2)}$$

3.2.4 Multilayer Perceptron (MLP)

A multilayer perceptron represents a type of artificial neural network that incorporates several layers of interconnected units, often referred to as perceptron or neurons. Commonly utilized in supervised learning scenarios, such as classification and regression tasks, an MLP is visually depicted in Figure 4 and is composed of the following key components.

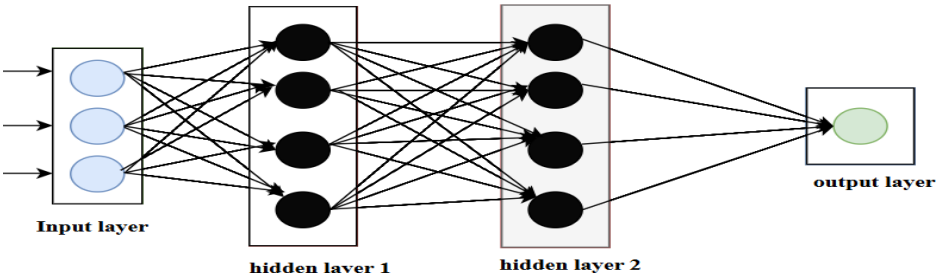


Figure 4: Multilayer perception model

The input layer receives the data, with each node representing a feature of input. Hidden layers process the data through neurons that learn complex patterns, and the number of layers and neurons influences the model's learning capacity. The output layer generates predictions based on the problem, with the number of nodes matching the output categories. Neurons process inputs using an activation function (see Equation 3) that can introduce non-linearity. Weights and biases control the strength of neuron connections and adjust during training to minimize prediction errors (Sakhtiyani et al., 2022). The model is trained through backpropagation, adjusting weights and biases iteratively to reduce the loss function, which measures performance.

$$a_j = f\left(\sum\left(w_{ij} * x_i\right) + b_j\right) \qquad \textit{(Equation 3)}$$

3.2.5 Long Short-Term Memory (LSTM)

The Long Short-Term Memory network is a widely used deep neural network that features specialized components known as memory blocks within its recurrent hidden layer. Each memory block is equipped with an input gate, which regulates the flow of input activations into the memory cell, and an output gate, which manages the flow of cell activations to the rest of the network (Shiwakoti et al., 2024). LSTM networks map an input sequence (x_1,x_2……x_n) and output sequence (y_1,y_2,……$y_{n)}$.

3.3 HYPERPARAMETERS

This study focuses on selecting the best model and corresponding hyperparameters for predicting next-day power consumption. A suitable model is one that accurately captures data patterns, avoids both overfitting and underfitting, and keeps the model structure simple and efficient. The sequence length refers to the number of previous days used as input to the model in order to predict the next day's electricity consumption. It is a key hyperparameter in this study because selecting the right sequence length is important for capturing patterns, seasonal trends, and variations in the data. If the sequence length is too short, the model may miss important long-term dependencies, reducing prediction accuracy. On the other hand, if it is too long, it can introduce noise and increase model

complexity. Therefore, optimizing sequence length helps the model effectively learn time-based patterns, which improves both accuracy and efficiency.

3.4 PROPOSED MODEL

The proposed workflow, illustrated in Figure 5, includes five key stages: (1) data preprocessing (handling outliers, separating training and testing data, and constructing a normalization model from the training set), (2) preparing sequences based on varying sequence lengths, (3) model training, (4) renormalising the predicted results, and (5) performance evaluation. Data preprocessing is essential for building an accurate forecasting model. It includes handling outliers and missing values using forward-filling, splitting data into training and testing sets, and applying min-max normalization based on the training data. Normalization is later reversed for interpretation. These steps ensure data consistency, fair evaluation, and improved model accuracy.

The original 15-minute interval electricity demand data are aggregated into daily electricity demand. The training set includes data from January 1, 2020, to December 31, 2022, while the testing set comprises data from January 1, 2023, to March 31, 2024. To prepare the sequences for training and testing, a sliding window process with a window size equal to the sequence length was applied to the data for each model. The forecasting models for experiments include both statistical models (LR, PR with degree 2 (PR2), degree 6 (PR6), and FFT) and deep learning models (MLP and LSTM). These models are trained using the pre-processed dataset. During training, each method follows a separate learning process to adjust internal parameters and improve predictive accuracy. The optimal sequence length hyperparameter is determined by evaluating multiple models across different sequence lengths for each forecasting approach. Once the internal parameters of each model have been optimized, the models are evaluated using the test dataset. Denormalization is applied to convert the predicted values back to their original scale. Each model is evaluated using Mean Absolute Percentage Error (MAPE), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) to assess forecasting accuracy. MAPE shows relative error in percentages, MAE captures average error, and RMSE highlights larger deviations. The model with the lowest values across these metrics is deemed best for future electricity demand forecasting.

This paragraph outlines the hyperparameters used for each model. For Linear Regression (LR) and Polynomial Regression (PR), separate models are built using a fixed number of previous days (sequence length) to predict next-day power consumption. LR has no additional hyperparameters beyond sequence length, while PR treats the polynomial degree as a key hyperparameter, using degrees 2 and 6 in the experiments. The FFT was applied to extract frequency-domain features from the time series. In the experiments, separate FFT coefficients were extracted and used for each next-day prediction. The coefficients were computed using only data within the sequence length. Apart from the sequence length, no additional hyperparameters were involved in the FFT process.

The proposed DL models, both MLP and LSTM, use simple architectures to minimize complexity and reduce overfitting risk. The MLP consists of three fully connected dense layers (32, 16, and 1 units) with Tanh, ReLU, and Linear activations. The LSTM model includes one LSTM layer (32 units) followed by two fully connected dense layers (16 and 1 units) using Tanh, ReLU, and Linear activations. Tanh is used for its effective non-linear transformation. From the training data, 10% was allocated for validation and 90% for model training. The model was trained using a batch size of 32, the Adam optimizer,

and MSE as the loss function. Early stopping with a patience of 50 epochs was used to restore the best weights based on validation loss, allowing the number of training epochs to adjust dynamically for optimal performance.

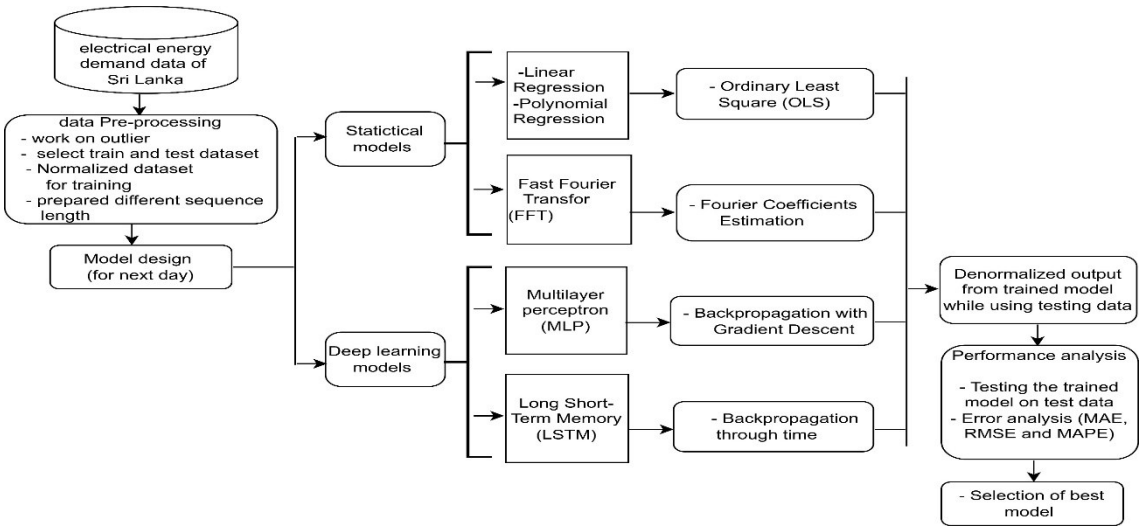


Figure 5: Proposed model for electrical demand forecasting

4. RESULTS AND DISCUSSIONS

This section presents and analyses the results of the study. Statistical and DL models were evaluated using sequence lengths based on weekly intervals. The complete set of sequence lengths is shown in Figure 6. Key lengths such as 7, 14, 21, and 28 days, along with monthly intervals, are detailed in Tables 1 to 3, presenting MAPE, MAE, and RMSE.

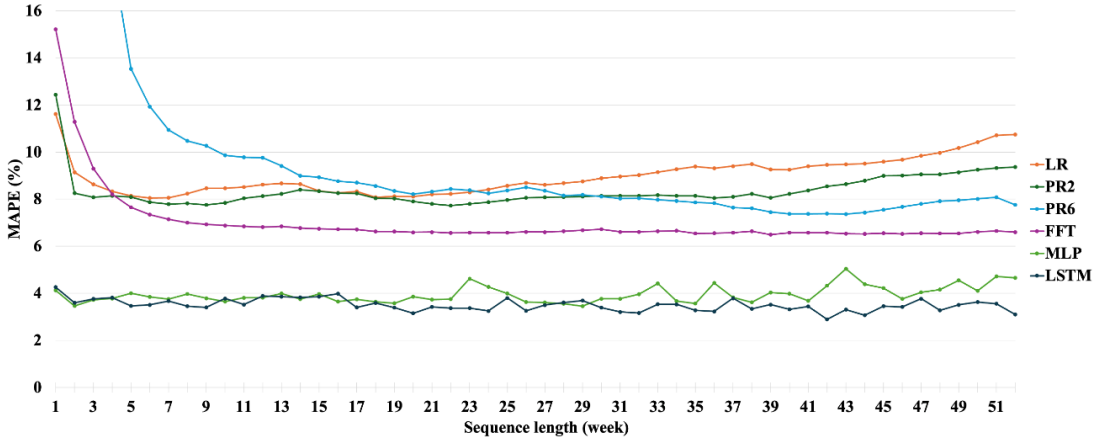


Figure 6: Demand prediction MAPE results for various sequence lengths (weekly)

The lowest error for each sequence length is highlighted in bold. Sequence length plays a significant role in forecasting accuracy. While longer sequences capture more temporal patterns, overly long ones may introduce noise and reduce model performance.

Table 1: Mean Absolute Percentage Error (MAPE) results of the models using different sequence lengths (days)

Models	7	14	21	28	56	84	112	140	168	196	224	252	280	308	336	364
LR	11.61	9.14	8.63	8.33	8.23	8.62	8.26	8.11	8.41	8.68	9.02	9.31	9.25	9.51	9.97	10.74
PR2	12.43	8.25	8.08	8.14	7.82	8.13	8.25	7.9	7.87	8.09	8.14	8.05	8.22	8.78	9.05	9.36
PR6	199.24	32.08	27.17	18.41	10.47	9.76	8.76	8.21	8.24	8.15	8.04	7.83	7.37	7.43	7.91	7.76
FFT	15.21	11.28	9.29	8.2	7	6.81	6.72	6.59	6.57	6.64	6.61	6.55	6.57	6.52	6.54	6.6
MLP	4.13	3.46	3.72	3.78	3.97	3.82	3.65	3.86	4.27	3.56	3.96	4.44	3.98	4.39	4.16	4.66
LSTM	4.26	3.6	3.76	3.82	**3.45**	3.89	3.98	**3.15**	**3.25**	**3.61**	**3.16**	**3.23**	**3.32**	**3.07**	**3.28**	**3.1**

Table 2: Mean Absolute Error (MAE) results of the models using different sequence lengths (days)

Models	7	14	21	28	56	84	112	140	168	196	224	252	280	308	336	364
LR	180.36	140.58	132.11	127.57	126.38	132.65	127.8	127.42	132.78	138.79	144.69	149.79	153.11	162.38	174.26	193.45
PR2	200.56	127.9	124.63	125.13	119.89	124.8	127.22	122.65	122	126.15	126.48	126.1	133	146.49	154.96	165.35
PR6	3257.73	522.39	434.71	297.26	165.22	152.28	135.47	127.41	127.78	125.9	123.94	120.44	114.19	118.26	128.72	131.51
FFT	254.07	188.97	155.61	136.84	114.32	109.53	107.09	105.1	104.27	105.43	104.26	102.84	104.3	105.72	108.16	111.51
MLP	63.5	52.29	57.25	59.17	61.32	58.78	55.91	60.75	67.94	56.16	62.56	69.23	62.63	71.18	68.22	78
LSTM	64.74	55.44	58.27	59.88	**52.78**	59.97	60.63	**48.73**	**50.47**	**56.45**	**49.23**	**51.18**	**53.8**	**49.78**	**53.36**	**51.48**

Table 3: Root Mean Square Error (RMSE) results of the models using different sequence lengths (days)

Models	7	14	21	28	56	84	112	140	168	196	224	252	280	308	336	364
LR	210.32	168.7	163.06	157.66	154.1	158.34	153.8	150.3	156.29	164.09	174.08	181.75	183.46	188.64	199.35	218.85
PR2	247.61	160.02	154.99	158.29	149.77	155.65	154.03	147.7	145.94	148.92	151.93	149.23	148.89	160.12	167.93	179.24
PR6	4224.31	676.93	523.08	364.82	206.67	187.95	166.78	154.65	155.03	156.96	157.16	154.53	150.78	151.89	156.6	151.8
FFT	280.09	216.06	185.43	169.08	147.78	143.81	142.72	140.49	140.09	141.87	141.02	140	141.84	143.02	145.93	149.68
MLP	95.35	84.31	87.91	86.32	86.98	89.01	83.79	84.35	92.61	82.22	84	92.79	86.83	93.31	88.17	100.57
LSTM	96.51	85.62	88.8	88.86	**84.31**	89.75	88.87	**78.38**	**79.8**	**81.96**	**75.83**	**76.17**	**76.48**	**74.95**	**82.99**	**77.29**

According to the results across all metrics, Sri Lanka's relatively stable climatic conditions, typical of a tropical country, cause little seasonal change in electricity demand, which improves forecasting accuracy. As shown in Figure 6, after using a sequence length of 14 days (two-week cycle), most forecasting models perform steadily up to 52 weeks. This suggests that weekly past data is effective for next-day demand prediction, helping with better energy planning and management in Sri Lanka.

In addition to determining the optimal sequence length, this study compared deep learning models with baseline statistical approaches. As shown in Figure 6, deep learning models outperformed statistical models by better capturing complex demand patterns. While the best statistical model (FFT) achieved a MAPE of 6.49%, the least accurate deep learning model (MLP) performed better, with a MAPE of 5.04%, highlighting the advantage of deep learning in forecasting accuracy. While FFT had the lowest error among statistical models, LSTM achieved the best overall accuracy with a MAPE of 2.89% at a 294-day sequence length. Statistical models offer simplicity and interpretability, but they fall short in accuracy. The proposed deep learning models, despite their simple architectures, significantly outperformed traditional statistical approaches.

4.1 STATISTICAL MODEL

In Figure 6, the suitable sequence length for statistical models is around 139 days (20 weeks). This means that the model learning from 20 weekly cycles provides the best results for statistical forecasting models. Interestingly, FFT provides the best performance among statistical models. FFT achieves a MAPE of 6.49% at a sequence length of 273 days (39 weeks). PR improves upon LR by capturing some non-linear trends using PR2 and PR6, but it still struggles with complex seasonal patterns. In contrast, FFT effectively captures recurring demand cycles, making it the most accurate of the four. As illustrated in Figure 7, the blue line shows actual demand, while the red line shows FFT predictions from January 2023 to March 2024.

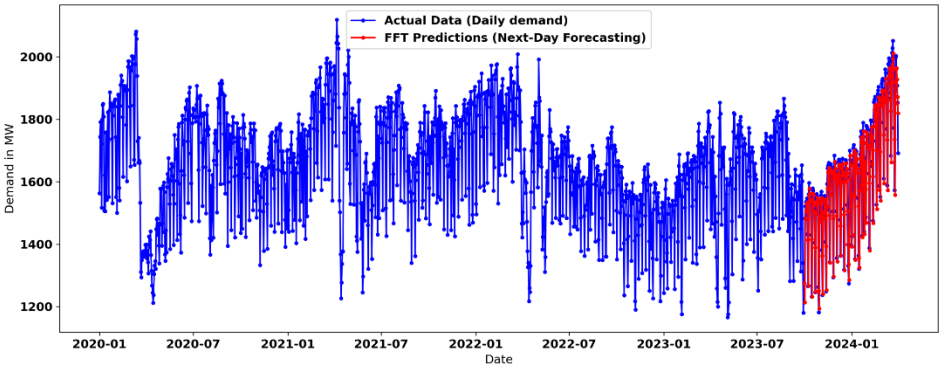


Figure 7: Demand prediction using FFT: using previous 273 days (39 weeks)

4.2 DEEP LEARNING MODELS

The results indicate that deep learning models significantly outperform statistical ones by capturing demand patterns more effectively. As shown in Figure 6, these models begin identifying patterns with just 14 days of input. This trend is also reflected across all error metrics in Tables 1 to 3, where deep learning models have more stable MAPE values. While LR and PR face difficulties with longer sequences, MLP performs more effectively with shorter sequences, especially those less than 140 days (20 weeks). However, LSTM excels with longer sequences, demonstrating a stronger ability to learn complex patterns compared to MLP.

The results reveal that LSTM achieves superior performance due to its ability to capture long-term dependencies and sequential patterns, making it better suited for modelling forecasting model. The LSTM model's performance significantly improved with sequence length extended, reaching optimal results at a sequence length of 294 days (42 weeks). Under these conditions, the LSTM achieved a MAPE of 2.89%. Figure 8 displays the prediction results, where the blue line represents actual demand data, and the red line shows LSTM model predictions from January 2023 to March 2024 (the testing data duration).

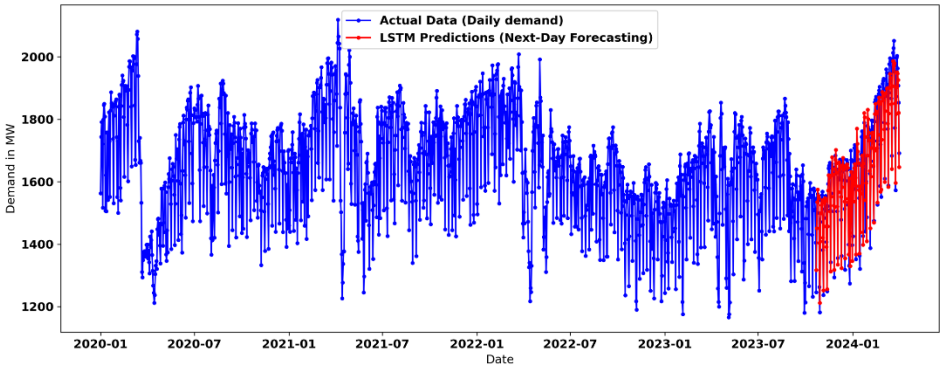


Figure 8: Demand prediction using LSTM: using previous 294 days (42 weeks)

5. CONCLUSIONS

Electricity is a form of energy generated by the flow of electric charge, used to power various devices and systems. As a key energy carrier, it plays a critical role in energy sustainability by ensuring that energy production and consumption support sustainable development throughout their lifecycle. This involves maintaining a secure and equitable energy future for both current and future generations, without compromising environmental or societal well-being. To advance energy sustainability in Sri Lanka, this study develops a STLF model using a quarter-hourly (15-minute) electricity demand dataset obtained from the CEB. The model aims to accurately predict day-ahead electricity demand across Sri Lanka.

Initially, this study examines statistical models (LR, PR, and FFT) alongside deep learning models (MLP and LSTM) for short-term load forecasting. Using 4 years and 3 months of demand data from the CEB, each model was trained with different sequence lengths to forecast day-ahead electricity demand from January 2023 to March 2024. Among the statistical methods, FFT delivered the best performance with a MAPE of 6.49%. However, deep learning models, particularly LSTM, significantly outperformed these techniques, achieving an impressive MAPE of just 2.89%. The results of this study show that the LSTM outperformed the baseline model, FFT, providing the most accurate short-term load forecasts. This indicates that the LSTM model is highly effective for electricity demand forecasting, especially for next-day predictions, even with simple model design of one LSTM layer (32 units) followed by two fully connected layers (16 and 1 units) using Tanh, ReLU, and Linear activations. The developed model can support Sri Lanka in optimizing renewable energy use, lowering operational costs, and maintaining grid stability. Accurate demand forecasting enhances energy management and long-term sustainability. However, the study is limited by not including weather-related variables, which could improve prediction accuracy and are suggested for future work.

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STRATEGIC APPROACH FOR OVERCOMING BARRIERS TO SUSTAINABLE ENTERPRENUERSHIP IN SRI LANKAN CONSTRUCTION INDUSTRY

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ABSTRACT

Entrepreneurs in the modern construction industry have adopted sustainable entrepreneurship instead of conventional entrepreneurship due to a high concern for sustainability in the world economy. However, entrepreneurs in Sri Lankan construction industry have not adequate awareness on sustainable entrepreneurship, and they are only applying sustainable practices to their construction projects. Sustainable entrepreneurship is a more complex concept than mere application of sustainable practices to their projects. For establishing effective sustainable entrepreneurship, it is required to identify the drivers and barriers and overcome these barriers. Thus, this study aims to propose suitable strategies to overcome barriers for sustainable entrepreneurship in the Sri Lankan construction industry. To obtain relevant data, semi-structured interviews were performed with entrepreneurs in construction enterprises in Sri Lanka, and data analysis was performed using manual content analysis. Findings revealed that government support, organizational culture, stakeholder influence, financial incentives, technology are the key drivers for sustainable entrepreneurship. In contrast, lack of financial resources, low market demand, lack of stakeholder support, and inadequate organizational structures, lack of technological innovations were emphasised, poor regulatory backing as barriers for sustainable entrepreneurship. To effectively implement sustainable entrepreneurship in the Sri Lankan construction industry, 13 strategies were introduced to avoid barriers and enhance drivers.

Keywords: *Construction industry; Sustainability; Sustainable Entrepreneurship.*

1. INTRODUCTION

Sustainability is a significant topic in every economy, and the markets are producing sustainable products while achieving principles of sustainability. Both commercial and business sectors have been much concerned about sustainability when performing their business activities (Konys, 2019). Furthermore, businesses have been introducing innovations related to products, services and processes while complying sustainable features (de Medeiros et al., 2014). Ultimately, it is caused to change the customer's

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mindset to purchase and consume sustainable products and services (Hojnik et al., 2019). As a result of that, entrepreneurs also tend to focus on integrating sustainability with their entrepreneurship (Vuorio et al., 2018). Entrepreneurs perform various functions such as innovations, risk management, organizational management, resource organizing, decision making, leadership, social and economic development (Kozubíková et al., 2017). Due to the high demand, sustainable development also became one of major functions in entrepreneurship (Saleh & Alalouch, 2015). Latterly, entrepreneurship is developed based on sustainability functions and has resulted in the creation of sustainable entrepreneurship around the world (Ahmed & Wahab, 2018).

Sustainable entrepreneurship (SE) can be considered as a new concept in business environment that builds a relationship between sustainable development and business practices while balancing goals of sustainable pillars (Sargani et al., 2020). It is focused on all economic, environmental and social goals and balanced all three dimensions of "Triple Bottom-Line (TBL)"(Arowoshegbe & Emmanuel, 2016). TBL concept is totally aligned with the purpose of sustainable entrepreneurship as it focuses more on the environment and social dimensions than conventional accounting measures, which focus on only economic dimensions (Tarnanidis et al., 2016). In the modern era, most of the industries in the world economy have been trended to achieve TBL while establishing sustainable entrepreneurship (Sargani et al., 2020). Construction industry can also be considered a major industry that promotes sustainable entrepreneurship by balancing economic, environmental and social dimensions (Rosalinde & Woolthuis, 2010).

According to Masroori and Momayez (2014), typical construction has been adapted to the conventional entrepreneurship when perform their business activities. Conventional entrepreneurship is only concerned with economic goals such as profit and return on investments. Entrepreneurs in the modern construction industry are establishing sustainable practices throughout the business life cycle (Konys, 2019). There are a number of drivers that lead to initiate sustainable entrepreneurship in construction industry. It can be related to three main categories, such as intrinsic rewards, extrinsic rewards and personality traits towards sustainable practices (Vuorio et al., 2018). On the other hand, there are a number of challenges faced when implementing sustainable entrepreneurship in the construction industry, such as institutional influences, financial obstacles, team compositions, policy interactions, technical interventions and market failures, etc (Butkouskaya et al., 2020; Roblek et al., 2018).

In Sri Lanka, SE is still not adapted well in a proper manner because entrepreneurs are more focused only on corporate social responsibility (Rizvi & Somachandra, 2019). Furthermore, entrepreneurs in Sri Lankan construction industry do not have adequate awareness of sustainable entrepreneurship and they are only applying sustainable practices to their construction projects (Athapaththu & Karunasena, 2018). However, compared to regular entrepreneurs, sustainable entrepreneurship is a more complex concept than mere application of sustainable practices to their projects (Hoogendoorn et al., 2019). Furthermore, understanding the barriers and drivers is crucial for policymakers and industry stakeholders to promote sustainable construction effectively (de Oliveira & de Melo, 2024). It is evident that a key reason for the lack of understanding of sustainable entrepreneurship among entrepreneurs in the Sri Lankan construction industry. W.D.I.V. Somachandra et al. (2021) stated that, due to lack of awareness, misconceptions and legal obligations, implementing 'Corporate Social Responsibility' in sustainable construction is often limited. Also, recent studies indicate a need for increased awareness and

innovative approaches to overcome barriers in sustainable entrepreneurship (Perera & Abeysekera, 2021; V. Somachandra et al., 2024). Therefore, this study focus on proposing suitable strategies to overcome barriers for sustainable entrepreneurship in the Sri Lankan construction industry.

2. LITERATURE REVIEW

Entrepreneurship has been defined by Hisrich and Peters (2005) spending the time and energy necessary, taking the corresponding financial, spiritual, and social risks, and capable of generating financial value and personal satisfaction and independence. According to Hafer (2013), entrepreneurs are business leaders who seek ideas and put them into practice to promote economic growth and development. Drucker (2014) stated that innovation is a crucial tool that should be consistently practised by entrepreneurs. The growing awareness of social and environmental issues has led to the emergence of SE, a unique entrepreneurial spirit that integrates social, environmental, and economic aspects (Parrish, 2010). Belz and Binder (2017) highlighted that, SE focuses on generating economic, social, and environmental value through business activities, unlike traditional entrepreneurship which primarily focuses on profit-driven activities.

2.1 APPLICABILITY OF SUSTAINABLE ENTREPRENEURSHIP IN CONSTRUCTION INDUSTRY

Sustainability remains vital to the construction industry because its final destination is to seek a joined-up and continuing equilibrium amid the economics, communal also ecological features of mortal activities (Uğural et al., 2020). Currently, building production focuses on maximizing energy use, area design, disposal processes, and selecting suitable materials. This includes addressing ecological issues in construction areas, while also ensuring the construction program is environmentally friendly (Mir-Babayev et al., 2017). Building with renewable and recyclable resources offers economic benefits, ecological duty, and communal consciousness to the newly built surroundings and amenities, benefiting the larger society (Christini et al., 2004) . Entrepreneurship in the construction industry contains various forms, including starting a new business, developing innovative building methods or materials, and identifying new markets (Jain, 2023). Construction entrepreneurs employ various tactics to advance green architecture and overcome resource constraints (Johnsen, 2023). The investment in sustainable construction has a direct relationship with structure price, output, and ecological benefits, but there is no direct connection between asset amount and nesting point (Dobson et al., 2013).

2.2 DRIVERS OF SUSTAINABLE ENTREPRENEURSHIP IN CONSTRUCTION INDUSTRY

Majid et al. (2012) have emphasized categorizations of the drivers, influencing Sustainable Entrepreneurship in the construction industry, including internal and external factors, public and private aspects, and proactive and reactive approaches. Table 01 indicates 15 drivers for Sustainable Entrepreneurship in construction industry.

Table 1:Drivers for sustainable entrepreneurship in construction industry

Drivers	Sources
Government support & incentives	(Ginsberg & Bloom, 2004)
Organization culture	(Tello & Yoon, 2008)
Community Surrounding	(Yadav et al., 2018)
Long term profit	(Matisoff et al., 2016)
Ability to funding	(Schlange, 2007)
Brand image and reputation	(Raja Mohd Rasi et al., 2010)
Stakeholder Influence	(Worthington & Patton, 2005)
Social and environmental awareness	(Kassim & Abdullah, 2008)
Level of internal bureaucracy	
Environmental Management Capability (EMC)	
Consumer satisfaction and demand	
Competitive advantage and strategic intent	
External support	
Technological advance	
Access to new markets	

2.3 BARRIERS OF SUSTAINABLE ENTREPRENEURSHIP OF IN CONSTRUCTION INDUSTRY

Although many of the developed and developing countries have gained benefits through the SE in the construction industry, most of the countries are experiencing a number of barriers. Table 02 indicates seventeen barriers identified towards Sustainable Entrepreneurship by researchers.

Table 2: Barriers for sustainable entrepreneurship in construction industry

Barriers	Sources
Lack of financial resources	(Costache et al., 2021)
Limited resources	(Álvarez Jaramillo et al., 2019)
High initial cost	(Stewart et al., 2003)
Lack of expertise	(Dawo et al., 2023)
Lack of awareness	(Cassells & Lewis, 2011)
Legislation and regulation	(Auer & Jarmai, 2017)
Lack of market demand	
Resistance to change	
Lack of time for training	
Limited external stakeholder support	
Lack of competences	
Additional time consumption	
Lack of customer demand	

Barriers	Sources
Short of help and supervision from regulatory system	
Weak organizational structure	
Lack of technological advancement	

2.4 STRATEGIES TO OVERCOME BARRIERS IN SUSTAINABLE ENTREPRENEURSHIP IN CONSTRUCTION INDUSTRY

Sustainable construction offers a fresh perspective on ecological and communal conditions, creating employment opportunities and reducing communal differences, while also improving population welfare (Hwang et al., 2017). Different strategies have been used to overcome the barriers in SE in the construction sector. Estimating normal resources is crucial for ecological financial systems, government decision-making, and investment redistribution (Stjepanović et al., 2017). Also, safety management capabilities help businesses identify and manage challenges, increasing the likelihood of achieving growth and objectives (Caliendo et al., 2015). Entrepreneurs' learning abilities can help overcome challenges in sustainable entrepreneurship through knowledge acquisition and experience summary, promoting long-term growth (Lis & Sudolska, 2015).

3. METHODOLOGY

The qualitative research approach is mostly used to answer research questions that start from "how" and "why"(Creswell, 2013). Considering the research question “how can be overcome barriers in SE construction industry by proposing suitable strategies”, this research was adopted the qualitative research approach. A comprehensive literature review was focused on the applicability of SE in the construction industry, drivers and barriers for SE in construction industry and current strategies used to overcome the barriers. Under qualitative approach, primary data collection was executed using semi structured interviews as a most sensible data collection technique for this study. In line with prior qualitative research, a total of 10 expert interviews were conducted, as theoretical saturation was reached at this point, with no new insights emerging beyond the tenth participant (Andarz et al., 2025). Interview participants were selected using purposive sampling by targeting entrepreneurs and senior professionals actively involved in sustainable construction projects in the Sri Lankan construction industry. A selection criterion included a minimum of 5 years’ experience in the construction industry, involvement in at least one project that incorporated sustainable or environmentally responsible construction practices and willingness to participate for an 30-45 minutes interview and share insights based on practical experience. Screening procedures involved an initial review of participants’ professional profiles on LinkedIn, project portfolios to ensure they met the selection criteria. Preliminary phone and email contact was made to confirm their eligibility and consent for participation. Table 3 indicates the details of participants selected for the interviews.

Table 3: Details of participants

Interviewee code	Designation	Experience (yrs.)	Sample questions asked
R-01	Director	5	How would you assess the current state of SE within the Sri Lankan construction industry? To what extent do global drivers for SE in construction apply to the Sri Lankan context? What are the key barriers to implementing SE in the Sri Lankan construction industry? In your opinion, how applicable are existing strategies for establishing SE to the Sri Lankan construction industry? Are there any additional strategies you would propose to promote SE within the Sri Lankan construction industry?
R-02	Owner	5	
R-03	Owner	7	
R-04	Director	10	
R-05	Managing Director	5	
R-06	Owner	5	
R-07	Owner	10	
R-08	Director	10	
R-09	Director	6	
R-10	Owner	7	

To investigate the collected data, manual content analysis was followed. The interview data, initially captured via audio recordings, were carefully transcribed. Subsequently, a deductive coding approach was employed. Pre-established themes derived from the literature review served as the foundational categories for organizing the qualitative data. Drivers were systematically categorized into distinct themes such as Government, Cultural, Financial, Managerial, External Support, Technological, and other drivers. Barriers were identified in the literature against interviewee and insights were identified as novel barriers. Finally, the proposed strategies were synthesized from the practical experiences and insights shared by the interviewees, and the literature findings ensuring their relevance and applicability.

4. DATA ANALYSIS AND RESEARCH FINDINGS

The data analysis for this study was executed under three main broader areas including the applicability of SE in Sri Lankan construction industry, drivers and barriers for SE in construction industry, and appropriate strategies for the effective implementation of SE in Sri Lankan construction industry.

4.1 APPLICABILITY OF SUSTAINABLE ENTREPRENEURSHIP WITHIN SRI LANKAN CONSTRUCTION INDUSTRY

The participants of semi-structured interviews validated that sustainable entrepreneurship as business that managed their all-internal organizational processes by promoting sustainability to achieve vision and mission that aligned with sustainability. However, R-03 highlighted, *"sustainable entrepreneurship was not limited to applying sustainable practices to internal organizational processes, because it should be extended to organizational performance also"*. Also, participants stated that, sustainable entrepreneurship covers all the functions from the initiation stage and leads to create sustainable outcomes. However, none of the participants were satisfied with the current status of SE within the Sri Lankan construction industry. All participants mentioned

"sustainable entrepreneurship is not effectively applied within Sri Lankan construction industry". Majority of interviewees highlighted *"most of construction entrepreneurs concerned to implement sustainable practices within their construction projects but they did not apply sustainable practices within their business operations that are performing in internal organizational environment".* , R-09 and R-10 highlighted, *"Organization's mission& vision also should be aligned with the concept of sustainability when adapting sustainable entrepreneurship and it was not still practiced within Sri Lankan construction industry.*

4.2 DRIVERS FOR SUSTAINABLE ENTREPRENEURSHIP WITHIN SRI LANKAN CONSTRUCTION INDUSTRY

Drivers have been analysed under several pre-defined categories named; governmental drivers, cultural drivers, financial drivers, managerial drivers, external support drivers, technological drivers and other drivers as per Table 4.

Table 4: Interview participants' responses on drivers for sustainable entrepreneurship in Sri Lankan construction industry

Category	Drivers for sustainable entrepreneurship in Sri Lankan construction industry	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Government Drivers	Government support & incentives	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cultural drivers	Organization culture	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Community Surrounding	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Financial Drivers	Long term profit	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ability to funding	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brand image and reputation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Managerial Drivers	Stakeholder Influence	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Social, environmental awareness	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Level of internal bureaucracy										
	Environmental Management Capability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Consumer satisfaction & demand	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
External support drivers	Competitive advantage & strategic intent	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	External support	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Technological advance										

Category	Drivers for sustainable entrepreneurship in Sri Lankan construction industry	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Technological Drivers	Access to new markets	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Other Drivers	Acceptance of legal & other standard requirement		✓	✓		✓		✓	✓	✓	✓
	Access to obtain different certifications	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

All participants highlighted that government support is an essential requirement to effectively maintain construction firms in Sri Lanka. Among the financial supports, providing incentives for firms that operate with SE in the Sri Lankan construction industry was highlighted. Further, R-05 emphasized *"government incentive systems support to SE in construction sector"*. This incentive system includes releasing tax charges and providing some funding to uplift business operations. Respondents emphasized *"government has been given priority to award government construction projects to sustainable entrepreneurs in the Sri Lankan construction industry"*. Nevertheless, most of interviewees emphasized *"support from Sri Lankan government is not adequate for sustainable entrepreneurship in construction industry and they still not properly maintain an incentive system to motivate entrepreneurs"*. Furthermore, Participants believed *"organization culture and community surrounding become as drivers for SE"*. Effective and systematic organization culture always create easy access to establish SE. Furthermore, community that are surrounding also highly encourage to adapt SE. On the other hand, R-08 highlighted, *"SE also leads to create strong organizational culture within Sri Lankan construction industry and to attract the community from surrounding of business environment"*.

All participants emphasized firms can be maximized long term profit using sustainable entrepreneurship, because of it saves costs by reducing wastages, minimizing energy consumption, reusing materials and reducing raw material requirements, etc. Furthermore, interviewees highlighted *"investors and financial services providers are more preferred to provide funds to construction firms that are operating with SE, because of they are always attempting to encourage the sustainable practices"*. The brand image and reputation also affect to get more attraction from clients and ultimately it will be increased the financial capabilities of firms.

In terms of managerial drivers, all participants mentioned that *"the level of internal bureaucracy is not applicable to establish sustainable entrepreneurship in Sri Lankan construction industry as a managerial driver due to their narrow management structure"*. As a result of that, four main managerial drivers were identified, such as stakeholder influence, social and environment awareness, environmental management capacity and customer satisfaction and demand. All participants believed, *"sustainable entrepreneurship leads to improved environment awareness, environmental management capacity, customer satisfaction, whereas it leads to a positive influence from stakeholders on business operations"*.

Sustainable entrepreneurship gains a competitive advantage in Sri Lankan construction by showcasing its sustainable practices in internal-organizational processes. Furthermore,

sustainable entrepreneurs can obtain benefits such as discounts, free services, and government support despite a lack of supervision from authorities. However, respondents highlighted *"establishing SE doesn't depend on firm size, as large-scale firms must meet additional requirements like legal, financial, and human resource requirements"*. All participants mentioned that SE provides access to new markets due to high demand and concern on sustainable products and performance. SE always increase advancement of organizational internal functions and operations, and it can be referred as technological advancement. On the other hand, R-09 mentioned, "*sometimes SE practices lead to preventing involvement of technological aspects when perform the business operations, as example reduce usage of automatic electric equipment to perform business operation due to high consumption of energy*".

4.3 BARRIERS FOR SUSTAINABLE ENTREPRENEURSHIP WITHIN SRI LANKAN CONSTRUCTION INDUSTRY

All participants confirmed 10 barriers for SE within Sri Lankan construction industry such as limited organizational resources including financial resources, high initial cost, lack of expertise, lack of awareness, resistance to change, lack of competences, additional time consumption, lack of support and guidance from regulatory authorities, weak organizational structure and poor supplier and/or distributor commitment to sustainability. Furthermore, participants agreed that the limited organisational resources including financial resources and high initial costs are barriers for implementing sustainable entrepreneurship in Sri Lankan construction industry. All participants further emphasised the lack of expertise is a barrier in successful implementation. According to participants most of the entrepreneurs in construction industry are not aware of the sustainable entrepreneurship. However, all participants stated that there are sufficient legal and regulatory establishments for sustainable entrepreneurs in construction filed.

The majority of participants validated limited external stakeholder support and lack of technological advancement as barriers for sustainable entrepreneurship within Sri Lankan construction industry. However, R-09 mentioned, *"due to high concern of external stakeholders on sustainability, they are providing adequate support to establish sustainable entrepreneurship"*. Furthermore, R-06 highlighted that, *"technological advancement sometimes prevents to establish SE in the Sri Lankan construction industry because involvement of technology always creates a complex process to adapt concept of sustainable entrepreneurship"*. However, other respondents mentioned that lack of technological advancement is a barrier to sustainable entrepreneurship. In addition to that, participants highlighted that the personal incapabilities of entrepreneurs such as poor attitudes, personal conflicts and lack of confidents to risk taking are major barriers in SE. All of the participants of semi-structured interviews did not agree to determine rules and regulations as barrier to establish SE in the Sri Lankan construction industry.

4.4 STRATEGIES TO OVERCOME BARRIERS IN SUSTAINABLE ENTREPRENEURSHIP WITHIN SRI LANKAN CONSTRUCTION INDUSTRY

Based on existing literature, 7 main strategies were identified to overcome the barriers in sustainable entrepreneurship in the construction industry. Table 6 indicates the responses of participants on the applicability of the identified strategies in the Sri Lankan context.

Table 5:Interview participants'' responses on strategies to overcome barriers on sustainable entrepreneurship in Sri Lankan construction industry

Strategies to overcome barriers in Sustainable entrepreneurship in Sri Lankan construction industry	R-01	R-02	R-03	R-04	R-05	R-06	R-07	R-08	R-09	R-10
Invest resources for long term change	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Invest sufficient financial resources	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adhere carefully to the market fluctuations	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Alignment of sustainable entrepreneurship objectives with the company's strategic goals	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Improve commitment and participation of management	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Allocation of sufficient time and resources for change	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Improve awareness on sustainable entrepreneurship	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

All participants believed all the above strategies are applicable to overcome barriers in sustainable entrepreneurship within Sri Lankan construction industry. Furthermore, the majority of participants highlighted *"the commitment of Sri Lankan government and other relevant authorities should be improved to establish sustainable entrepreneurship within Sri Lankan construction industry"*. R-01 also emphasized, *"introducing different standards and regulations also leads to sustainable entrepreneurship within Sri Lankan construction industry"*. R-02 believed, *"organization culture in the Sri Lankan construction industry should be reorganized to facilitate sustainable entrepreneurship establishment"*. Acquiring expertise knowledge from the global context, conduct a workshop to establish sustainable entrepreneurship and improve personal factors of entrepreneurs of including improving confidence to risk taking, making positive attitudes and improving thinking and creativity, etc also proposed by the participants. The following strategies are basically identified through interview rounds.

- Improve the commitment of Sri Lankan government and other relevant authorities and introduce standards and regulations.
- Reorganize organization culture of firms in the Sri Lankan construction industry.
- Acquiring expertise knowledge from the global context.
- Conduct workshop to establish sustainable entrepreneurship
- Improve personal factors of entrepreneurs including improving confidence in risk taking, making positive attitudes and improving thinking and creativity, etc.
- Restructuring the finding options and incentive systems for construction firms by promoting sustainable entrepreneurship.

5. DISCUSSION

The literature and interview findings on sustainable entrepreneurship in the construction industry indicate a strong alignment in identifying both drivers and barriers. Also, these findings provide detailed insights based on real experiences in the Sri Lankan context. From the literature, the applicability of SE in the construction industry emphasizes energy efficiency, eco-friendly material use, and design innovation (Mir-Babayev et al., 2017). Further literature emphasised that there are a number of drivers and challenges in SE in the construction industry. However, it was revealed that entrepreneurs are more focused on only corporate social responsibility, and due to a lack of awareness they are only applying sustainable practices to their construction projects (Athapaththu & Karunasena, 2018; Rizvi & Somachandra, 2019). There is a strong correlation between the literature and interviews on the key drivers. Both identify government support, organization culture, stakeholder influence, and financial incentives as critical enablers. Literature adds a broader view with aspects like technological advancement, access to new markets, and long-term profit potential (Tello & Yoon, 2008). The interviews justified them and were tailored to the Sri Lankan context. Interviews emphasised the government incentives (tax relief, funding), cultural alignment within organizations, and the influence of sustainability on organizations' reputation and investor appeal. Notably, technological drivers are seen as double-edged. Literature views technology as an enabler, while interviewees point out that sustainable operations sometimes avoid high-energy technologies, showing a complex local adaptation.

Considering the barriers, both literature and interview findings emphasize a lack of financial resources, limited experience, and significant upfront fees. Interviews, on the other hand, reveal more context-specific issues such as a lack of stakeholder support, low market demand, and inadequate organizational structures. While the literature highlights bureaucracy and regulation (Auer & Jarmai, 2017), respondents focus on a lack of technical innovation and poor regulatory backing as actual barriers. Additionally, interviewers mentioned that entrepreneurs' lack of confidence and creativity, suggesting internal personal limitations are overlooked but crucial barriers.

Scholars and interviewers agree on enhancing government involvement, improving organizational culture, and building management capabilities. However, interviews provide more actionable strategies relevant to the Sri Lankan context. These include acquiring global expertise, conducting workshops, and focusing on personal development, such as promoting risk-taking, creative thinking, and confidence building. This study provides significant implications across theoretical and practical domains, stemming from its comprehensive analysis of barriers and drivers to sustainable entrepreneurship. In addition, it proposed 13 actionable strategies based on literature and expert interviews. Theoretically, this study highlights the personal attributes of entrepreneurs, such as risk-taking, creativity, and confidence as critical enablers of SE. These insights provide a foundation for scholars to further investigate the interplay between institutional support and entrepreneurial mindset in developing countries. Practically, the study presents six targeted strategies identified through expert interviews that address the unique challenges specific to Sri Lanka. These include enhancing regulatory frameworks, fostering supportive organizational cultures, promoting access to international expertise, and improving funding systems. Also, it provides a roadmap for implementation by conducting workshops and entrepreneur development programs. These implications are especially valuable underdeveloped SE, offering a replicable

structure that aligns with local needs. Also, these implications inform policymakers, educators, and industry leaders about where support mechanisms should be strengthened.

6. CONCLUSIONS

This study explored the drivers and barriers to sustainable entrepreneurship within the Sri Lankan construction industry by integrating insights from both literature and semi-structured interviews. The findings revealed a strong alignment between academic perspectives and practical experiences, particularly in recognizing key drivers such as government support, organizational culture, stakeholder influence, and financial incentives. However, a notable gap remains in the understanding of sustainable entrepreneurship among local entrepreneurs, as they solely consider it with corporate social responsibility and the adoption of isolated sustainable practices. Barriers such as limited financial resources, low market demand, lack of stakeholder support, and inadequate organizational structures were contextually emphasized in interviews. Furthermore, challenges like a lack of creativity, confidence, and risk-taking capacity were identified as limitations. The study concludes by proposing strategic approaches to promote sustainable entrepreneurship. It recommends actionable strategies such as enhancing government initiatives, fostering innovative organizational cultures, investing in personal and professional development, and facilitating knowledge transfer from global best practices. Addressing these areas will contribute to the development of a robust, sustainable entrepreneurship framework in Sri Lanka's construction sector, ultimately supporting long-term environmental, social, and economic goals.

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SUSTAINABLE SOLAR: ADDRESSING THE GROWING NEED FOR PV PANEL RECYCLING

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ABSTRACT

The rapid expansion of solar energy has raised critical concerns regarding the disposal of end-of-life photovoltaic (PV) panels. This research aims to assess the current landscape of solar panel recycling and explore the effectiveness of regulatory frameworks, recycling technologies, and policy interventions in supporting a sustainable solar energy future. Employing a mixed-methods approach, the study combines secondary data analysis of regulatory framework and policies from European Union, United Kingdom, United States and Asia with cross-national case studies of Germany, Japan, and the United Kingdom. The research evaluates recycling infrastructure, cost implications, material recovery rates, and public awareness to understand existing gaps and opportunities. Findings indicate that while recycling offers substantial environmental and economic benefits—such as resource conservation, job creation, and emissions reduction—barriers including high costs, limited facilities, and low consumer engagement impede widespread adoption. Emerging innovations in mechanical and chemical recycling processes show promise in improving material recovery rates and reducing energy input. The study also highlights how extended producer responsibility (EPR) schemes and circular economy policies can strengthen compliance and investment. Addressing these challenges is essential to reinforce solar energy's contribution to climate goals and to ensure that PV technology remains sustainable over its entire lifecycle. The study's implications call for coordinated global action, stronger regulatory enforcement, technological advancement, and public awareness to build an efficient and economically viable recycling ecosystem for solar panels.

Keywords: *Energy; Solar Energy; Renewable Energy; Solar Panel Recycling; Waste Management and Disposal.*

1. INTRODUCTION

The rapid expansion of solar power generation has led to a sharp rise in the number of installed photovoltaic (PV) panels worldwide (Wanner, 2019). While these panels are essential for achieving low-carbon energy goals, their eventual disposal presents a mounting environmental concern (Kaliyannan et al., 2025). At the end of their lifecycle, decommissioned panels may contribute to electronic waste if not managed properly, releasing hazardous materials such as lead and cadmium into the environment (Mitra &

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Maiti, 2021). In this context, solar panel recycling offers a crucial opportunity to recover valuable resources such as silicon, silver, and aluminium, reduce dependency on virgin materials, and minimise environmental degradation (Preet & Smith, 2024).

The United Kingdom, in alignment with global climate objectives, has actively promoted the deployment of solar energy systems (Gan et al., 2023). With over 13.5 GW of installed capacity, the UK is expected to experience a significant increase in end-of-life PV modules in the coming years (The Engineer, 2024). Regulatory mechanisms such as the Waste Electrical and Electronic Equipment (WEEE) Directive have been introduced to ensure that solar manufacturers and suppliers take responsibility for the disposal and recycling of PV panels (Majewski et al., 2021). Programmes like PV Cycle have emerged to support compliance and facilitate producer responsibility initiatives across the UK and Europe (Nain & Anctil, 2024).

Globally, other countries are also recognizing the need for comprehensive recycling solutions. Germany has incorporated PV waste into its broader electronic waste management policy frameworks (Sharma et al., 2019), while Japan has pioneered innovative chemical recycling processes for silicon extraction (Chen et al., 2024). In the United States, states such as California have established legislative frameworks to regulate PV disposal, alongside institutional efforts to improve recycling efficiency (Ali et al., 2023).

Despite these developments, a unified and scalable approach to solar panel recycling remains elusive (Badran & Lazarov, 2025). High costs, insufficient infrastructure, and limited public awareness persist as major barriers to widespread adoption (Lawal, 2024; Nain & Kumar, 2023). These challenges are particularly urgent as the volume of decommissioned solar panels is expected to surge globally in the next two decades.

The aim of this study is to examine the policy landscape, technological approaches, and implementation challenges of solar panel recycling, with a specific focus on the UK and comparative international contexts. This paper seeks to assess the current state of practice, identify critical gaps, and offer insights for shaping a more sustainable and circular end-of-life strategy for photovoltaic technologies.

2. RESEARCH METHOLODY

This study adopts a qualitative, multiple-case study design to examine solar panel recycling practices in the UK with a comparison with other selected countries. The aim is to assess waste management strategies, regulatory frameworks, and industry-led initiatives associated with photovoltaic (PV) panel recycling. Countries selected for case study analysis include Germany, and the UK, with a comparison with regulatory framework in EU, United States and Aisa – mainly Japan. These were chosen based on three criteria: (1) the presence of well-established PV recycling programmes, (2) compliance with extended producer responsibility (EPR) policies, and (3) the scale of solar panel deployment and waste generation. The selection reflects variation in regulatory maturity and implementation effectiveness across contexts.

The research integrates secondary data analysis with case study evaluations to provide a holistic understanding of the topic (Guetterman & Fetters, 2018). Data sources include government reports, academic publications, and industry white papers (Calantone & Vickery, 2010). Key documents analysed comprise the Waste Electrical and Electronic Equipment (WEEE) Directive, International Energy Agency (IEA) reports, and PV Cycle

publications, which offer insights into regulatory structures and technological advancements (Bowen, 2009). Data from policy institutions and market research firms were also reviewed to estimate the growth of PV installations and forecast waste management requirements.

The analytical approach is primarily qualitative. Thematic analysis was applied to case study materials to identify recurring patterns and major themes (Clarke & Braun, 2017). These themes included policy effectiveness, technological barriers, and industry collaboration. A coding framework was developed to systematically organise and interpret the data (Brown et al., 2003). Although the original research design referenced mixed-methods (Foroudi & Foroudi, 2024), the study ultimately did not incorporate primary quantitative analysis due to inconsistent availability of reliable numeric data across the selected countries. As such, references to quantitative content are limited to descriptive statistics available within secondary sources.

Case study analysis, guided by Stake (2013) methodology, was employed to explore real-world applications of PV recycling. The countries included offered diverse yet comparable regulatory and technical experiences, which allowed for identification of best practices and barriers that may inform policy transfer or improvement.

The research adhered to ethical guidelines by ensuring proper citation of all secondary data sources to acknowledge intellectual property rights (Patel et al., 2016). Efforts were made to present an unbiased analysis by including diverse perspectives from multiple sources (Loscalzo & Giannini, 2025). Data triangulation was used to reduce bias and enhance reliability. Limitations include variation in data availability and possible biases within source materials.

3. THE IMPORTANCE AND IMPACT OF SOLAR PANEL RECYCLING

The global shift towards renewable energy has accelerated solar panel installations, with projections indicating that millions of tons of photovoltaic (PV) waste will be generated by 2050 (Tawalbeh et al., 2021). Without adequate recycling, this growing volume of waste threatens to overwhelm landfills, resulting in environmental degradation and resource loss (Abdolmaleki et al., 2025). Solar panel recycling offers far-reaching benefits across environmental, economic, and social dimensions, supporting global sustainability goals and the circular economy (Srivastava et al., 2025). To structure these benefits, Table 1 presents a summary of key thematic insights regarding the importance of PV panel recycling.

Table 1: Key aspects of solar panel recycling and their impacts

Theme	Summary	Key references
Resource Recovery	Recovers valuable materials like silicon, silver, and aluminium, reducing raw material extraction and pollution.	(Gajare et al., 2025; Preet & Smith, 2024; Al-Alimi et al., 2024)
Environmental Protection	Prevents hazardous substances (e.g. lead, cadmium) from contaminating ecosystems; supports circular economy.	(Nain & Kumar, 2022; Siddiqua et al., 2022; Rabaia et al., 2022)

Theme	Summary	Key references
Economic and Job Creation	Drives green innovation, creates new industries and employment in waste management and material recovery.	(Dias et al., 2022; Sarkhoshkalat et al., 2024; Collis et al., 2023)
Reduced Energy Demand	Significantly lowers energy use in panel manufacturing by reusing materials such as silicon wafers.	(Fernández-González, 2025; Bulińska et al., 2025; Maghraby et al., 2025)
Alignment with SDGs	Contributes to SDG 12 (Responsible Consumption) and SDG 13 (Climate Action) through reduced emissions and sustainable production.	(Gan et al., 2023; Arora & Mishra, 2023; Oduro et al., 2024)
Need for Infrastructure	Highlights the urgent requirement for robust recycling infrastructure and policy enforcement globally.	(Morone et al., 2025; Altassan, 2023; Adebisi et al., 2023)

Following this overview, it is evident that solar panel recycling is a cornerstone of sustainable solar deployment. The recovery of high-value materials like silicon and aluminium not only reduces the environmental costs of mining but also promotes resource efficiency (Preet & Smith, 2024; Al-Alimi et al., 2024). Additionally, the containment of toxic materials like cadmium and lead addresses crucial public health and land contamination risks (Nain & Kumar, 2022; Siddiqua et al., 2022).

Economically, solar recycling introduces job creation and innovation opportunities, particularly where regulatory support incentivises circular supply chains (Dias et al., 2022; Sarkhoshkalat et al., 2024). Energy savings from reusing processed materials, such as silicon, further enhance the lifecycle efficiency of solar technology (Bulińska et al., 2025; Maghraby et al., 2025). Furthermore, recycling aligns directly with the United Nations' Sustainable Development Goals, making it a necessary pillar for environmentally responsible policy agendas (Gan et al., 2023; Arora & Mishra, 2023).

Yet, these benefits remain largely unrealised in many parts of the world due to gaps in infrastructure, regulation, and public awareness. Although countries like Germany and France have established dedicated PV recycling plants, other regions face logistical and financial challenges that hinder scale-up (Morone et al., 2025; Altassan, 2023). Bridging these gaps will require coordinated efforts from governments, industries, and civil society to expand infrastructure, implement policy incentives, and increase consumer awareness (Daniela-Abigail et al., 2022; Adebisi et al., 2023).

4. REGULATORY FRAMEWORK AND POLICIES

4.1 EUROPEAN UNION REGULATIONS

The European Union (EU) has been at the forefront of solar panel recycling policies, primarily through the Waste Electrical and Electronic Equipment (WEEE) Directive (Lesniewska, 2017). This directive classifies solar panels as e-waste, making manufacturers responsible for their collection and recycling at end-of-life. The Extended Producer Responsibility (EPR) model mandates that producers finance the proper disposal and recycling of solar panels, ensuring that recycling programs are sustainable

and widely accessible (Khawaja et al., 2021). PV Cycle, an industry-led compliance scheme, has been instrumental in facilitating the collection and recycling of solar panels across EU member states (Gerold & Antrekowitsch,2024).

4.2 UNITED KINGDOM POLICIES

Following Brexit, the UK has retained the core principles of the WEEE Directive while making adjustments to fit national policies (Cole et al., 2019). The UK Environment Agency enforces solar panel recycling regulations, requiring manufacturers and importers to register and contribute to end-of-life management schemes (Nidhi et al., 2024). Companies failing to comply face penalties, ensuring accountability. Additionally, the UK's Circular Economy Strategy emphasizes the need for improved solar panel recycling infrastructure and incentives for developing efficient material recovery technologies (Gregson et al., 2015).

4.3 UNITED STATES REGULATIONS

Solar panel recycling regulations in the United States vary by state (Curtis et al., 2021). California, a leader in solar energy, has implemented strict regulations under the California Department of Toxic Substances Control (DTSC), classifying solar panels as universal waste and requiring responsible recycling (Heath et al., 2022). Other states, such as Washington and New York, have introduced similar policies, but federal legislation remains limited (Tabassum et al., 2021). The Solar Energy Industries Association (SEIA) has launched voluntary recycling initiatives, encouraging manufacturers to participate in panel take-back and recycling programmes (Komoto et al., 2018).

4.4 POLICIES IN ASIA

In Asian, Japan has pioneered advanced solar panel recycling methods, supported by the Ministry of the Environment and the Ministry of Economy, Trade, and Industry (METI) (Goh et al., 2024). The country has developed innovative chemical recycling techniques to extract high-purity silicon from PV panels. China, the world's largest producer of solar panels, is working on implementing a national recycling framework, driven by environmental concerns and the need for sustainable resource management. Government-backed initiatives encourage research and development in recycling technologies, aiming to establish large-scale solar panel recycling plants (Song & Feng, 2024).

4.5 FUTURE POLICY DIRECTIONS

As the global volume of decommissioned solar panels continues to rise, there is a growing need for standardized international regulations (Mahmoudi et al., 2021). Key recommendations arriving from Lunardi et al. (2018) and Abila and Kantola (2019) include: (i) Strengthening EPR mandates to ensure global manufacturers contribute to recycling efforts, (ii) Establishing international guidelines for solar panel disposal and recycling efficiency benchmarks, (iii) Providing financial incentives for companies investing in innovative recycling technologies.

By harmonizing global policies and expanding regulatory frameworks, governments can create a more sustainable future for solar energy, ensuring that the industry remains environmentally responsible in the long term.

5. COMPARATIVE EFFECTIVENESS OF REGULATORY APPROACHES: A CASE STUDY PERSPECTIVE

5.1 GERMANY: SYSTEMATIC IMPLEMENTATION AND POLICY-DRIVEN SUCCESS

Germany demonstrates a highly structured and centralised recycling model. Under the ElektroG law, aligned with the WEEE Directive, PV modules have been categorised as e-waste since 2015, placing financial responsibility for collection and recycling on producers (Electrical and Electronic Equipment Act., 2005). The PV Cycle scheme operates over 300 collection points nationally. Germany's recycling infrastructure is comprehensive, supported by national policy enforcement and technical R&D investments from the Federal Environment Agency (Andersen, 2024). The country achieves collection rates above 85%, with material recovery efficiencies of 80–90% for glass and aluminium, and 60–70% for silicon. Recycling costs range from $270 to $325 per ton, partially offset by material resale and regulatory subsidies (Held & Wessendorf, 2024). Environmental benefits include avoidance of 400,000 tonnes of CO_2-equivalent emissions annually (Germany Trade & Investment, 2024). Closed-loop recycling systems are integrated with e-waste infrastructure, enhancing scalability (Sarkhoshkalat et al., 2024). This model reflects a high-performing system with well-aligned regulatory and operational mechanisms.

5.2 JAPAN: INNOVATION-LED, TECHNOLOGY-INTENSIVE RECYCLING

Japan's regulatory strategy prioritises R&D and technological precision, backed by the Ministry of Environment and METI (Herrador et al., 2022). The policy focus is on innovation-led efficiency through chemical separation and modular eco-design (Sakao et al., 2024). Japan achieves PV recycling rates of 65–70%, varying by prefecture (Komoto et al., 2022). Advanced hydrometallurgical and thermal techniques allow recovery of up to 95% of silicon and 80% of silver, exceeding global benchmarks (Theocharis et al., 2022). Costs range from $230 to $300 per ton—lower than Germany's—due to improved yield from sophisticated processes (Cheng et al., 2022). Environmental indicators show a 32% reduction in toxic leachate incidents near legacy solar sites (Moshkal et al., 2024). Initial investments are significant, with state-supported pilot projects driving innovation. While effective in high-density regions, the model's scalability hinges on continued public investment and national coordination.

5.3 UNITED KINGDOM: REGULATORY CONTINUITY AMIDST IMPLEMENTATION GAPS

Post-Brexit, the UK has retained WEEE-aligned principles but lacks PV-specific enforcement measures. Only an estimated 35–45% of decommissioned panels are recycled through certified channels; the rest enter general waste streams (Czajkowski et al., 2022). The country operates just three dedicated PV recycling facilities, limiting geographic coverage and accessibility (Ganpatsinh et al., 2024). Recycling costs range between $225 and $275 per ton—higher than landfill disposal—creating economic disincentives (Ganpatsinh et al., 2024). While the Circular Economy Strategy supports responsible waste practices, it lacks binding targets specific to solar recycling (Sundar et al., 2023). Potential environmental risks from unmanaged waste include heavy metal leaching. However, recycling is estimated to reduce lifecycle carbon emissions by 65%

per module. Public–private partnerships have emerged, but most are in early stages and lack national coordination.

5.4 CROSS-CASE INSIGHTS AND POLICY IMPLICATIONS

The comparative analysis reveals significant regulatory divergences. Germany's model is policy-driven, enforceable, and integrated with national e-waste infrastructure, enabling high performance. Japan's model prioritises high-tech innovation and eco-design, yielding superior material recovery but with high initial investment and scalability challenges. The UK, while maintaining regulatory continuity, suffers from weak enforcement, fragmented infrastructure, and limited uptake.

Regulatory Alignment and Divergence: All three countries align with EPR principles, but only Germany enforces producer compliance rigorously. Japan leverages R&D policy, while the UK lacks binding PV-specific targets. The presence or absence of enforceable regulations appears to be a key determinant of implementation success.

Outcomes and Metrics: Germany leads in collection and recovery rates, while Japan surpasses in technical efficiency. The UK lags across most performance indicators. Recycling rates relative to estimated end-of-life product volumes are highest in Germany (~85%), followed by Japan (~65%), and lowest in the UK (~40%).

Infrastructure and Investment: Germany and Japan have robust infrastructure networks, supported by public funding. Japan's initial investments in chemical recycling technologies offer long-term returns via material purity and energy savings. The UK's limited facilities constrain scale and efficiency.

Environmental and Economic Impact: All three countries demonstrate positive environmental outcomes, with PV recycling reducing carbon emissions and landfill pressure. However, cost recovery is strongest in Germany, where resale of materials and regulatory subsidies help offset processing expenses. Japan's advanced recovery efficiencies justify its upfront costs, while the UK struggles due to low economies of scale and weak policy support.

This comparative framework highlights that successful solar panel recycling depends on a combination of regulatory enforcement, infrastructure investment, technological capability, and cost-recovery strategies. Policymakers seeking to scale PV recycling must consider a hybrid model that integrates Germany's policy coordination with Japan's innovation and addresses the UK's implementation challenges. These case studies offer a practical roadmap for embedding circular economy principles in solar energy transitions worldwide.

6. OVERCOMING CHALLENGES AND ADVANCING SOLAR PANEL RECYCLING

To assess the real-world impact of solar panel recycling initiatives, this study evaluated case studies from Germany, Japan, and the United Kingdom. These countries were selected based on the presence of mature regulatory frameworks, national solar deployment scale, and differing approaches to recycling infrastructure and policy enforcement.

6.1 KEY CHALLENGES IN SOLAR PANEL RECYCLING

Despite the growing recognition of solar panel recycling, several obstacles hinder its widespread adoption (Salim et al., 2019). One major challenge is the high cost of recycling. The process of separating materials from decommissioned panels is complex and requires specialized technology, making it more expensive than landfill disposal (Krauklis et al., 2021). In addition, the lack of dedicated recycling infrastructure in many countries limits the accessibility of recycling programmes, particularly in regions with high solar energy adoption but insufficient waste management facilities (Kinally et al., 2022).

Another critical challenge is the low public awareness and participation in solar panel recycling programmes. Many solar panel owners, including residential and commercial users, are unaware of available recycling options, leading to improper disposal (Okoroigwe et al., 2020). Additionally, the varying composition of solar panels—with different materials and designs—adds to the complexity of recycling, requiring customized recycling techniques for different types of PV modules (Chowdhury et al., 2020).

6.2 INNOVATIONS AND FUTURE PROSPECTS

To overcome these challenges, technological advancements are being developed to improve recycling efficiency and cost-effectiveness (Kamboj & Ray, 2025). New chemical and mechanical recycling techniques allow for higher recovery rates of materials such as silicon and silver, making the process more economically viable (Theocharis et al., 2022). Researchers are also exploring design improvements, such as modular and easily disassemble solar panels, to facilitate recycling at the end of their lifecycle (Su et al., 2024).

Furthermore, government incentives and industry collaborations are essential to promoting solar panel recycling (Acharya et al., 2024). Policymakers can introduce financial incentives, such as tax credits and subsidies, to encourage manufacturers to adopt recycling-friendly designs and invest in advanced recycling facilities (Haksevenler et al., 2023). Public-private partnerships can also help scale up recycling programs, fostering innovation and expanding infrastructure.

In the long term, the development of a global standard for solar panel recycling could ensure consistent regulations and guidelines across different countries. International cooperation in research and policymaking will be vital in addressing the increasing volume of PV waste and establishing sustainable solutions for the solar energy industry.

By addressing these challenges through innovation, policy support, and industry engagement, solar panel recycling can become a key pillar in the transition to a truly circular and sustainable renewable energy system.

7. CONCLUSION

Solar panel recycling is an essential component of the sustainable energy transition. While solar energy offers a cleaner alternative to fossil fuels, the growing accumulation of end-of-life PV modules presents significant environmental and economic challenges. Without appropriate recycling measures, these panels could contribute to electronic waste, exacerbating landfill overflow and environmental degradation. However, by

implementing effective recycling strategies, the renewable energy sector can achieve a truly circular economy that reduces waste, conserves valuable resources, and minimizes environmental harm. The current state of solar panel recycling presents both challenges and opportunities. While high costs, limited infrastructure, and lack of public awareness remain key barriers, advancements in recycling technology, policy support, and industry collaboration are paving the way for a more efficient and scalable recycling system. Countries such as Germany, Japan, and the United States are demonstrating successful models for PV recycling, proving that investment in recycling infrastructure can lead to significant long-term benefits. To enhance solar panel recycling efforts, a multi-faceted approach is required. Governments must implement stronger policies that mandate recycling and incentivize sustainable design. The private sector should continue investing in innovative recycling techniques that increase material recovery rates and reduce processing costs. Furthermore, raising public awareness about the importance of solar panel recycling will encourage responsible disposal practices and greater participation in recycling programs. Looking ahead, international cooperation will be crucial in standardizing recycling practices and ensuring a consistent, global approach to managing solar panel waste. Establishing a unified framework for recycling guidelines, best practices, and research collaboration can drive efficiency and scalability across different regions. By integrating sustainability into every stage of the solar panel lifecycle—from design to disposal—the renewable energy sector can fulfil its promise of delivering a cleaner, greener future. In conclusion, solar panel recycling is not merely a necessity but an opportunity to enhance the sustainability of the renewable energy industry. With continued technological advancements, policy improvements, and public engagement, solar panel recycling can evolve into a well-established, economically viable industry that supports both environmental protection and circular economy principles. The time to act is now—to ensure that solar energy remains a truly sustainable solution for generations to come.

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SUSTAINABLE URBAN MOBILITY IN SRI LANKA: THE IMPERATIVE FOR AN INHERENT HUMAN-CENTERED APPROACH FOR HOLISTIC DEVELOPMENT

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ABSTRACT

Urban mobility plays a crucial role in the sustainable development of cities, shaping economic growth, supporting environmental sustainability, and enhancing social well-being. However, in Sri Lanka, urban transport infrastructure has failed to address key challenges in urban mobility, such as traffic congestion, air pollution, poor public transportation, and road safety. This research examines the necessity of a unique sustainable urban mobility approach that integrates human behaviour, cultural values, and environmental conditions. The study identifies the role of inherent solutions shaped by environmental, social, and cultural values in developing sustainable urban mobility approaches. By incorporating social values and behavioural theories, this study explores the role of human behaviour in sustainable urban mobility. The findings highlight the need for policies that align with local socio-cultural characteristics, emphasizing community-driven solutions rather than solely infrastructure-based approaches. The study concludes with policy recommendations to improve urban mobility through inclusive planning, enhanced public transportation, and promotion of active mobility. These findings contribute to the global discourse on sustainable urban mobility by demonstrating that a human-centered, context-specific approach is vital for ensuring the long-term success of transport policies in developing nations.

Keywords: *Context-specific; Human-centered; Sustainability; Urban Mobility.*

1. INTRODUCTION

Although the sustainable development concept became a topic of social discourse following the establishment of the Sustainable Development Goals (SDG) in 2015, current progress reports show that progress on more than 50 percent of targets across these goals, including poverty reduction, climate action, and sustainable cities, is insufficient, leaving more than half the world behind (United Nations Department of Economic and Social Affairs, 2023). Recent research in the field of sustainable development suggests that a key factor in achieving sustainability lies in the development

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of robust, sustainable, and resilient cities (Profiroiu et al., 2020; Sopiana et al., 2023). However, as of today, urban cities have reached a tipping point of severe environmental challenges, including air pollution, noise pollution, biodiversity loss, traffic congestion, occupation of public spaces by traffic, and greenhouse gas emissions (Pobrklić et al., 2022; Brůhová et al., 2020). Additionally, these challenges can negatively impact people's health and quality of life (Ileperuma, 2020) and are associated with a higher prevalence of mood disorders, such as depression, in urban areas (Tonne et al., 2021).

Research indicates that urban cities are experiencing above mentioned challenges due to transport systems, and most of them are intertwined with poor urban mobility planning (Torrisi et al., 2020; Raza et al., 2022). However, the traditional common solution of constructing road infrastructure has failed to resolve the urban mobility failures in city areas (Ortúzar, 2019). In this context, the European Union noted that a sustainable city must be consistent with sustainable and healthy mobility (Ravazzoli & Torricelli, 2017). Therefore, the concept of sustainable urban mobility became a discourse among the experts, aiming to ensure that transport systems support environmental, economic, social, and mental well-being (Gallo & Marinelli, 2020). Sustainable urban mobility refers to a mobility system that enables safe, affordable, reliable, and comfortable movement while meeting societal needs without compromising environmental or human well-being, now or in the future (Ravazzoli & Torricelli, 2017; Chatziioannou et al., 2023).

Similar to the global challenge, urban mobility has become a major issue in the Sri Lankan context. The transport sector in Sri Lanka is a significant contributor not only to the economy, by accounting for nearly one-third of Sri Lanka's total energy consumption (Sri Lanka Sustainable Energy Authority, 2015), but also a leading source of greenhouse gas (GHG) and other pollutant emissions. Moreover, due to the unsatisfactory public transport system, the private vehicle ownership level has increased to 28%, which should be maintained at around 10% based on the current per capita GDP in Sri Lanka (Samarasekera et al., 2023). Consequently, according to Kumarage (2012), the average network speed in peak hours for commuter traffic to Colombo will drop to 9.1 Km/h in 2031. This situation advocates the implementation of sustainable urban mobility approaches within Sri Lanka.

However, in the recent past, it has experienced the severity of economic challenges, and it has forced the government to make developments that would be sustainable and bring maximum return on investment (Samarasekera et al., 2023). In recent decades, there have been several failed city development projects, including the Rathnapura New City Development Project (J. A. C. D. Jayalath et al., 2021), the Moratumulla New Retail Outlet Project in 1998, and the Radampola Mini-Town Development Project, all of which were implemented without considering social behaviour, thinking patterns, cultural aspects, environmental features, or the meaning and sentiment associated with the city (Perera, 2016). Without a comprehensive exploration of this issue, existing design and planning approaches fail to effectively mitigate inefficiencies and unsustainable practices in urban mobility.

1.1 AIM AND OBJECTIVES

In this context, urban mobility in Sri Lanka faces significant environmental, economic, and social challenges, further compounded by the lack of understanding of human behaviour and needs, highlighting a critical research gap. Accordingly, this study aims to emphasize the need for context-specific urban mobility planning that prioritizes human

behaviour and cultural aspects, alongside environmental and economic considerations, to enhance sustainable urban mobility. To achieve this aim, the objectives were established as (1) To identify the current challenges and limitations in urban mobility in Sri Lanka, (2) To assess the need for developing context-specific approaches in designing sustainable urban mobility plans, and (3) To identify unique strategies to achieve holistic sustainable urban mobility in Sri Lanka. Furthermore, the scope of this research is limited to examining the implementation of mobility strategies in existing urban commercial cities in Sri Lanka, particularly those that are developing, low to middle-income, medium to high-density, and located in tropical regions.

2. LITERATURE REVIEW

When looking at the current state, sustainable development will become a challenge due to rapid population growth in many countries (Rai & Fulekar, 2023). As discussed above, while cities today are designed to meet human necessities, they are grappling with challenges such as population growth, traffic congestion, and air quality, which are intertwined with the transport sector across the world (Giles-Corti et al., 2020). Thus, in order to address these pressing challenges, it is necessary to implement a farsighted policy to achieve efficient transportation for city planning (UN, 2023). However, in the context of Sri Lanka, urban mobility has shown significant drawbacks in every dimension, and it is time for an in-depth examination of these challenges to overcome them effectively.

2.1 URBAN MOBILITY IN SRI LANKA

The transport sector accounts for almost one-third of the total energy consumption in Sri Lanka (Sri Lanka Sustainable Energy Authority, 2015). In this context, Sri Lankan transport sector causes environmental pollution and other severe challenges that directly impact humans, animals, and the environment (Gamage et al., 2022). Among those challenges, air pollution is a growing problem in the Sri Lankan context due to the increase in the number of motor vehicles, traffic congestion, and it causes the rapid growth in health hazards in Sri Lanka (Ileperuma, 2020). Moreover, due to the rapid increase in energy demand of the transport sector in Sri Lanka, the government needs to spend a considerable amount of money to import diesel and gasoline (Sri Lanka Sustainable Energy Authority, 2020). On the other hand, there has been rapid growth in private vehicles after 2010, when the vehicle import tax was heavily reduced and vehicle ownership was widely promoted politically, especially as an indicator of a growing economy (Samarasekara et al., 2023). Although the Sri Lankan transport sector strives for effective and efficient mobility solutions, public transport continues to decrease because of deterioration in the service quality of all transport systems (Samarasekera et al., 2023). Thus, even more than 50% of the population uses public transport within Colombo, the majority of the passengers are unsatisfied with the waiting time, safety and comfort level of a passenger while waiting for the bus (Amarasingha & Malagalage, 2023).

Moreover, as a tropical country, Sri Lanka potentially experiences a higher number of road injuries due to distraction, slower response times, and driver fatigue caused by elevated temperatures (Hsu & Rodríguez, 2024). This elevated temperature and pervasive humidity also contribute to making outdoor walking more uncomfortable in tropical countries.

However, the projects that have greater political appeal, such as expressways that serve limited user groups, particularly the corporate sector and high-income households, have been prioritized over public transport in budget allocations for nearly two decades (Samarasekara et al., 2023). Therefore, Sri Lanka is at a tipping point to invest in new projects in order to address the aforementioned challenges and drawbacks by enhancing sustainable urban mobility in city areas.

3. RESEARCH METHODOLOGY

This study adopts a critical literature review methodology, aiming to explore human perspectives, behaviours, and lived experiences related to urban mobility in Sri Lanka. Aligned with the study's objectives, the review focused on understanding how cultural, behavioural, and contextual factors influence the effectiveness of mobility strategies and policies in urban environments.

The literature was selected through a relevance-based and purposive approach, focusing on sources that contribute to understanding sustainable mobility, transport behaviour, and planning strategies in developing urban contexts. Key databases such as Scopus, ScienceDirect, Google Scholar, and Web of Science were used to locate relevant academic publications. The review included more than 80 scholarly sources, comprising peer-reviewed journal articles, books, and conference papers, published primarily between 2010 and 2025. These sources were critically analysed to identify recurring themes, conceptual gaps, and practical challenges, with special attention to human behaviour and urban planning frameworks applied to the Sri Lankan context. The findings support the development of context-sensitive, human-centric mobility strategies tailored for commercial cities in developing, low- to middle-income, and high-density tropical regions.

4. DESIGNING A SUSTAINABLE URBAN MOBILITY PLAN

A sustainable urban mobility plan is inherently interdisciplinary, focusing on core objectives such as economic, environmental, and social well-being (Pawlyszyn & Ryzhkova, 2021). Unlike traditional transport planning, which increases the road supply based on the demand, this multi-criteria planning approach focuses on managing mobility demand within urban areas (Torrisi et al., 2020). Additionally, it promotes shared vehicle use and active mobility options as alternatives to private vehicle use (Torrisi et al., 2020). In this context, low-carbon transport, active transport, improved public transport systems, changes in urban form (mixed land use), and advances in vehicle technology are among the top transport-related topics being discussed to achieve sustainable development goals.

However, the sustainable urban mobility policies of each city depend on several factors, including the condition of the road network, availability of public facilities, technological development, environmental conditions, lifestyles, cultural traditions, and social activities (Pawlyszyn & Ryzhkova, 2021). In addition to these practical factors, sustainable urban mobility's philosophical and theoretical foundation significantly differs from traditional approaches. According to Pawlyszyn and Ryzhkova (2021), while traditional urban mobility planning mainly focuses on traffic flow, speed, road functionality, and demand-based expansion involving only the transport sector, the philosophy of sustainable urban mobility goes beyond this by prioritizing people, viewing

streets as spaces of vitality, integrating urban form, and considering all transport modes through interdisciplinary planning teams.

Considering all these features, the human-centered approach, emphasizing social and human dimensions in planning, emerges as a central element of sustainable urban mobility (Pawlyszyn & Ryzhkova, 2021; Torrisi et al., 2020). A successful sustainable mobility plan is inherently human-centered and reflects community-specific values that embody individuals' experiences, emotions, and needs (Ahmed et al., 2019). Moreover, this approach addresses not only environmental, social, and economic aspects but is also linked to greater subjective well-being by enhancing community travel satisfaction (Mouratidis et al., 2023). As the human-centered approach becomes more prevalent in sustainable mobility planning, increased levels of public engagement are observed compared to traditional practices. In this context, it is worthwhile to examine the foundations of the human-centered approach in depth before applying it to optimize its relevance and effectiveness.

4.1 NECESSITY OF A UNIQUE DEVELOPMENT APPROACH

In evaluating philosophies within social, human, and environmental sciences, there is an emerging tendency to rethink the role of humans in modern social and ecological systems. In this context, the concept of the noosphere, which is described as the global sphere of collective wisdom, memory, culture, and human thought, has gained significant popularity (Ouyang, 2021). The modern view of the noosphere has expanded its boundaries by adding human knowledge, human behaviour, and beliefs. Nevertheless, this knowledge and these thoughts are shaped by our surrounding environment, and they influence our culture and behaviour (Ouyang, 2021). Noosphere represents one of the most critical components of the spiritual response of humanity related to global problems in society (Gubanov et al., 2019). The noosphere is especially tightly interwoven with our survival in the biosphere by generating knowledge that originates from our daily understanding of the world around us (Ouyang, 2021). Moreover, humans share a profound interconnection with the geosphere through their memories, stories, and daily experiences, giving rise to identity, values, and social responsibility (Bellaubi, 2021).

Additionally, each regional group or community develops unique ways of thinking shaped by religious, professional, regional, and national influences. These modes of thought are essential for solving global issues and preserving the Earth's civilization and humanity (Gubanov et al., 2019). Consequently, this knowledge, way of thinking, and these experiences aid in developing unique solutions at the right time and place. In Sri Lankan culture, this is referred to as *"sthanochitha prachnava" (wisdom of place),* and such solutions become more practical and accurate because they originate from an inherent sense of the time and the surrounding environment, including ecosystem, culture, and society.

Furthermore, a space becomes a meaningful place when humans interact with it, imbuing it with value through feelings, symbols, and cultural expressions. This human-geosphere connection, grounded in "soil", "society," and "soul", fosters a sense of responsibility and inspires visions of future possibilities (Bellaubi, 2021). The renowned urbanist Jane Jacobs similarly argued that the term "urban" should not be interpreted merely in physical or structural terms but as a dynamic cultural landscape shaped by strong social capital, economic vitality, and local identity (Ravazzoli & Torricelli, 2017). In the context of Sri Lanka, *"handiya"* represents the foundation of urban life. According to Perera (2016),

since the "*handiya*" is not merely a physical place but a social space defined by a set of activities and processes, it has become a complex form and illegible place for planners, policymakers, and scholars. Therefore, this situation calls for focusing on the inherent environmental, economic, and social features with Indigenous knowledge when developing effective and efficient sustainable urban mobility policies in Sri Lanka. The previous projects that failed due to a lack of consideration for these features always advocate this statement, highlighting the necessity of unique approaches to establish efficient and sustainable urban mobility in the country.

4.1.1 Implementation of a Unique Sustainable Urban Mobility Approach

In the last few decades, sufficient evidence has emerged to prove that authorities are precisely unable to read this complex form, which is shaped by a set of social, physical, and economic factors. Rathnapura's new city, which was built to avoid natural disasters, is one of the best examples of a failure in rearranging urban forms in Sri Lanka. The reason for the flood disaster problem in Rathnapura district is not only due to the location of Rathnapura city, which is positioned at the lower part of the Kalugaga Basin, but also due to factors related to the location of population settlements and their behaviour (Edirisooriya et al., 2018). In the early 1980s, the government of Sri Lanka decided to move the main functions to a higher elevation near the city's original location to avoid facing major floods every year. But the new town becomes inactive after the regular working hours of the government offices, since all city activities, except a few administration institutions, are still in the old town (Bandara et al., 2010). Further to the author, due to a lack of study regarding human behaviour, social behaviour and economic factors, the government has spent considerable cost on roads and infrastructure investments and maintenance for this rearrangement, even the original problem of flood and related hazards continues with losses recurrently recorded almost every year (J. A. C. D. Jayalath et al., 2021).

Radampola mini town development plan is further evident in the failure of attempts to replicate the city, which was implemented with huge political support (Perera, 2016). According to the author, in the newly developed city, it was strictly prohibited for betel-chewers to spit on the newly paved sidewalks or sit on the walls, and wide roads were restricted to interacting with users on both sides of the road. Certainly, these kinds of urban forms tend to fail in social, economic and environmental aspects, as the people are not welcome in their own city.

In this context, although urban forms play a major role in sustainable urban mobility, Sri Lankan authorities and policymakers have still failed to align urban form with social, cultural, and lifestyle factors to implement efficient and sustainable urban mobility. In fact, Sustainable urban mobility policies always should be shaped by the city's lifestyle, cultural traditions, and social activities (Pawlyszyn & Ryzhkova, 2021). As an example, when designing urban mobility plans and policies for Eastern countries or regions, planners have to consider more spaces for gathering people, as Eastern culture is group-oriented (collectivism), in contrast to Western culture, which is individual-centered or individualistic (Beckett, 2023). Moreover, Eastern people would see a society with interrelated members, and they attend closely to the social world, while Westerners believe that it is a collection of independent persons (Nisbett, 2004). Therefore, these cultural features need to be considered when developing cities, such as streets, because the street plays a crucial role in shaping the life of the society by involving cultural, social,

and economic functions of the city, such as walking, eating, meeting friends, and going shopping (Abdulmughni et al., 2021).

Additionally, a notable observation in Eastern culture is that people always search for relationships between things, and the world seems more complex to Eastern people (Nisbett, 2004). Further, according to the author, studies revealed that Eastern people prefer to group objectives based on thematic relationships. Moreover, as previously mentioned, they perceive the world as a network of interrelated objects and change in a single objective impacts the entire system, in contrast to the perspective of Westerners (Nisbett, 2004). This phenomenon is also focused on place attachment theory, and when rearranging urban forms, place attachment between people and places needs to be explored. Place attachment is "a set of feelings about a geographic location that emotionally binds a person to that place as a function of its role as a setting for an experience (Sun, 2020). Most studies to date advocate that place attachment encompasses place identity, including emotional meanings, rules, regulations, norms, behavioural intentions, attitudes, beliefs, knowledge, and place dependence, which describes general behaviour and functional relationships with specific settings (Koohsari et al., 2023). Furthermore, Sri Lankans exhibit strong attachment to their families, workplaces, and daily routines. As such, urban mobility planning that disregards place attachment becomes inherently more complex and less effective. In this context, as per the Eastern ways of thinking and Jane Jacobs' guidelines, Sri Lankan authorities need to focus on more performance zoning and relocate the features based on easy-to-function (looping the interrelated features) and feel comfortable and acceptable to citizens as per the place attachment theory and their way of thinking. In addition, when planning an urban city, it warrants considering cultural and Indigenous knowledge, which encompasses a wide range of categories, not limited to socio-economic context but also cultural context, experiences, and geomorphology that have been built upon and passed on from one generation to the other by word of mouth (Tran et al., 2009).

Additionally, supporting pedestrian mobility is also a key factor in sustainable urban mobility development. However, people's preferences and willingness to choose walking are different in countries, regions, personal behaviours, and due to many other reasons (Perera, 2016). Recent studies have shown that the travel behaviour of citizens is also shaped by several factors such as culture, personal habits and preferences, socioeconomic status, climate, transportation management, transportation frequency, and general safety (Chen & Felkner, 2020). Thus, Urban mobility can be defined as "a complex system of social, economic and spatial interactions" (Wang et al., 2022). Consequently, under these circumstances, although the established sustainable urban mobility development goals are similar globally, the economic, social, and environmental policies and challenges are uniquely dynamic across the regions, countries, and other local contexts (Hossain & Jami, 2023). In this context, literature findings advocate that, to overcome these challenges and promote sustainable urban mobility, understanding and addressing influence factors on social behaviours is just as important as studying the economic and environmental features of the city.

4.1.2 Integrating Human Behaviour to Promote Sustainable Urban Mobility

The concepts related to behavioural aspects, which play an important role in attempts to predict and explain human behaviour (Siqueira et al., 2022), can be applied by authorities to encourage people to adopt environmentally friendly behaviours, such as using

sustainable urban mobility options like public transport and active transportation. According to these concepts, human behaviour is consistently shaped by their attitude, values, and beliefs (Yuriev et al., 2020). In promoting sustainable urban mobility, as a form of pro-environmental behaviour, individuals' environmental concerns, beliefs, and values play a prominent role in shaping societal outcomes.

However, even though society has less environmental concern, as a dominant influencer on the beliefs and attitudes of people, cultural values can fill the gap between environmental concern and pro-environmental behaviours (Chwialkowska et al., 2020). Previous case studies have proven that people's cultural values and beliefs help to form environmental beliefs or attitudes that are directed towards environmentally friendly behaviours (Samarasinghe, 2012). The story behind Adam's Peak, located in Sri Lanka, is one of the greatest pieces of evidence for this phenomenon. Adam's Peak is a conical mountain with 2,250 meters, featuring a highly sensitive ecosystem and serving as the source of three major rivers in Sri Lanka (Raikar, 2025). According to Living Heritage Trust (2017), the inhabitants of Sri Lankans believe that this mountain is in the kingdom of God, "*Saman*", one of the four guardian deities of the island. Our ancestors held this utmost belief and respect as a cultural and emotional value to preserve this ecosystem by enhancing the pro-environmental behaviours of the people. As a result, people were scared to damage this sensitive ecosystem, and this folklore has been spread strongly as a result of a collectivist cultural background. Another notable observation is that our ancient spatial planning had been given an iconic ideology for the hard rocks by establishing religious sites at the peak (G. R. Jayalath & Jayalath, 2019). They have identified that by ensuring the longevity of the complex rock form, the ecosystem. After establishing religious sites at peaks, no human settlements were found inside and around the landscape due to the utmost respect (G. R. Jayalath & Jayalath, 2019). In light of the foregoing, social, cultural beliefs and collectivist cultural backgrounds also play a major role in planning environmentally friendly behaviour in Sri Lanka.

Moreover, these scenarios advocate that in Sri Lanka, which has an Eastern culture with collectivistic characteristics, the social network is the primary source of information in the culture (Chwialkowska et al., 2020). Therefore, as of today, social marketing has emerged as a straightforward approach to promoting pro-environmental behaviour by focusing on identified domains, including health promotion, injury or accident prevention, environmental protection, and community mobilization (Setiawan et al., 2021). In this context, when implementing sustainable urban mobility, it is important to focus not only on developing infrastructure but also on engaging social norms and characteristics to ensure success. Additionally, many studies have revealed some more factors, such as pro-environmental activism, moral norms, and social responsibility, that influence human intention and behaviour (Ali et al., 2023). Taken together, these conditions highlight that on the path toward sustainable urban mobility, social values, human perspectives, and beliefs play a major role.

4.2 UNIQUE SUSTAINABLE URBAN MOBILITY APPROACHES FOR A HOLISTIC SUSTAINABLE DEVELOPMENT

To achieve holistic and sustainable urban mobility that addresses both objective dimensions (such as environmental protection, social equity, and economic resilience) and subjective dimensions (such as mental and emotional well-being), mobility strategies must be fundamentally people-oriented. Under the concept of people-oriented

development, enhancing human life satisfaction has gradually become the goal across the globe (Li & Liu, 2021). After widespread attention has attracted on life satisfaction, recent studies identified that objective characteristics (Urban safety, natural environmental comfort, convenience of transportation, environmental health), subjective characteristics (government integrity, environmental protection, gap between rich and poor, medical level) and personal attributes (gender, age, material status, health status, income level) are the main variables which effect on life satisfaction in urban areas (Li & Liu, 2021). Considering the aforementioned areas, it is evident that numerous factors influencing human life satisfaction are intertwined with urban mobility. Additionally, a notable observation is that indices, which focus on the conditions for happiness (Chetri, 2023), are also formulated based on factors such as standard of living, health, environment, social support, healthy life expectancy, community vitality, time use, psychological well-being, good governance, and cultural resilience culture (Keiff, 2022), all of which are directly interrelated and interconnected with urban mobility. Therefore, to develop unique development approaches that address holistic sustainable development, it is essential to focus not only on environmental features and the country's economic stability but also on social characteristics such as gender, age distribution, income levels, health status, values, beliefs, and more.

Consequently, literature findings highlight that since each city has inherent social, cultural, and environmental characteristics, solutions tailored to these unique features are more effective and efficient in addressing the challenges of urban mobility. Moreover, as sustainable urban mobility plays a major role in life satisfaction, varying based on social and environmental factors, it is essential to establish unique sustainable urban mobility approaches shaped by social and anthropological characteristics in the context of Sri Lanka.

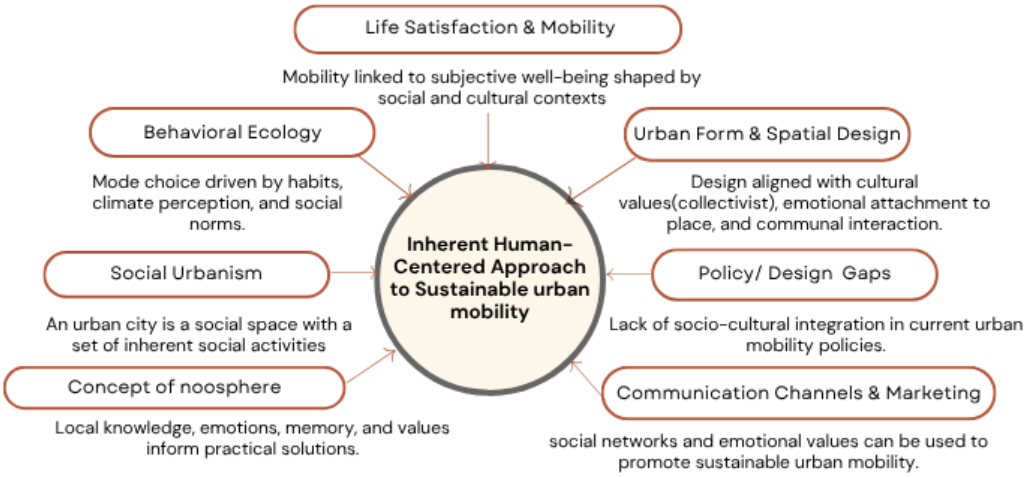


Figure 1: Conceptual framework highlighting the necessity of an inherent human-centered approach to sustainable urban mobility

In this context, even recent global studies have identified several key strategies for achieving sustainable urban mobility, including changes in urban form, investment in active transport infrastructure, enhancement of public transportation and shared mobility, policy reform, and the integration of advanced technologies, such strategies must be carefully contextualized to address the specific socio-cultural, environmental, and behavioural realities of Sri Lanka. According to literature findings, urban form

transformations should emphasize performance zoning, communal spaces, and locally grounded solutions aligned with Sri Lankan socio-cultural values and behaviours. Additionally, to promote active and public mobility, facilities must suit the tropical climate, support social interaction, ensure comfort, and use social networks for behaviour change, to address both challenges and opportunities to enhance sustainable urban mobility in Sri Lanka. Lastly, policy and technological innovations should be inclusive and avoid rigid rules that weaken social cohesion or alienate citizens. However, beyond these measures, there is a critical need to deeply explore transitional dynamics and identify policies and strategies best suited to the Sri Lankan context. This will foster a meaningful shift from 'planning for people' to 'people for planning,' encouraging bottom-up, participatory policy development. To achieve this, the integration of multidisciplinary expertise, community feedback and opinions, and indigenous knowledge is essential to ensure contextual relevance and effectiveness. By following these processes, policymakers can gain valuable insights for developing holistic, sustainable urban mobility solutions that address social, environmental, and economic dimensions. Simultaneously, this evolving field offers academics rich opportunities for in-depth research and knowledge generation.

5. CONCLUSION

Urban mobility in Sri Lanka faces significant challenges due to the infrastructure-focused planning that disregards human-centered development. The study highlights the failures of past urban projects that neglected socio-cultural dynamics, environmental features, resulting in inefficiencies and public dissatisfaction. By integrating environmental considerations, economic factors, human thinking patterns, social norms, and cultural traditions, alongside multidisciplinary approaches and indigenous knowledge, this research demonstrates that urban mobility can effectively address the environmental, social, economic, and mental well-being of communities. Key recommendations include enhancing public transportation and active mobility, reforming urban forms, adopting inclusive policy and technological innovations, and promoting sustainable travel modes. These strategies must be carefully contextualized to reflect Sri Lanka's indigenous knowledge, unique cultural values (collectivism), emotional attachments (sense of place and beliefs), social behaviours, and environmental conditions. In conclusion, Sustainable mobility planning should transition towards a localized, participatory approach, shifting from "planning for people" to "people for planning", to enhance quality of life and ensure the optimal performance of urban mobility strategies that support holistic sustainable development.

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SYSTEMATIC LITERATURE REVIEW FOR RE-DEFINING 'GREEN' IN HOSPITALITY: TYPOLOGY-SENSITIVE INTERPRETATIONS

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ABSTRACT

"Green" practices are central to sustainability in hospitality, influencing environmental, social, and economic outcomes. Yet, definitions of "green" remain ambiguous and often fail to reflect the diverse operational realities of hotel typologies. This study offers a typology-sensitive redefinition of "green hospitality" through a Systematic Literature Review (SLR), guided by the Context–Intervention–Mechanism–Outcome (CIMO) framework. Excluding the mechanism to focus on conceptual mapping, 137 peer-reviewed Scopus articles were reviewed to trace the evolution of "green," identify 19 thematic dimensions, and analyse their relevance across five hotel types: beach/island, mountain/lake, jungle/forest, urban/city, and mixed-type. Findings reveal significant variation in sustainability priorities by typology—urban hotels emphasize technology and HR equity, while forest lodges prioritize biodiversity and community engagement. A typology-based matrix highlights these contextual differences, challenging the adequacy of one-size-fits-all certification systems. Thematic dimensions span core areas like energy efficiency and water stewardship, and extend to emerging concerns such as staff equity, green financing, and green mobility. By mapping sustainability themes to hotel contexts, this study advances a more nuanced understanding of "green hospitality." The findings inform the development of context-aware strategies and offer practical guidance for researchers, policymakers, and industry stakeholders seeking more effective, typology-sensitive sustainability practices.

Keywords: *Green Certification; Green Hospitality; Hotel Typologies; Thematic Dimensions; Systematic Literature Review.*

1. INTRODUCTION

As global sustainability efforts accelerate, the hospitality sector faces increasing pressure to reduce its environmental and climate impacts. Characterised by high energy use, water consumption, and waste generation, hospitality spans accommodation, food, and recreation services, making it a resource-intensive industry (Kim et al., 2017; Zhan et al., 2022). In response, "green" practices—strategies that promote environmental

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responsibility and operational efficiency—have gained momentum (Kim et al., 2017). Yet, definitions of "green" remain inconsistent, often merging authentic efforts with marketing narratives (Kim et al., 2017; O'Gorman, 2010). Though technological progress and rising environmental awareness have improved practices (Asadi et al., 2020; Songur et al., 2022), a coherent, typology-sensitive framework remains absent (Silva et al., 2021). This ambiguity persists even as the concept of "green" has evolved from a narrow focus on environmental stewardship (Bohdanowicz, 2005; Villares et al., 2007) to a multidimensional paradigm that includes social, economic, and technological dimensions (Kim et al., 2017; Abdullah-Fauzi et al., 2024; Elkhwesky et al., 2022). Practically, green practices are now strategic differentiators in an increasingly competitive hospitality industry (Dodds & Holmes, 2023). Yet, in the absence of context-aware frameworks, sustainability efforts often fall short of addressing diverse stakeholder needs (Rassiah et al., 2024; Jacob et al., 2025). Theoretically, existing literature tends to generalise green practices and lacks a consolidated synthesis that accounts for varied hotel typologies—such as beach, mountain, forest, city, and mixed-use—each with unique sustainability priorities (Rodríguez-García et al., 2023). This highlights a critical research gap. To address this, the present study offers a typology-sensitive redefinition of "green hospitality" through a systematic literature review (SLR). The objectives are: (1) to trace the evolution of the term "green" in hospitality literature, (2) to identify key thematic dimensions of green hotels, and (3) to examine how these dimensions vary across hotel typologies. The paper is structured as follows: Section 2 reviews relevant literature, Section 3 outlines the methodology, Section 4 presents findings and thematic analysis, and Section 5 concludes with implications and future directions.

2. LITERATURE SYNTHESIS

2.1 EVOLUTION OF GREEN HOTEL DEFINITIONS

The definition of "green hotels" has shifted from a general environmental notion to a structured sustainability model that enhances guest experience (Abdullah-Fauzi et al., 2024). Certifications such as LEED and Green Key provide standardised criteria for evaluating sustainability in hospitality (Rokip et al., 2022), supporting operational transparency aligned with consumer expectations (Budarma et al., 2020). Green practices—energy efficiency, water conservation, and waste reduction—vary across hotel typologies (Mishra & Shekhar, 2019). Coastal resorts prioritise marine conservation (Kunchornsirimongkon & Ditta-Apichai, 2020), mountain and forest hotels favour ecological design (Damaianti et al., 2023), while urban hotels adopt green building technologies (Kunchornsirimongkon, 2020). Younger travellers also show greater willingness to pay for sustainable options (Phan-Huy et al., 2023). Despite growing adoption, limited research addresses how typology-specific practices impact guest satisfaction or operational performance—underscoring the need for context-sensitive frameworks in green hospitality.

2.3 LIMITATIONS OF GREEN CERTIFICATIONS ACROSS HOTEL TYPOLOGIES

Certifications like LEED, BREEAM, Green Key, and EPC standardise green practices but vary in addressing product plus process paradigms. LEED and BREEAM cover materials and energy management, suiting urban hotels (Darko & Chan, 2017), yet falter in beach and forest settings where biodiversity matters (Damsari et al., 2021). Green Key focuses on operational training, fitting beach and forest needs (Rokip et al., 2022), while

EPCs target energy performance, missing community engagement (Hadjithoma et al. 2024). Ayuso (2007) and Kim et al. (2017) note generalised limitations, suggesting typology-specific adjustments.

3. METHODOLOGY

Systematic literature reviews (SLRs) reduce bias and structure complex inquiry (Naldi et al., 2022). This review applies the CIMO framework to address definitional inconsistencies in green hospitality (Denyer et al., 2008), omitting Mechanism to prioritize conceptual mapping. Following PRISMA guidelines (Page et al., 2021; Chen et al., 2022), Scopus was selected for its broad peer-reviewed coverage. The search string combined terms on hotel typologies and definitions as follows:

(("greenhotel*"OR"ecohotel*"OR"sustainablehotel*"OR"greenhospitality"OR"ecohospitality"OR"sustainablehospitality"OR"beachresort*"OR"islandresort*"OR"mountainresort*"OR"lakeresort*"OR"foresterort*"OR"jungleresort*"OR"urbanresort*"OR"cityresort*")AND("definition*"OR"criteria"OR"concept*"OR"interpretation*"OR"standard*"OR"certification*")AND("evolution"OR"change*"OR"trend*"OR"development*"OR"variation*OR"difference*"OR"inconsistency*"))

After filtering for relevance, 112 articles were retained from 10,343 records (see PRISMA diagram, Figure 1).

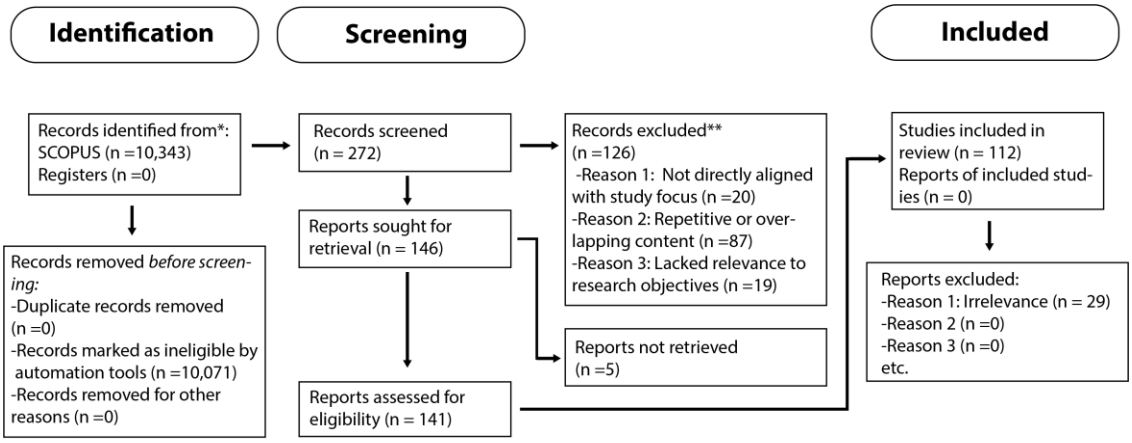


Figure 1: Stages of PRISMA systematic literature review

4. FINDINGS AND DISCUSSION

This section traces the evolution of "green" in hospitality literature, identifies its key themes, and analyses them through a typology-sensitive lens.

4.1 "GREEN" EVOLUTION IN HOSPITALITY LITERATURE

Figure 2 illustrates the concept of "green" in hospitality evolved from cost-saving and stewardship (Kirk, 1995; Horobin & Long, 1996) to certified accountability via ISO 14001. By the 2000s, it encompassed efficiency, branding, and consumer appeal (Bohdanowicz, 2005; Ayuso, 2007; Manaktola & Jauhari, 2007; Han et al., 2009; Kim & Han, 2010). From 2011 to 2019, "green" in hospitality expanded to include CSR, ethical consumption, and Green HRM (Merli et al., 2019; Pham et al., 2019). Recent trends emphasise digital integration and ethical alignment in shaping consumer expectations

(Kruesi & Remy, 2024). Technology now complements ecological goals—e.g., energy monitoring supports water resilience in beach resorts and biodiversity in forests (Jacob et al., 2025). This marks a shift toward holistic sustainability. Consumer mindsets have also evolved, favouring a transparent, product-plus-process paradigm over product-centric products (Han et al., 2009; Kim & Han, 2010; Abdullah-Fauzi et al., 2024; Abdullah et al., 2019).

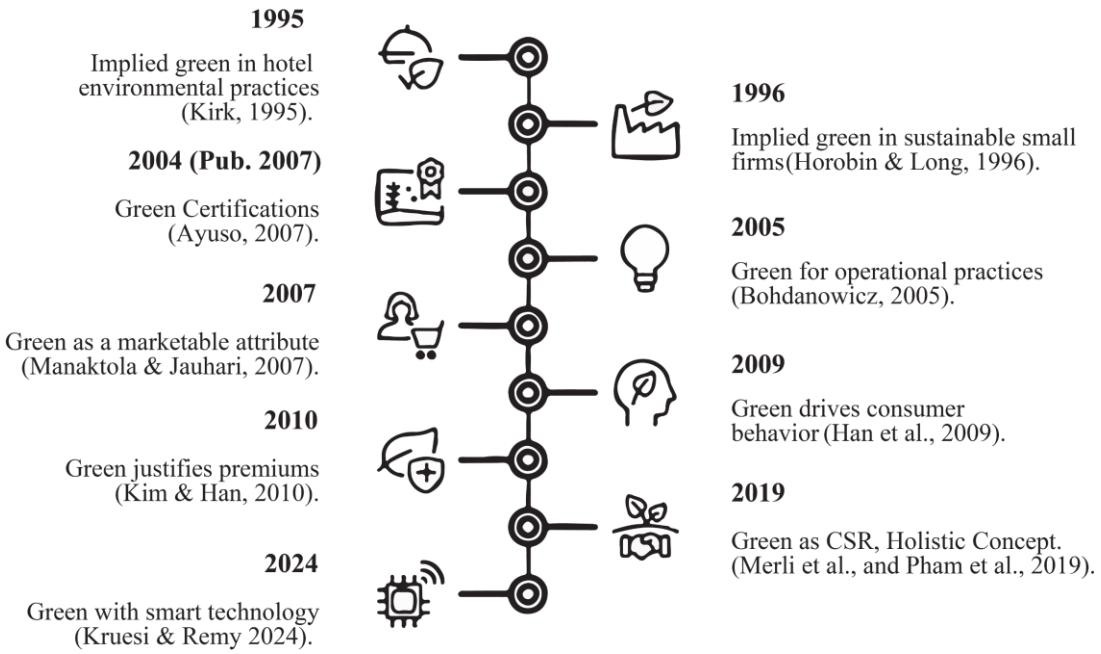


Figure 2: Evolution of the term 'green' within hospitality sustainability literature

4.2 KEY THEMATIC DIMENSIONS OF "GREEN" HOSPITALITY

A context-driven coding process identified 19 key "green" dimensions in hospitality, from core themes like energy efficiency to emerging areas like wellness and resilience. Each is traceable via P-code references linked to the reviewed papers in Table 1.

Table 1: Key thematic dimensions of 'green' hotels

Theme	Description	Codes
Water resilience and stewardship	Strategies for efficient water use, recycling, rainwater harvesting, and greywater treatment within hospitality settings.	P10, P104, P105, P116, P125, P128, P130, P131, P132, P133, P44, P8, P95,
Overtourism and carrying capacity	Addressing the ecological and social pressures from excessive tourist numbers, especially in sensitive zones.	P15, P8, P96
Carbon emissions and climate action	Policies and operational strategies that target the reduction of greenhouse gas emissions in the hospitality industry.	P12, P2, P21, P22, P27, P29, P30, P32, P4, P64, P70, P73, P74, P86, P9
Tourist education and behaviours	Guest-facing communication and programs designed to promote responsible travel behaviour.	P110, P111, P114, P115, P17, P18, P26, P28, P29, P32, P42, P45, P67, P86, P88,

Theme	Description	Codes
Green financing	Investment models, funding mechanisms, and financial incentives to support green hotel development.	P11, P119, P67, P95
Technology integration	Use of digital and smart technologies to enhance sustainability, from energy monitoring to mobile check-in.	P14, P29, P33, P35, P42, P5, P63, P64, P67, P75, P78, P84
Staff equity and social sustainability	Fair employment practices, diversity, gender equity, and worker well-being in hospitality HR systems.	P116, P117, P122, P14, P25, P37, P55, P59, P76, P86, P93
Green mobility and access	Encouraging low-impact transport such as bicycles, electric vehicles, or walkable tourism infrastructure.	P14, P22, P42, P45, P61, P98
Cultural heritage	Preservation and promotion of local traditions, architectural styles, and intangible heritage within hotel practices.	P114, P115, P134, P4, P40, P42, P45, P58, P85, P96
Sustainable construction and materials	Use of environmentally friendly building techniques, green architecture, and sustainable sourcing of construction materials.	P10, P24, P29, P30, P51, P6, P60, P64, P67, P71, P78,
Community engagement and local economies	Involvement of local communities in tourism supply chains, employment, and decision-making processes.	P25, P3, P30, P72, P84, P86, P90, P95
Certification and regulatory governance	The role of eco-labels, sustainability standards, and legal compliance in defining and assessing green hotels.	P2, P24, P30, P4, P44, P52, P55, P7, P8
Disaster resilience	Preparedness for climate-related risks such as storms or floods, and operational resilience in hospitality.	P103, P104, P32, P4, P90, P95,
Generational responsiveness and experience	Tailoring sustainability features and green messaging to suit millennial, gen z, or older demographics.	P1, P111, P14, P15, P30, P46, P54, P95,
IEQ	Indoor environmental quality factors including lighting, air quality, noise levels, and thermal comfort.	P116, P87
Wellness restorative hospitality	Integration of spa, nature-based healing, and wellness architecture as part of green hotel design.	P22, P30, P32, P4, P41, P5, P50, P51, P6, P8
Energy efficiency and renewable integration	Practices focused on reducing energy consumption and integrating solar, wind, or other renewable energy sources in hospitality operations.	P105, P116, P124, P133, P64, P74
Biodiversity and ecosystem conservation	Efforts aimed at preserving local flora, fauna, and habitats, especially in ecologically sensitive areas such as coastal or forest resorts.	P11, P21, P25, P30, P4, P54, P60, P74

Theme	Description	Codes
Food sustainability	Practices related to organic sourcing, food waste reduction, and support for local agriculture in hotel operations.	P116, P20, P37, P52, P60
P1 Staffieri et al. (2018), P2 Thomas et al. (2020), P3 Cai et al. (2024), P4 Jamilah et al. (2025), P5 Kauppila et al. (2004), P6 Halford et al. (2004), P7 Hyde et al. (2007), P8 Villares et al. (2007), P10 Kaiser et al. (2010), P11 Lowe et al. (2008), P12 Horstman et al. (2009), P14 Roper et al. (2010), P15 Zhong et al. (2011), P17 Wei (2011), P18 Goh et al. (2014), P20 Pirani et al. (2014), P21 Tolvanen and Kangas (2016), P22 Unger et al. (2016), P24 Darko and Chan (2017), P25 McDougall (2017), P26 Al-Aomar and Hussain (2017), P27 Zhong and Chen (2019), P28 Juliao et al. (2019), P29 Anzagira et al. (2019), P30 Kulusjarvi (2019), P32 Thomas et al. (2020), P33 John (2020), P35 Ibarnia et al. (2020), P37 Gandhi et al. (2020) , P40 Saracevic and Schlegelmilch (2021), P41 Yin et al. (2021), P42 Anzorova et al. (2021a), P44 Damsari et al. (2021), P45 Sarbassova et al. (2021a), P46 Kele et al. (2021), P50 Elkhwesky et al., (2022), P51 Han, & Zhang (2022), P52 Kasavan and Mohamed (2022), P54 Checon et al. (2022), P55 Bawa et al. (2022) , P58 Králiková and Kubát (2022), P59 Aggarwal and Sharma (2022), P60 Dilshan and Toko (2022), P61 Hoagland et al. (2023), P63 Arsawan et al. (2023), P64 Wallius et al. (2023), P67 De-beer and Kajimo-Shakantu (2023), P70 Xames et al. (2023), P71 Abdulaali et al. (2023), P72 Singh and Khanwani (2023), P74 Fan et al. (2023), P75 Singh et al.(2024), P76 Tahir et al. (2024), P78 Li et al. (2024), P84 Sanz-Lopez et al. (2024), P85 Kurniawan et al. (2024), P86 Lim et al. (2024), P87 Abdulaali et al. (2024), P88 Hadjithoma et al. (2024), P90 Zielinski et al. (2025), P93 Jamil et al. (2010), P95 Narain et al. (2015), P96 Sari and Rahayu (2018), P98 Bachtiar (2020), P103 Mead and Atkin (2023), P104 Velea et al. (2024), P105 Khuri et al. (2024), P110 Lim et al. (2019), P111 Abdullah et al. (2019), P114 Sarbassova et al. (2021b), P115 Anzorova et al. (2021b) , P116 Dani et al. (2021), P117 Qiu and Zhao (2024), P119 Kruesi and Remy (2024), P122 Han et al. (2009), P124 Kirk (1995), P125 Manaktola and Jauhari (2007), P128 Jacob et al. (2025), P130 Hu et al. (2020), P131 Foster (2021), P132 Ibrahim and Yusof (2017), P133 Prakash et al. (2023), P134 Owen (2018).		

As summarised in Table 1, 19 key thematic dimensions reflect the evolution of green hospitality into a multidimensional sustainability model. Core environmental themes—water stewardship, carbon reduction, biodiversity, and energy efficiency—remain central, especially in ecologically sensitive areas (Villares et al., 2007; Thomas et al., 2020; Saracevic et al., 2021). Urban contexts prioritise technological and economic themes like green financing, sustainable construction, and digital innovation (Cai et al., 2024; Halford et al., 2004). Social and cultural dimensions—staff equity, community engagement, and heritage—underscore stakeholder inclusion (Zhong et al., 2011; Goh et al., 2014). Regulatory, wellness, and resilience themes reflect growing concern for guest well-being and governance (Thomas et al., 2020; Narain et al., 2015).

4.3 TYPOLOGY-BASED THEME MATRIX

Findings reveal a shift from generic checklists to typology-sensitive sustainability strategies. As shown in Figure 3, 19 green themes vary by hotel type and are categorised as Core, Contextual, or Peripheral. The heat map illustrates theme distribution across typologies. Guided by qualitative content analysis, the heat map aids interpretation but is not used as a standalone analytical tool.

Themes	Beach/ Island	Mount	Lake	Forest/ Jungle	Mixed	Urban/ City
Energy Efficiency & Renewable Integration	🟢	🟢	🟢	🟢	🟢	🟢
Staff Equity & Social Sustainability	🟢	🟢	🟢	🟢	🟢	🟢
Carbon Emissions & Climate Change	🟢	🟢	🟢	🟢	🟢	🟢
Overtourism & Carrying Capacity	🟢	🟢	🟢	🟢	🟢	🟢
Water Resilience & Stewardship	🟢	🟢	🟢	🟢	🟢	🟠
Sustainable Construction & Materials	🟢	🟢	🟢	🟢	🟢	🟠
Community Engagement & Local Economies	🟢	🟢	🟢	🟢	🟢	🟠
Food Sustainability	🟢	🟢	🟢	🟢	🟢	🟠
Tourist Education & Behaviour	🟢	🟢	🟢	🟢	🟢	🟠
Disaster Resilience	🟢	🟢	🟢	🟢	🟢	🟠
Wellness Restorative Hospitality	🟢	🟢	🟢	🟢	🟢	🟠
Biodiversity &Ecosystem Conservation	🟢	🟢	🟢	🟢	🟢	🟡
Certification & Regulatory Governance	🟠	🟠	🟠	🟠	🟠	🟢
Cultural Heritage	🟠	🟠	🟠	🟠	🟠	🟢
Technology Integration	🟠	🟠	🟠	🟠	🟠	🟢
Generational Responsiveness	🟠	🟠	🟠	🟠	🟠	🟢
IEQ	🟠	🟠	🟠	🟠	🟠	🟢
Green Financing	🟠	🟠	🟠	🟠	🟠	🟢
Green Mobility	🟡	🟡	🟡	🟡	🟠	🟢

Figure 3. Key thematic dimensions across different hotel typologies

Core Themes (🟢): Core sustainability themes are consistently prioritised across hotel typologies due to their foundational role in green operations. **Energy Efficiency and Renewable Integration** is universally critical in both off-grid and high-consumption environments (Ivanov et al., 2014; Nicholls & Kang, 2012; Prakash et al., 2023; Jacob et al., 2025). **Water Resilience and Stewardship** is vital in Beach/Island, Lake, Forest/Jungle, Mixed, and Urban hotels, where ecological fragility and consumption pressure necessitate careful management (Omune et al., 2021; Nicholls & Kang, 2012; Sanjiwani & Dewi, 2023). Similarly, **Carbon Emissions and Climate Change** demand strategic attention, particularly in climate-sensitive or high-footprint settings such as Lake, Forest, and Urban hotels (Prakash et al., 2023; Jacob et al., 2025). **Biodiversity Conservation** is essential in Beach/Island and Forest/Jungle hotels, where guest experiences are closely tied to ecosystem integrity, while **Overtourism and Carrying Capacity** further reinforce the need for ecological balance in these nature-dependent contexts. Additional core themes include **Staff Equity and Social Sustainability**, which spans all typologies due to the role of HR and CSR in sustaining green practices (Prakash et al., 2023; Jacob et al., 2025); **Sustainable Construction,** especially in ecologically sensitive areas (Hu et al., 2020; Foster, 2021); and **Wellness, Tourist Education, Community Engagement, and Disaster Resilience**, which together reflect the experiential and socio-environmental dimensions of sustainable hospitality (Miller et al., 2015; Jamaludin & Yusof, 2013). While these themes form the backbone of green hotel strategy, others fluctuate based on location and operational structure, transitioning us into the domain of contextual priorities. **Contextual Themes (🟠):** Contextual themes in green hospitality gain or lose prominence depending on the unique characteristics of a

hotel's typology. For example, while **Community Engagement** is central to Island and Forest hotels, it is more peripheral in Urban settings where supply chains and community linkages are less direct (Zambrano et al., 2010). Themes such as **Certification, Cultural Heritage, Technology Integration, Generational Responsiveness, and Indoor Environmental Quality (IEQ)** hold contextual value across most typologies, with increased significance in cities due to tighter regulatory controls and advanced infrastructure (Zambrano et al., 2010; Foster, 2021). **Certification and Regulatory** governance vary by typology. LEED and BREEAM excel in urban hotels with their technology focus (Darko and & Chan, 2017), but struggle with biodiversity in beach and forest settings, where Green Key's operational training fits better (Rokip et al., 2022; Damsari et al., 2021). EPCs often neglect factors like varying operating conditions where beach resorts operate with high cooling demands due to warm climates, and Forest resorts could indicate heating needs depending on the remote location and its climate thus relying on generalised rating may not fully capture the unique complexity of the hotel type (Yilmaz & Cesur, 2023). Ayuso (2007) highlights that generalised certifications cause coastal misalignment, supporting typology-specific standards. **Green Financing**, though critical in Urban contexts, is less accessible in remote regions, where funding tends to align with specific conservation or local development goals (Jacob et al., 2025; Sanjiwani& Dewi, 2023; Ibrahim & Yusof, 2017). These contextual patterns underscore the importance of tailoring financial, regulatory, and operational sustainability approaches according to typology-specific realities. However, certain themes, while relevant, remain consistently limited in applicability—especially in remote environments—thereby falling into the category of peripheral concerns. **Peripheral Themes (🟡):** Among all sustainability dimensions, **Green Mobility** is the only theme widely classified as peripheral across typologies, with the notable exception of Urban hotels where it holds strategic value (Jamaludin & Yusof, 2013). In cities, green mobility takes the form of EV charging, bicycle rentals, and transit partnerships, enhancing low-carbon access. In contrast, Mountain and Island hotels often face infrastructure constraints that limit mobility choices, focusing instead on local shuttles or limited transit initiatives (Hu et al., 2020; Jacob et al., 2025). Although green transport plays a role in reducing emissions, its typology-dependent feasibility reflects the broader challenge of applying uniform sustainability measures across diverse hospitality environments. The findings demonstrate that the concept of "green" in hospitality has progressively evolved between 1990 and 2024—from an operational focus on environmental efficiency to a multidimensional framework incorporating social, economic, technological, and experiential dimensions. The identification of 19 thematic dimensions, along with their typology-sensitive variation, highlights the contextual nature of sustainability priorities across hotel types, reinforcing the need for adaptive, typology-specific strategies over standardized green frameworks.

5. CONCLUSIONS AND RECOMMENDATIONS

This study redefines "green" in hospitality by tracing its evolution and variation across hotel typologies. A systematic literature review identified 19 thematic dimensions, reflecting a shift from basic environmental actions to a multidimensional sustainability model encompassing ecological, economic, social, and technological domains. These themes were classified into: **Core themes;** Universal elements (e.g., energy efficiency, water stewardship, carbon reduction, biodiversity, and staff equity), **Contextual themes;** typology specific (e.g., community engagement, green financing, and cultural heritage),

and **Peripheral themes;** location limited elements (e.g., green mobility, especially in urban settings). Findings underscore the importance of typology-sensitive strategies that reflect ecological settings, infrastructure, and stakeholder needs. Existing certification systems should evolve from standardised models to modular frameworks that accommodate operational diversity. Practitioners are encouraged to prioritise core themes while adapting contextual and peripheral elements to local challenges. Future research should assess these frameworks' impact on operations, guest satisfaction, and environmental outcomes. This study offers a foundation for advancing green hospitality.

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THE APPLICABILITY OF CARBON EMISSION ESTIMATION WITH BIM ENVIRONMENT: SRI LANKAN CONTEXT

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ABSTRACT

The global construction industry is increasingly adopting sustainable practices and advanced technologies to enhance efficiency and reduce environmental impacts. Within this context, managing carbon emissions has emerged as a critical component of sustainable development, with Building Information Modelling (BIM) serving as a pivotal tool in this pursuit. While developed countries have already integrated BIM and carbon emission estimates, there is a notable opportunity for similar advancements in developing countries, potentially leading to significant progress within the industry. Hence, this paper aims to explore the applicability of implementing BIM for carbon emission estimations in the Sri Lankan construction industry. A comprehensive review of existing literature identified the importance of carbon emission simulations, BIM implementation strategies and estimation procedures in other countries. Further, this research involved a survey to assess the familiarity and experience levels of construction professionals with BIM tools for carbon emission estimations in Sri Lanka. Findings from the research point to Autodesk Insight as the primary software tool used within the industry. While the industry demonstrates an awareness of these processes, its progress is hampered by a lack of experience in using these technologies for carbon emission estimation scenarios and the absence of crucial databases such as Environmental Product Declarations. The study recommends enhancing industry capacity through targeted training and the adoption of advanced tools. It also encourages further research to assess the compatibility of BIM technologies in the local context, aiming to bridge the gap and drive sustainable transformation in Sri Lanka's construction sector.

Keywords: *BIM; Carbon Emission; Construction Industry; Factors; Sustainability.*

1. INTRODUCTION

The construction industry plays a vital role in driving economic growth and fostering socio-economic advancement (Jiang et al., 2022). In line with the global progression of this sector, the integration of digitalisation has become a defining trend. As a result, Building Information Modelling (BIM) has emerged as an indispensable integrated approach, providing comprehensive project information spanning the stages of design,

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construction, and operations as illustrated in Figure 1 (Chen et al., 2024). The shift from conventional construction methodologies to BIM-based design has been a prominent subject of discourse within the construction domain since the 1970s. Within the realm of BIM, the various types and specificities of digitised building-related data essential for a construction project are termed BIM dimensions, encompassing a spectrum from 2D to 7D (Ding et al., 2014).

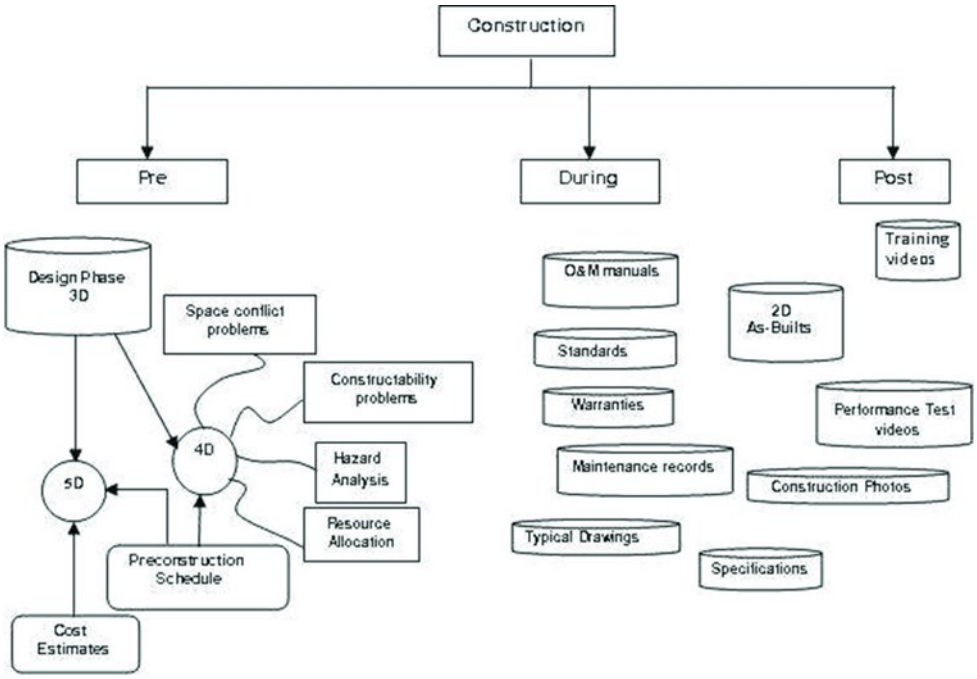


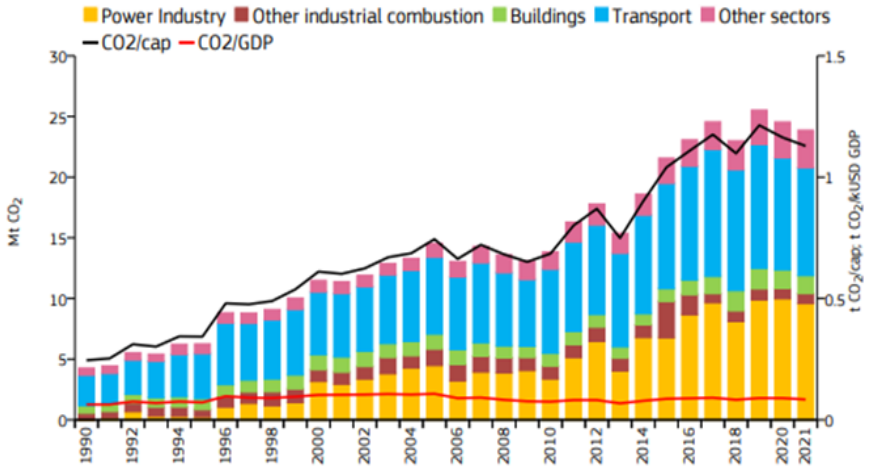
Figure 1: Current status of BIM in construction

The construction sector is progressively embracing sustainable development strategies to attain a harmonious blend of economic progress, environmental preservation, and societal welfare (Yao et al., 2023). Within this context, the growing utilisation of BIM technology is geared toward addressing sustainability concerns at various stages of construction. These include the selection of eco-friendly building materials, the analysis of energy efficiency, and the assessment of the feasibility of renewable energy systems (Wong and Fan, 2013).

Conversely, the term "carbon footprint" denotes the complete volume of greenhouse gases generated by human activities. This encompasses both direct emissions from energy production and indirect emissions stemming from the combustion of fossil fuels during manufacturing, warming, and transportation (Whig et al., 2022). Carbon dioxide (CO2) emissions are a major concern for ecological conservation and sustainable development. Buildings account for 39% of global energy-related carbon emissions, with 28% being functional and 11% from materials and development processes (World Green Building Council, 2023). In Sri Lanka, carbon emission contribution in different sectors is shown in Figure 2. Though Sri Lanka own insignificant amount of CO2 emission compared to other countries, the CO2 emission gradually increased every year (United States Environmental Protection Agency [US EPA], 2016). CO2 emissions contribute to global warming, exacerbate glaciers and polar ice melting, cause hazardous rainfalls, and lead to coastal and ocean acidification (Nußholz et al., 2019). They further illuminated that while acting as a greenhouse gas it also retains heat in the environment like a blanket,

making it difficult for the earth to cool. Construction operations, such as clearing land, burning waste, and using engine-emitting equipment, contribute to environmental pollution. Further, the manufacturing and transportation of materials account for 82-96% of all CO2 emissions during the construction period (Sizirici et al., 2021).

In the world context, China, the US, the EU, India, the Russian Federation, and Japan are the largest emitters of carbon dioxide, with global fossil (Nejat et al., 2015). Yet, CO2 emissions decreased by 5.3% in 2020 due to the COVID-19 pandemic. In 2021, global emissions returned to pre-pandemic levels, reaching 37.9 Gt, 0.36% less than in 2019, according to the European Commission Joint Research Centre. In June 2022, building regulations mandate significant industry changes, with developed countries requiring new homes to produce 30% less CO2 emissions (Woodfield, 2022).



Year	CO_2 emissions Mt CO_2/yr	CO_2 emissions per capita t CO_2/cap/yr	CO_2 emissions per unit of GDP PPP t CO_2/kUSD/yr	Population
2021	23.863	1.128	0.084	21.146M
2020	24.537	1.164	0.089	21.084M
2005	14.535	0.744	0.107	19.525M
1990	4.250	0.245	0.063	17.330M

Figure 2: CO2 emissions by sector in Sri Lanka
Source: (Crippa et al., 2023)

Calculations of carbon emissions might differ based on the technique and data sources utilised (Cherubini et al., 2009). However, direct and indirect emissions are some typical approaches for estimating carbon emissions. Carbon emissions are detected throughout a building's life cycle, including design, manufacturing, and distribution. It derives in the design stage, as architects, planners, and engineers use energy and transportation (Hussain et al., 2023). Manufacturing involves local development and imports of goods. Distribution releases CO2 during freight and business travel.

On the other hand, Life Cycle Assessment (LCA), BIM, Environmental Product Declarations (EPDs), and Energy Modelling are several approaches for estimating carbon emissions in the construction sector (Nußholz et al., 2019). They further emphasised that LCA is a method for evaluating the environmental impact of a product, process, or service throughout its life cycle, considering every stage from extraction to disposal. LCA considers various environmentally affected areas, such as resource depletion, waste generation, water use, greenhouse gas emissions, and energy use. It is essential for calculating carbon emissions and estimating carbon footprints throughout a product's life

cycle (Nguyen et al., 2021). The approach and main concepts used in LCA in Sri Lanka are the same as those used in other locations. However, the evaluation might take into account certain factors and data sources that are pertinent to Sri Lanka (Amarasinghe et al., 2021).

A building's carbon emissions during construction, usage, and end-of-life can be estimated using BIM (Peng, 2016). Accordingly, the application of BIM can make it easier and more accurate to detect and measure the emissions brought on by the usage of materials, energy, transportation, and waste. Improved accuracy, early design analysis, and cost savings are some main advantages of utilising BIM for carbon emission estimation (Zhang et al., 2022). They further emphasised that assigning emission factors, gathering data, calculating emissions, and analysing the results are the steps that can be used to calculate carbon emissions using BIM. BIM software can be complemented with specialist software or plugins for carbon emission studies, even if it doesn't directly compute emissions (Mousa et al., 2016). Common software used in conjunction with BIM for carbon emission analysis are Autodesk Insight, IES Virtual Environment (IESVE), Design Builder, Green Building Studio (GBS), and Sefaira.

The construction sector's carbon emissions can be estimated with BIM. The factors are necessary for BIM's estimation of carbon emissions, such as building design data (including a building's geometry, components, and systems, can be recorded using BIM), energy consumption data (the energy consumption of a building can be simulated using BIM, which is necessary for estimating operational carbon emissions), transportation data (the transportation of equipment and materials to locations and from the building sites can be monitored using BIM), location data (the location of construction can have an impact on the carbon emissions related to the transportation of materials and the energy utilized throughout the operation), and material data (data about the materials involved in developing the building can be collected with BIM) (Heydari & Heravi, 2023).

According to Ministry of Environment (2023) Sri Lanka is expected to achieve net zero status by 2050. Further, as a non-annex-I-member country of Paris agreement Sri Lanka has pledged 14.5% GHG emissions by 2030 (Fernando et al., 2023). However, Sri Lanka lacks the proven evidence to use BIM for carbon emission estimations. This has been further acknowledged by Amarasinghe et al. (2021), stating that the integration of BIM with LCA presents a valuable area for further research. This lack of knowledge accumulates in reducing possible early design analysis, value-engineered sustainable approaches, cost savings and accurate carbon emission calculations. In line with this, the present study aims to explore the applicability of implementing BIM for carbon emission estimations in the Sri Lankan construction industry. To achieve this aim, it is necessary to assess the level of new technology adoption within the construction industry, identify the key factors involved in carbon emission estimation using BIM, and identify the key challenges of carbon emission estimation using BIM within the Sri Lankan construction industry. To close the knowledge gap two rounds of data were gathered and analysed. The findings of the data collection are discussed in later sections of this paper.

2. METHODOLOGY

The preliminary study addresses significant and pertinent facts from a work's perspective, identifying a gap in research. It reveals that while recognised construction projects use

BIM technology to estimate carbon emissions, no one has examined its use in Sri Lankan building construction. The study aims to fill this gap in the Sri Lankan building sector.

The research aimed to achieve its initial objectives through a comparative literature review and data collection. A mixed-methods approach was adopted in this research to achieve the objectives by capturing both measurable trends, such as familiarity with BIM tools, and deeper contextual understanding through qualitative insights (Taguchi, 2018). Given the need to identify the knowledge gap regarding the use of new technologies in the construction industry, a questionnaire survey was conducted. As the research explores an emerging area that requires specialised expertise, snowball sampling was selected as an appropriate strategy to access and recruit knowledgeable professionals in the industry (Leighton, 2021). Fifty responses were received out of sixty sent questionnaires, where only forty-one completed questionnaires were available. To gather data about factors used for carbon emission estimation with BIM and for the advancements within the industry, semi-structured interviews with experts in different domains of expertise were carried out. The gathered data was then analysed to establish a comprehensive understanding of the topic. The research sample and participants for the questionnaire survey are illustrated in Table 1.

Table 1: Classification of responses by profession and years of experience

	Project Manager	**Engineer**	**Architect**	**Quantity Surveyor**	**BIM Manager**
0 - 5 Years		3	1	18	
6 - 10 Years	1	6	1	1	
11 - 15 years	1	2	3	1	1
16 – 20 years		2			
More than 20 Years					

Since, this study initially aimed to determine the awareness of Sri Lankan construction industry professionals regarding BIM software and tools used for carbon emission estimation in building construction projects, data, collected through questionnaires were analysed using MS Excel. Relative Importance Index (RII) is used to rank the frequency of used BIM based carbon emission estimate software and tool. Also, this study aimed to determine the frequency of use of various BIM software and tools and their collaboration for carbon emission estimation. The next step of the study was conducted through semi-structured interviews with industry professionals and experts, including BIM experts, carbon emission estimating professionals, and professionals familiar with carbon emission estimation projects and BIM technologies, to understand the concept of carbon emission estimation in the Sri Lankan construction industry. The summary of the methodology conducted in this research is shown in figure 3.

The study conducted semi-structured interviews with industry professionals and BIM specialists in Sri Lanka focused on estimating carbon emissions using BIM. Three experts were chosen for the study as shown in Table 2. The literature review explores the concept of carbon emissions in construction projects and the process of carbon emission estimation using BIM. Interviewees E(1) and E(3) have good knowledge about carbon emission estimation scenarios, yet E(2) has a better understanding and experience in zero carbon emission projects. E(2) has contributed to implementing carbon emission estimation software, while E(3) has extensive experience working with such software.

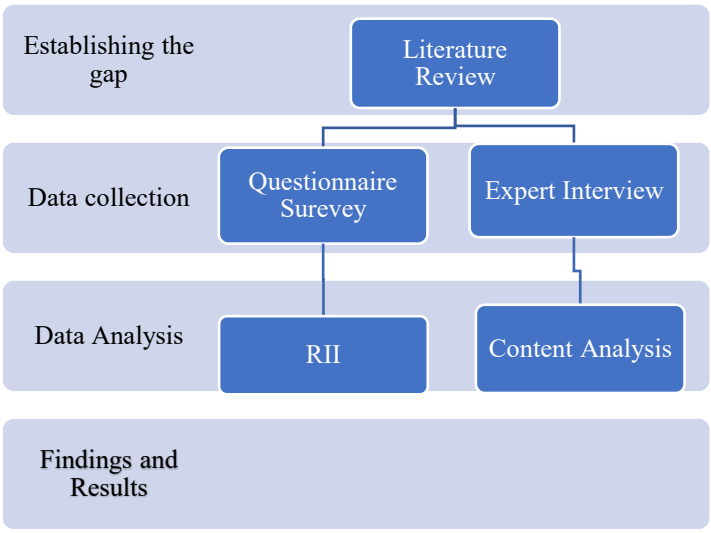


Figure 3: Summary of the methodology

Table 2: Professionals and their designation, qualification, and years of experience

Interview	Designation	Qualifications	Years of experience
E (1)	BIM Specialist	BSc. Physical science, UOC MSc. In GIS, USJ	13
E (2)	Professor of Civil Engineering	Researcher Carbon emission estimation expert	> 20 years
E (3)	Civil Engineer	Chartered Civil Engineer	12

3. DATA ANALYSIS AND DISCUSSION

3.1 EXPERIENCE WITH COMMON BIM SOFTWARE AND TOOLS

Figure 4 shows that all respondents of the questionnaire survey are experienced with AutoCAD, with a majority not having experience with Tekla Structures. 75% of respondents have experienced Autodesk Revit, while 22% have no experience.

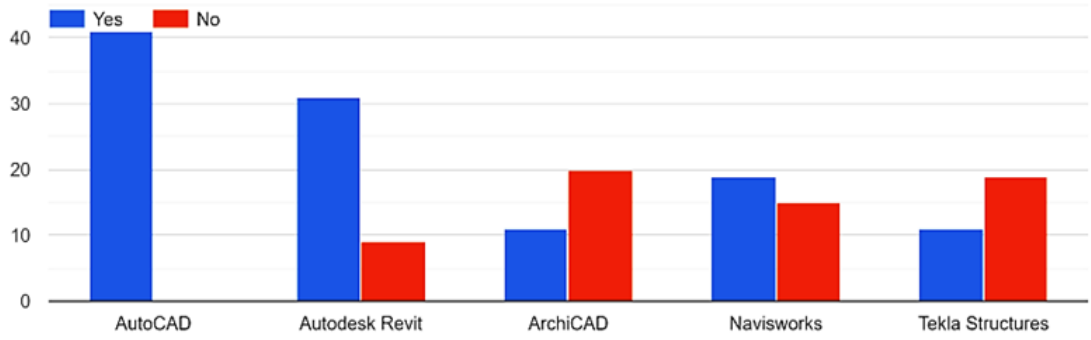


Figure 4: Classification of responses using common BIM software and tools

ArchiCAD software has a higher number of inexperienced respondents than experienced ones, while Navisworks has the opposite result. The research indicates that while most construction professionals have experience with 2D BIM software tools, they lack in extensive experience with 3D modelling software tools, with an average professional having a good understanding of Revit software.

3.2 The Awareness and Involvement in Carbon Emission Estimation Scenarios

The study aims to identify the level of knowledge and experience in developing countries regarding carbon emission estimation. The survey showed that 48.8% of respondents were moderately aware of carbon emission scenarios, with one respondent having a very high level of awareness. 22% had a high level of awareness, 17.1% had a low level of awareness, and 9.8% had the least awareness. This information further illustrated in Figure 5, is crucial for advancing carbon emission estimation in developing countries.

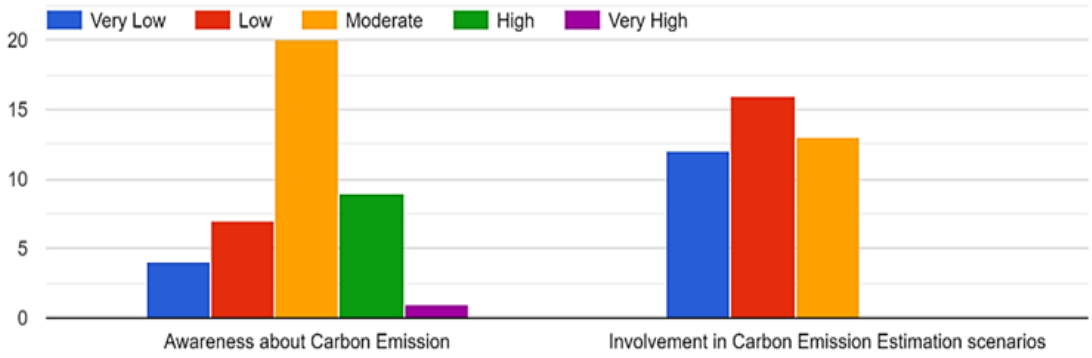


Figure 5: Awareness and involvement in carbon emission estimation scenarios

The majority of construction industry professionals in Sri Lanka have a moderate level of awareness about carbon emission processes, still their involvement in carbon emission estimation scenarios is low. The survey indicates that 29.3% have been involved in very low levels, and 31.7% have been involved up to a moderate level. Despite this, the majority of professionals have limited experience with carbon emission estimation scenarios, indicating a need for further education and training in this area.

3.3 The Awareness of Software and Tools Used for Carbon Emission Estimation with BIM

BIM can help predict and measure carbon emissions from a development's construction, use, and end-of-life. Professionals have moderate experience with Autodesk Insight (48.8%) and Design Builder (36.6%), yet have a low experience of 39% with IESVE, GBS, and Sefaira as shown in Figure 6. Accordingly, Autodesk Insight, IESVE and Green Building Studio ranked the highest aware software used with BIM. However, a few professionals have good experience with these tools, indicating a need for further development in this area. The majority of respondents are familiar with Autodesk Insight and Design Builder software for carbon emission estimation with BIM, yet have limited knowledge about IESVE, GBS, and Sefaira tools. A few respondents claim to be proficient in using this software and tools.

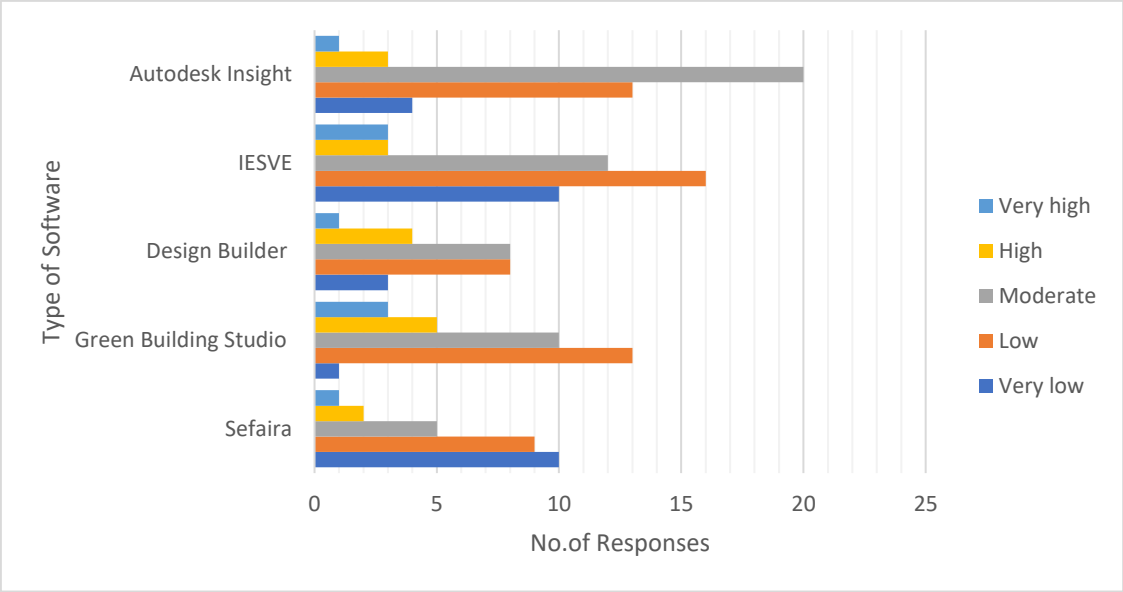


Figure 6: Awareness of software and tools used for carbon emission estimation with BIM

3.4 FACTORS REQUIRED FOR CARBON EMISSION ESTIMATION WITH BIM AND WAY OF COLLECTING THEM

Carbon emission estimation using BIM involves identifying factors such as building design data, energy consumption data, transportation data, location data, material data, and waste data. Building design data can be easily gathered using BIM, while material and transportation data can also be identified using BIM. Autodesk Revit is recommended for this purpose. In developing countries like Sri Lanka, the government lacks good documentation with the EPD, making it difficult to estimate carbon emissions before construction. However, new technology-based tools can automate and will minimise errors, making carbon emission estimation more efficient and accurate. Data can be derived from previous similar projects, as there is no advanced database for collecting information. Waste data is not suitable for BIM-based carbon emission estimation, and operational data may also be considered. The companies are planning to start projects using Revit software for carbon emissions estimation, creating new opportunities in estimation processes in Sri Lanka and developed countries.

3.5 CHALLENGES OR LIMITATIONS ASSOCIATED WITH USING BIM FOR CARBON EMISSION ESTIMATION IN SRI LANKA

The construction industry in Sri Lanka faces challenges in adopting new technology-based scenarios due to various factors. Many professionals lack the knowledge and skills to work with BIM software and tools, and the government lacks a good database for EPDs. Traditional procedures are preferred, and the government changes and inflation are implementing new rules and regulations that may negatively impact the industry. Common challenges were identified, including lack of data quality and availability, lack of BIM adoption, localised guidelines and standards, lack of BIM libraries and resources, and limited knowledge and training. Despite these challenges, the Sri Lankan construction industry is moving towards implementing BIM technology yet facing challenges such as a lack of EPD data, limited awareness about carbon emission

estimation factors, and limited knowledge and training. Despite these obstacles, the industry is moving towards a more advanced and efficient approach to construction.

4. CONCLUSIONS

The research aimed to determine the potential of the Sri Lankan construction industry in carbon emission estimation using Building Information Modelling (BIM). The objectives were to identify the concept of carbon emissions in construction projects, which have a significant impact on global climate change. Buildings are currently responsible for 39% of all energy-related carbon emissions worldwide. New legislation requires new construction developments to produce 30% less CO2 emissions.

The process of carbon emission calculation with BIM was identified with some main BIM software, such as Autodesk Insight, IESVE, Design Builder, GBS, and Sefaira, as effective for carbon emission estimation. However, most professionals had moderate awareness of these tools, with Autodesk Insight being the most well-known. Factors required for carbon emission calculation with BIM include building design data, transportation data, material data, location data, energy consumption data, and waste data. Additionally, operational data could be added as a new factor. The Sri Lankan government lacks proper documentation for obtaining data like EPD data, which poses challenges for carbon emission estimation scenarios. All factors were applicable except waste data, and it was suggested to add operational data.

In a nutshell, the Sri Lankan industry is working with carbon emission estimation projects using BIM, yet there is a need for more databases and better documentation. Industry professionals know software, tools, and working procedures; nonetheless, carbon emissions are not widely considered in construction projects. As sustainability continues to gain momentum globally, future construction projects in Sri Lanka must calculate carbon emissions as a main requirement due to continuous sustainability updates and validated considerations. BIM is a key component for this, and early identification of carbon emissions is advantageous. While the industry possesses the foundational knowledge and tools needed to support such initiatives, the availability of updated documentation and clear regulatory frameworks remains crucial.

Building on these findings, this study provides valuable insights into the applicability of implementing BIM for carbon emission estimation in the Sri Lankan construction industry. Nevertheless, certain limitations should be acknowledged, including a constrained sample size due to the specialised expertise required and the lack of access to comprehensive national databases. The study recommends enhancing industry capacity through targeted training and the integration of advanced technological tools to support more effective BIM adoption. It also emphasises the need for further research to assess the suitability of BIM technologies within the local context, particularly in addressing the challenges identified. Bridging these gaps is essential for promoting sustainability and enabling meaningful transformation within the Sri Lankan construction sector.

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THE EFFECT OF VERTICAL GREENERY SYSTEMS ON BUILDING ENERGY PERFORMANCE: OVERALL THERMAL TRANSFER VALUE-BASED COMPARATIVE ANALYSIS

R.A.A. Munsif[1], Harshini Mallawaarachchi[2] and Dimuthu Vijerathne[3]

ABSTRACT

The construction industry significantly contributes to world energy consumption, representing around 40% of overall energy usage and a considerable portion of greenhouse gas emissions. Tropical cities are exploring sustainable solutions, and passive cooling systems like Vertical Greenery Systems (VGSs) have drawn interest for their potential to enhance energy efficiency. This study examines the influence of VGSs on the energy performance of high-rise buildings in Sri Lanka, utilising the Overall Thermal Transfer Value (OTTV) as the key performance metric. Two high-rise buildings were evaluated: one with a VGS-integrated façade and the other with a standard design without vertical greenery. OTTV were computed using standardised procedures that consider local climate data and envelope features. The OTTV analysis indicates a favourable impact from VGS integrated building, as the average OTTV reduced from 3.681 W/m² in the VGS absence of VGS to 3.527 W/m² with VGS present. The nearly 4.18% reduction appears modest, indicating a considerable improvement in thermal performance. These findings suggest that while VGSs may not drastically reduce OTTV in isolation, they contribute positively to overall energy efficiency strategies in tropical urban settings. The findings offer robust empirical support for the integration of vertical green systems into urban construction plans in tropical environments. This study contributes to the limited body of knowledge on VGS applications in South Asia and advocates for the integration of nature-based solutions in urban building practices. It provides practical insights for architects, policymakers, and green building consultants aiming for energy efficiency and climate resilience in the built environment.

Keywords: *Building Energy Performance; High-rise Buildings; Overall Thermal Transfer Value; Tropical climate; Vertical Greenery System.*

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1. INTRODUCTION

In recent years, the swift pace of urbanization combined with global warming has intensified concerns over Urban Heat Island (UHI) effects and the rising energy demand for building cooling (Shah et al., 2023). At present, buildings account for approximately 40% of energy consumption (Martínez-Rocamora et al., 2016) and 39% of global greenhouse gas (GHG) emissions (Chen et al., 2023), largely resulting from fuel combustion to satisfy their energy requirements (Vijerathne et al., 2022). Consequently, energy conservation has become even more compelling (Demski et al., 2018). Given that air-conditioning (AC) cooling accounts for around 37% of total building energy use globally and up to 56% in tropical regions, increasing temperatures, partly driven by the performance of these AC systems, are expected to elevate energy consumption further, creating a self-reinforcing cycle (Katili et al., 2015). The building envelope, which separates indoor spaces from the external environment, can be optimized to reduce heating and cooling energy needs, as its design greatly impacts both the building's cooling demand and the surrounding environment (Al-Yasiri & Szabó, 2021; Pérez et al., 2017; Shah et al., 2023). Implementing efficient envelope systems can potentially lower total building energy consumption by more than 50% (Al-Masrani et al., 2018).

Energy-efficient technologies help reduce building energy consumption, lower costs, and lessen environmental impacts, including contributions to global climate change (Lee et al., 2015). Many design features in a building and façade characteristics hold huge potential in predicting energy use intensity for each construction (Martinez & Choi, 2017). The adoption of energy-efficient technologies in buildings offers a promising solution to reduce energy consumption, lower costs, and mitigate environmental impacts, particularly those linked to climate change (Lee et al., 2015). To investigate the correlation between the building façade characteristics and the energy efficiency of buildings, it was found that possibly much smaller energy use may result from determining the optimal combinations of façade attribute resolutions (Martinez & Choi, 2017). Accordingly, buildings that integrate green architecture and engineering principles, along with innovative energy-efficient technologies, enhance environmental sustainability, improve energy performance, and contribute significantly to climate change mitigation while remaining economically beneficial (Vijerathne et al., 2024). Green Architecture emphasizes integrating buildings with local ecosystems and the global environment, with a key passive design strategy being the development of an energy-efficient building skin that minimizes heat gain and captures cooling breezes (Haggag, 2010). In this context, passive cooling emerges as a fundamental approach, utilizing design features and technologies that reduce indoor temperatures with minimal or no energy consumption, thereby playing a critical role in enhancing building energy efficiency and thermal comfort (Oropeza-Perez & Østergaard, 2018). Accordingly, Vertical Greenery Systems (VGS), commonly referred to as green walls, have become vital elements of green infrastructure, delivering significant benefits for both current and long-term environmental goals (Jayasooriya et al., 2025), and stand out as one of the most promising solutions as a feature of passive green architecture. Green walls and roofs further offer multiple environmental benefits, including cooling urban areas, mitigating climate change, improving thermal comfort and air quality, reducing noise pollution and greenhouse gas emissions, enhancing heat transfer and thermal performance, and lowering annual energy demand, thereby decreasing the need for mechanical heating and cooling (Daemei et al., 2021). Accordingly, through the strategic use of shading,

insulation, and vegetation, green walls can significantly reduce heat buildup, leading to indoor temperature drops of up to 10 °C (Jayasooriya et al., 2025). Moreover, the vegetation functions as a natural thermal barrier, which can cut energy consumption by up to 20% (Haggag, 2010).

In building science, the VGSs are regarded as not only having aesthetic appeal but also forming an integral part of passive cooling design; thus, they can significantly enhance energy savings. Their application is particularly valuable in densely populated urban areas, where green facades are often integrated into building envelopes (Jim et al., 2011). The potential of VGS is especially notable in low- to mid-rise residential, industrial, and commercial buildings, where green facades can play a critical role in improving thermal performance (Widiastuti et al., 2018). As a passive energy-saving solution, green facades contribute to indoor comfort and reduce reliance on mechanical cooling systems, making them particularly suitable for warm climates (Coma et al., 2017; Convertino et al., 2022). The thermal benefits of VGS in enhancing comfort, reducing indoor temperatures, and cutting energy use remain underexplored, with limited research and technical knowledge available, particularly in tropical climates (Shuhaimi et al., 2022). However, despite these promising benefits, the thermal performance of VGS remains underexplored, with limited research and technical knowledge available, especially in tropical regions. While VGS shows great potential in enhancing the energy performance of buildings, particularly commercial ones, current findings are still limited and somewhat inconclusive. Although studies suggest VGS can increase thermal lag and lower cooling loads (Widiastuti et al., 2018), further research is essential to fully understand its effectiveness across various climates and building types.

Moreover, green walls are widely used internationally and, although still limited in Sri Lanka, are gaining popularity. Given this growing trend, it is important to evaluate their thermal performance, as the materials used can significantly affect a building's cooling demand (Senalankadhikara et al., 2022). The Overall Thermal Transfer Value (OTTV), which measures the average heat gain through a building envelope, is a widely adopted metric for promoting energy-efficient building design (Chan & Chow, 2013). It serves as a basis for comparing the thermal performance of different buildings. Accordingly, this study aims to evaluate the influence of VGS on the energy performance of high-rise buildings in Sri Lanka. A comparative analysis will be conducted using the OTTV of two buildings, one incorporating VGS and the other without, to assess the effectiveness of VGS in enhancing thermal performance and reducing energy demand. Accordingly, 03 objectives were formulated: (i) To review the importance of VGS as a passive mechanism for energy performance improvements in buildings, (ii) To identify measures and techniques to evaluate the impact of VGS on energy efficiency in Buildings emphasizing OTTV and (iii) To evaluate the effect of VGS on the building energy performance of high-rise buildings in Sri Lanka based on OTTV.

2. LITERATURE REVIEW

Many factors have a major influence on reducing the energy consumption in the building sector such double glazed windows, vertical greenery systems (VGS), integrating of semi-transparent photovoltaic device with architectural design of buildings, energy saving by using heat reflecting coating, passive climate control methods, energy saving by shading, building energy performance enhancement by using optimisation technique, double skin green facade, etc. (Akram et al., 2023). Accordingly, two primary energy-

saving techniques are employed to reduce the energy load on buildings: active energy-saving techniques and passive energy-saving techniques (Chetan et al., 2020). Active energy-saving techniques are mechanical devices that employ heat and electricity as a power source to meet a building's cooling needs that are not naturally provided (Oropeza-Perez & Østergaard, 2018). Passive energy saving is a design or technical feature used to improve the energy efficiency of buildings by cooling them with minimal energy consumption (Geetha & Velra, 2013). Passive energy-saving mechanisms include shading devices like overhangs and self-shading façades to reduce heat gain, and advanced glazing systems that limit heat transfer while allowing daylight (Aldawoud, 2013). Natural ventilation strategies, such as solar chimneys and nighttime cooling, improve airflow and indoor air quality (Carli & Giuli, 2009). Phase change materials help stabilize temperatures by storing and releasing heat, while radiant heat barriers reflect solar radiation to enhance insulation (Al-Yasiri & Szabó, 2021). Innovations like eco-evaporation cooling and adaptive façades further boost energy efficiency and indoor comfort without relying on mechanical systems (Amirifard et al., 2019). VGS has emerged as a significant passive energy-saving mechanism in urban environments, contributing to energy efficiency and sustainability. Vertical vegetation creates a more aesthetically pleasant and improved environment, which has the greatest social relevance (Leong et al., 2021). VGS is a crucial part of urban planning as studies show that being among greenery may enhance mental health and well-being (Poulsen et al., 2020). The health and well-being of urban dwellers can be improved by vertical landscaping as plants in vertical gardens can absorb pollutants and particulate matter, serving as natural air filters (Yu et al., 2016). According to Jaafar et al. (2011), the cooling impact of VGS can result in significant energy savings, especially in high-rise structures where conventional cooling techniques might not be as successful, and buildings can become more energy-efficient by using less energy for cooling because of the shadowing that vertical flora provides (Campiotti et al., 2022).

2.1 THE EFFECT OF VGS ON ENERGY PERFORMANCE

VGS significantly enhances building energy performance by shading facades and mitigating the effects of direct solar radiation (Widiastuti et al., 2018). In tropical regions, VGSs help to regulate interior temperatures, reducing the cooling energy demands and improving overall building efficiency (Wang et al., 2016). These systems lower surface temperatures by up to 20°C compared to conventional building materials, thereby decreasing the cooling energy requirements during hot weather (Cuce et al., 2018). Additionally, the cooling effect of plants, facilitated through processes like evapotranspiration, further reduces the dependence on air conditioning (Pan et al., 2020). During colder months, VGSs function as windbreaks, minimizing heat loss and reducing heating energy consumption by around 25% (Cuce et al., 2018). VGS contributes to energy savings at both the building and urban levels by minimizing active cooling loads (Pérez et al., 2017). Studies highlight that passive cooling from vertical gardens reduces the energy loads of air conditioning systems, which are typically energy-intensive (Davis et al., 2019). In urban settings, VGSs mitigate UHI effects, reducing surface temperatures and curbing heat transfer to building envelopes (Coma et al., 2017). Comparative analyses of green walls and green façades reveal variations in energy efficiency based on daily solar irradiation and environmental factors, with substantial reductions in AC energy consumption observed in Mediterranean climates (Perini et al., 2017).

2.2 MEASURING THE EFFECT OF VGS

The assessment of the influence of VGS on energy efficiency in buildings is a complex study domain (Coma et al., 2017). Diverse technologies and approaches have been established to evaluate the efficacy of VGS in improving energy efficiency in buildings (Akram et al., 2023). VGS enhances heat resistance primarily through the insulating qualities of the vegetation and substrate materials (Blanco et al., 2018). Research indicates that the heat resistance (R- R-value) of VGS can be affected by several aspects, such as the species of plants utilized, the substrate thickness, and the system's design (Blanco et al., 2018). According to Evangelisti et al. (2015), thermal resistance of a layer can be calculated by $Ri{=}di\lambda i$, where Ri is thermal resistivity; di is the thickness of the specific layer; λi is its thermal conductivity. Further, total thermal resistance can be calculated by $Rtotal{=}\ Rsi{+}\Sigma Rii{+}Rse$, where $Rtotal$ is the total thermal resistance including the internal and external surface resistances Rsi and Rse, respectively.

Research reveals that VGS can dramatically lower interior air temperatures, hence minimizing the cooling demand on buildings (Perini et al., 2017). Additionally, the efficiency of VGS in decreasing cooling loads is impacted by the interior heat loads of buildings, as emphasized by Coma et al. (2017). who discovered that energy savings might reach up to 58% when VGS are implemented successfully (Coma et al., 2017). According to Pan et al. (2020), the cooling load of VGS can be calculated by Qfabric = U·A·ΔT = U·A· (T out – T in), where U is the heat transfer coefficient, in W/m2 ºC; A is the surface area of each wall, in m2; while ΔT is the difference between Tin and Tout, in ºC (Pan et al., 2020). Another essential part of analysing VGS implications is the use of OTTV estimations (Alghamdi & Alviz-Meza, 2023). Research by Bahdad et al. (2021) expressed that OTTV in their study of vertical green walls, emphasizing how these systems might increase cooling efficiency in residential buildings. Additionally, the study by Pérez et al. (2017) analysed numerous VGS applications and their passive energy-saving potential, emphasizing the relevance of OTTV in assessing the thermal performance of these systems. In addition to that, Kunchornrat et al. (2009) express the OTTV equation by considering 3 main elements. Such as conduction of heat through opaque walls, heat conduction of glass windows, and glass window solar radiation. According to that Singhpoo et al. (2015) expresses the OTTV equation as, $OTTV{=}\ TDeq{\times}(1{-}WWR){\times}Uw{+}\Delta T{\times}WWR{\times}Uf\ {+}SF{\times}WWR{\times}SC$, where, OTTV= overall thermal transfer value (W/m^2), WWR= window-to-wall ratio, Uw= thermal transmittance of opaque wall (W/m2 ◦C), Uf = thermal transmittance of fenestration (W/m2 ◦C), TDeq = equivalent temperature difference (◦C), ΔT = temperature difference (◦C), SF = solar factor (W/m^2), and SC = shading coefficients of fenestration.

In addition to these techniques, the Leaf Area Index (LAI) has been discovered as a relevant metric in analysing the shading impacts of VGS (Pérez et al., 2022). The study by Pérez et al. (2017) emphasized the importance of LAI and facade orientation on the shadow effect, which directly influences energy savings by limiting solar heat gain. Although the LAI is one of the most important factors influencing a VGS's thermal impacts, previous research has rarely looked at and compared how LAI affects VGSs' thermal performance (Bakhshoodeh et al., 2022). According to Perera et al. (2021) the LAI can be expressed as LAI=Leaf area/ Ground area. The Solar Heat Gain Coefficient (SHGC) is also applied for analysing the thermal performance of VGS in buildings (Basher et al., 2022). Research has demonstrated that the incorporation of VGS may considerably modify the SHGC of a building's façade (Ahn et al., 2023). The SHGC is

calculated as the ratio of Qtotal to Qin, where Qin is the amount of solar radiation entering the building through the glazing, and Qtotal is the total solar radiation incident on the glazing surface; this ratio can be influenced by the specific characteristics of the Vertical Greenery System (VGS) applied to the façade (Ahn et al., 2023). Research reveals that VGS can successfully reduce ambient temperatures through evapotranspiration, hence boosting thermal comfort in urban environments (Blanco et al., 2018). Further evidence for the cooling effect comes from Campiotti et al. (2022) who observe that VGS can function as natural temperature regulators, successfully reducing surface temperatures through transpiration's cooling effects, which can be used as a gauge of VGS's energy efficiency.

Furthermore, the incorporation of VGS into building design is commonly tested by simulation models, tools, and software that anticipate energy consumption and thermal comfort levels (Convertino et al., 2022). For instance, research applying EnergyPlus models has shown that VGS may lead to large energy savings, with anticipated reductions in cooling loads ranging from 35% to 90%, depending on the climatic setting and building orientation. Such simulations can combine many aspects, including climatic data, building orientation, and plant characteristics, to offer a thorough assessment of energy performance (Shuhaimi et al., 2022). These measures were used to evaluate the effect of VGS on building energy performance. Among them, OTTV-based comparative analysis of the effect of VGS on building energy performance will be presented in this paper.

3. RESEARCH METHODOLOGY

The choice of research approach significantly influences the research design, as it determines how data will be collected and analysed. Since Research approaches indicate how data will be gathered and evaluated, the research approach selection has a big impact on the research design. Common research approaches include inductive and deductive reasoning. Inductive approaches involve generating theories based on observations and data, while deductive approaches test existing theories through hypothesis-driven research (Ravishankar & Komarasamy, 2022). The use of a deductive approach within a quantitative research design is well justified in this study, as it enables the investigation to build upon established theoretical frameworks and empirical studies, particularly those examining the relationship between VGS and the thermal performance of building envelopes, which is typically measured using the OTTV (Shuhaimi et al., 2022). The OTTV is selected for this study as it provides a standardized and practical measure of the average heat gain through building envelopes, making it suitable for evaluating and comparing the thermal performance of façade systems, including VGS, in the context of energy-efficient design (Akram et al., 2023; Bahdad et al., 2021; Chan & Chow, 2013; Kunchornrat et al., 2009; Shah et al., 2023; Vighio et al., 2025).

A case study strategy was adopted as the most suitable approach for this investigation, as it allows for an in-depth, context-specific analysis of real-world buildings. The study focused on two high-rise office buildings located in Colombo, Western Province, Sri Lanka. Both buildings were comparable in function, height, orientation, and occupancy type but differed in one key design feature: Building A was constructed using conventional design without vertical greenery, while Building B integrated a Vertical Greenery System (VGS) on selected exterior façades as a passive cooling measure. This comparative case selection was based on purposeful sampling, ensuring that both cases were functionally and climatically similar to isolate the effect of the VGS on thermal

performance. The VGS in Building B consisted of modular green wall panels installed on the western and southern façades, designed to provide shading and reduce heat absorption. The buildings were selected to allow a controlled comparison of OTTV values under similar operating and environmental conditions, ensuring the reliability of findings.

Three semi-structured interviews were conducted for each building with industry professionals directly involved in design, operation, or sustainability assessment. Participants were selected through convenience sampling, focusing on professionals with hands-on experience and technical knowledge relevant to energy performance and façade systems. The profile of interviewees is shown in Table 1.

Table 1: Profile of interviewees

Cases	Designation	Years of experience
Case A building without VGS	Energy Consultant	06 years
	MEP Engineer	05 years
	MEP Engineer	08 years
	Sustainability Executive	05 years
Case B building with VGS	MEP Engineer	06 years
	Operations Manager	09 years

The numerical data necessary for calculating the OTTV of the two case buildings were collected from the respondents. The OTTV of each building was then determined using the following equation mentioned below, as recommended and validated in Chan and Chow (2013), Shah et al. (2023), and Vighio et al. (2025). These studies focus on the evaluation and monitoring of OTTV in tropical climates, examining the effects of passive design strategies, façade materials, and green roof applications on building thermal performance.

$$TV = TD_{eq} \times (1 - WWR) \times U_w + \Delta T \times WWR \times U_f + SF \times WWR \times SC \quad \textit{Equation (1)}$$

Where, OTTV = overall thermal transfer value (W/m^2), WWR = window-to-wall ratio, U_w = thermal transmittance of opaque wall (W/m^2 ◦C), U_f = thermal transmittance of fenestration (W/m^2 ◦C), TDeq = equivalent temperature difference (◦C), ΔT = temperature difference (◦C), SF = solar factor (W/m^2), and SC = shading coefficients of fenestration.

The OTTV of both cases was compared, and the variation in OTTV due to the effect of VGS was subsequently determined. Secondary data sources included documents providing key performance metrics, material information, and other parameters necessary for calculating cooling load values, thermal resistance (R-values), and OTTV before and after the installation of VGS.

4. KEY RESEARCH FINDINGS

As aimed in this study, the OTTV values of both cases were separately calculated as shown below.

4.1 CALCULATION OF OTTV OF CASE A BUILDING

The data collected to calculate the OTTV through interviews are shown in Table 2.

Table 2: Parameters and data collected from the Case A building (without VGS) for OTTV calculation

Parameter	Details Required	Data Provided
Wall Heat Transfer		
Wall Area (m²)	Total area of the walls	220 m² (North and South), 250 m² (East and West)
Window Heat Transfer		
Window Area	For the ratio of window area to wall area	78 m²
Glass U-value (W/m²·K)	Overall heat transfer coefficient for windows	5.8 W/m²·K
Other Parameters		
Sol-air Temperature (T_e)	Surface temperature due to solar radiation	106°F (41.11°C)
Shading Coefficient (SC)	Shading coefficient of fenestration	0.4
Solar Factor (SF)	Solar factor for the fenestration	56.5 W/m²
Thermal Transmittance of Opaque Wall (U_x)	Uw – Wall U-value	0.09 W/m²·°C
Thermal Transmittance of Fenestration (Uf)	Uf – Single-pane glass	1.12 W/m²·°C

The thermal transmittance (U-value) of the glass, taken as 5.8 W/m²·K, was referenced from the study by Kou et al. (2021), which provides empirical data on single-glazed window performance (Kou et al., 2021). Other measures (assuming the measurement is taken on the peak time of 12.00 noon as per the ASHRAE standard)

Total wall area = Northern wall area + Southern wall area + Eastern wall area Western wall area

Total Wall Area $= 220\ m^2 + 220\ m^2 + 250\ m^2 + 250\ m^2$

Total Wall Area $= 940\ m^2$

Total Window Area $= 78\ m^2$

Window to Wall Ratio (WWR) $= \frac{78m^2}{940\ m^2}$

Window to Wall Ratio (WWR) $= 0.083\ (8.3\%)$

According to Singhpoo et al. (2015), the equivalent temperature difference (TD_{eq}) can be expressed as,

$TD_{eq} = T_e - T_i$ *Equation (2)*

Where TD_{eq}= equivalent temperature difference, T_e = sol-air temperature and T_i = indoor temperature.

$TD_{eq} = 41.11°C - 26\ °C$

$TD_{eq} = 15.11\ °C$

Hence,

$$OTTV = (TD_{eq} \times (1 - WWR) \times U_w) + (\Delta T \times WWR \times U_f) + (SF \times WWR \times SC)$$

$$OTTV = (15.11°C \times (1 - 0.083) \times 0.09\,W/m^2\,°C + (32℃ - 26℃) \times 0.083 \times 1.12\,W/m^2\,℃ + 56.5W/m^2 \times 0.083 \times 0.4$$

$$OTTV = 15.11°C \times 0.917 \times 0.09\,W/m^2\,°C + 6℃ \times 0.083 \times 1.12\,W/m^2\,℃ + 56.5W/m^2 \times 0.083 \times 0.4$$

$$OTTV = 1.247W/m^2 + 0.558\,W/m^2 + 1.876W/m^2$$

$$\boldsymbol{OTTV = 3.681W/m^2}$$

4.2 CALCULATION OF OTTV OF CASE B BUILDING

The data collected to calculate the OTTV through interviews are shown in Table 3.

Table 3: Parameters and Data Collected from Case B Building (with VGS) for OTTV Calculation)

Parameter	Details Required	Data Provided
Wall Heat Transfer		
Wall Area (m²)	Total area of the walls	280 m² (North and South), 250 m² (East and West)
Window Heat Transfer		
Window Area	For the ratio of window area to wall area	80 m²
Glass U-value (W/m²·K)	Overall heat transfer coefficient for windows	5.8 W/m²·K
Other Parameters		
Sol-air Temperature (T_e)	Surface temperature due to solar radiation	106°F (41.11°C)
Shading Coefficient (SC)	Shading coefficient of fenestration	0.4
Solar Factor (SF)	Solar factor for the fenestration	56.5 W/m²
Thermal Transmittance of Opaque Wall (Uw)	Uw – Wall U-value	0.09 W/m²·°C
Thermal Transmittance of Fenestration (Uf)	Uf – Double-glazed with ¼" air space	0.68 W/m²·°C

Total wall area = Northern wall area + Southern wall area + Eastern wall area + Western wall area

Total wall area = 280 m^2 + 280 m^2 + 250 m^2+ 250 m^2

Total wall area = 1060 m^2

Total Window area = 80 m^2

So, Window to Wall Ratio (WWR) $= \frac{80m^2}{1060\,m^2}$

Window to Wall Ratio (WWR) = 0.075 (7.5%)

According to Singhpoo et al. (2015) the equivalent temperature difference can be expressed as,

$TD_{eq} = T_e - T_i$

Where TD_{eq}= equivalent temperature difference, T_e = sol-air temperature and T_i = indoor temperature.

$TD_{eq} = 41.11°C - 24\,°C$

$TD_{eq} = 17.11\,°C$

Hence,

$OTTV = (TD_{eq} \times (1 - WWR) \times U_w) + (\Delta T \times WWR \times U_f) + (SF \times WWR \times SC)$

$OTTV = (17.11°C \times (1 - 0.075) \times 0.09\,W/m^2\,°C) + ((32℃ - 24℃) \times 0.075 \times 0.68\,W/m^2\,℃) + (56.5W/m^2 \times 0.075 \times 0.4)$

$OTTV = (17.11°C \times 0.925 \times 0.09\,W/m^2\,°C) + (8℃ \times 0.075 \times 0.68\,W/m^2\,℃) + (56.5W/m^2 \times 0.075 \times 0.4)$

$OTTV = 1.424W/m^2 + 0.408\,W/m^2 + 1.695W/m^2$

$\boldsymbol{OTTV = 3.527W/m^2}$

The OTTV analysis confirms a positive contribution of VGS, as reflected by a slight decrease from 3.681 W/m² in the VGS-free building to 3.527 W/m² in the building with VGS. The absolute reduction of OTTV appears modest (approximately 4.18%), however, it is the cumulative effect of reduced heat transfer through opaque walls, fenestration, and solar radiation absorption heat transfer. The relatively small variation of OTTV compared to other calculations might be attributed to the calculation method, which estimates an average effect across the entire envelope and adjusts for many components (walls, windows, shading), as opposed to just the façade with the VGS treatment. Even a slight decrease in OTTV can result in notable long-term energy savings, particularly in energy-intensive buildings, reinforcing the value of VGS as an effective passive design strategy for improving thermal performance.

5. CONCLUSIONS AND A WAY FORWARD

This study assessed the influence of VGS on the energy efficiency of commercial high-rise buildings in Sri Lanka, concentrating on thermal performance as measured by the OTTV. The findings revealed a positive impact of integrating VGS, with the average OTTV decreasing from 3.681 W/m² in the building without VGS (Case A) to 3.527 W/m² in the building with VGS (Case B), indicating a 4.18% improvement in the thermal envelope efficiency. The numerical difference appears moderate, carries substantial implications for long-term energy savings, particularly in densely populated urban areas and tropical regions with constantly elevated cooling demands.

The findings confirm that VGSs significantly enhance passive cooling by improving the insulating characteristics of building façades, diminishing direct solar heat gain, and decreasing thermal transmittance via walls and windows. These technologies additionally facilitate overarching environmental goals by mitigating urban heat island effects and enhancing urban microclimates. In addition to energy efficiency, the integration of

vertical greenery provides supplementary advantages, like enhanced air quality, diminished noise levels, and greater psychological well-being for inhabitants. This study addresses a significant gap in the South Asian context by presenting empirical data on the thermal efficiency of VGSs in commercial high-rise structures in tropical climates. It enhances the expanding corpus of knowledge that advocates for nature-based solutions in urban planning and sustainable construction.

While this research offers valuable insights, it is limited to two buildings and focuses solely on OTTV without accounting for dynamic occupant behaviour, HVAC system efficiency, or long-term vegetation performance. Future research should expand to include a wider variety of building typologies, climatic zones, and incorporate long-term monitoring, maintenance, and cost-benefit analyses. The integration of advanced simulation tools with real-time energy monitoring will further enhance understanding of VGS performance over time. Additionally, studying the effects of different plant species, substrate types, and management practices will provide a more comprehensive evaluation of VGS thermal behaviour.

The demonstrated benefits of VGS highlight the need for its integration into national building codes, green building rating systems, and urban development policies. Encouraging the widespread adoption of VGS through incentives, guidelines, and regulatory frameworks can accelerate the transition toward energy-efficient and climate-resilient buildings across Sri Lanka's construction industry. Policymakers, architects, urban planners, and developers should collaborate to incorporate vertical greenery as a standard practice in façade design, especially in high-density urban centres facing rising cooling demands and urban heat challenges. Promoting VGS at an industry-wide level will support national sustainability targets, reduce environmental impacts, and enhance the liveability of urban environments.

Future studies should broaden this approach to encompass a wider array of building typologies and climatic zones, while also addressing long-term performance, maintenance considerations, and cost-benefit assessments. The integration of sophisticated simulation tools and real-time energy monitoring systems can enhance the comprehension of VGS performance over time. In conclusion, although VGS may not alone resolve energy concerns, it constitutes a significant element of a comprehensive design strategy focused on improving thermal performance and environmental sustainability in urban architecture.

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THE IMPACT OF INCREMENTAL VERTICAL HOUSING DEVELOPMENT ON QUALITY OF SPACE AND RESIDENTIAL ENVIRONMENTAL SATISFACTION: A CASE STUDY OF SWARNA PLACE, COLOMBO, SRI LANKA

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ABSTRACT

This study critically investigates how incremental vertical expansion in low-income housing affects the quality of space (QoS) and residential environmental satisfaction (RES) over time. Using Swarna Place, a low-income settlement in Colombo, Sri Lanka, as a case study, the research examines the transition from single-story core units to four-story structures. Through a mixed-methods approach, the study employs spatial observation, architectural documentation, and resident surveys based on the QoS framework and the Residential Environmental Satisfaction Scale (RESS).The analysis identifies seven stages of physical transformation and evaluates each using six QoS indicators (lighting and ventilation, thermal quality, acoustic quality, spatial layout, functionality, and accessibility) and three RESS domains (internal neighbourhood reputation (INR), dwelling satisfaction (DS), and social climate (SC)). Findings reveal that, although DS increases due to improved housing quality and aesthetics, the overall RES declines in later stages as a result of reduced social engagement and community cohesion. Originally a multifunctional communal area, the ground floor living space becomes increasingly restricted in later stages due to staircase additions and fixed layouts. As vertical growth progresses, the QoS declines, and although residents make minor adaptations to the built environment, these adjustments offer limited relief. The study concludes that unregulated vertical expansion may compromise spatial and social liveability in incremental housing, leading to reduced environmental satisfaction despite physical improvements. It highlights the importance of balancing flexibility with design regulation and resident guidance to prevent the evolution of vertical slums. The research contributes to the discourse on sustainable housing by offering actionable insights into how urban settlements can preserve community identity, functionality, and spatial quality amidst vertical densification.

Keywords: *Dwelling Satisfaction; Incremental Housing; Internal Neighbourhood Reputation; Quality of Space; Residential Satisfaction.*

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1. INTRODUCTION

In the context of global urbanization and rapid population growth, incremental housing has emerged as a widely adopted solution (Turner, 1976; Boonyabancha, 2005) for addressing the shelter needs of low-income communities along with their economic growth. Particularly in the Global South, where formal housing programs often fall short (Gilbert, 2016), self-built incremental developments offer residents flexibility to adapt and expand their homes over time based on financial capacity, family growth, and social aspirations. While this approach allows for a gradual improvement in housing conditions, it also presents new spatial, social, and environmental challenges; especially as communities move from horizontal to vertical development without regulatory oversight.

In Sri Lanka, this phenomenon is evident in settlements like Swarna Place, a low-income community in Colombo, where residents have incrementally expanded their dwellings from single-story starter homes to multi-story vertical structures, a pattern consistent with observations in other Sri Lankan informal settlements (Warakapitiya et al., 2024).These transformations, often informal and self-managed, have reshaped not only the architectural form but also the quality of living spaces and community interactions. Although physical upgrades are visible, questions arise regarding how these changes affect the QoS (quality of space) within individual homes and the broader RES (residential environmental satisfaction) of occupants.

This study critically examines the implications of such vertical incremental development by evaluating seven stages of physical growth in Swarna Place. By integrating the QoS framework, comprising lighting and ventilation, thermal comfort, acoustic quality, spatial layout, functionality, and accessibility and the RESS (Residential Environmental Satisfaction Scale), which includes INR (internal neighbourhood reputation), DS (dwelling satisfaction), and SC (social climate), this research offers a comprehensive, resident-informed analysis of the evolution of space and satisfaction.

The study has three specific objectives: (1) to evaluate the impact of vertical growth on QoS and RES across seven incremental stages; (2) to highlight the trade-offs between physical improvement and social liveability; and (3) to emphasize the need for design regulations, spatial planning, and participatory approaches in managing self-built housing in low-income urban settings. By doing so, it challenges the assumption that vertical expansion automatically translates to better living conditions and contributes to the discourse on sustainable and inclusive housing.

2. LITERATURE REVIEW

The evolving dynamics of incremental housing have sparked critical academic debate across urban studies, environmental psychology, and housing policy. This section situates the current study within established literature, emphasizing theoretical foundations, empirical insights, and identified gaps related to incremental development, spatial quality, and residential satisfaction.

2.1 CONCEPTUAL FOUNDATIONS OF INCREMENTAL HOUSING

Turner (1976), a pioneering voice in self-help housing, argued that incremental housing offers autonomy and empowerment to low-income residents. He emphasized that allowing households to build over time, based on their evolving needs and resources, leads to more meaningful and adaptable environments, which is known as incremental

development. This philosophy underpins many Global South housing strategies and remains influential in current participatory development frameworks. Boonyabancha (2005) reinforced this view through Thailand's Baan Mankong initiative, showing that community-led upgrading fosters self-reliance and better socio-spatial outcomes.

However, critiques have emerged. Gilbert (2016) warned that incremental housing, though conceptually appealing, often results in substandard living environments, especially when vertical expansion lacks regulatory oversight. These criticisms are echoed in Gifford's (2007) psychological analysis, which associates high-rise living with social isolation, stress, and poor well-being. In the Sri Lankan context, Warakapitiya et al. (2024) observed similar behavioural adaptations and dissatisfaction in high-rise settlements like "Sahaspura", indicating a disconnect between policy goals and lived experiences.

2.2 SPATIAL QUALITY AND HOUSING SATISFACTION

According to Kurian and Thampuran (2011), the quality of space is a subjective concept that depends on various parameters, including spatial functions and environmental qualities. It reflects not only the physical characteristics of a dwelling, such as size and organization, but also how well the space can be adapted to the needs and preferences of its users, considering factors like location, infrastructure, design, aesthetics, materials, construction techniques, sustainability, and cultural context. The QoS is central to evaluating the success of incremental housing as established by Rashid (2019) and Mohit et al. (2010), who empirically demonstrated that spatial quality directly determines the long-term viability and resident satisfaction in self-built environments. Rashid (2019) highlighted that in low-income settlements, domestic spaces often serve multiple functions, evolving with household needs. His study in Ershad Nagar, Bangladesh, emphasized the value of spatial flexibility. Likewise, Kaitilla (1993) identified user participation and adaptability as critical to satisfaction in Papua New Guinea's public housing. Although this study is over three decades old, its insights remain foundational for understanding participatory design in Global South contexts, and recent studies (e.g., Rashid, 2019; Warakapitiya et al., 2024) confirm the ongoing relevance of these factors in contemporary vertical housing developments.

Nevertheless, as housing becomes denser and vertically layered, QoS can deteriorate. Nix et al. (2015), in a study of Delhi's low-income housing, found that indoor environmental quality (IEQ) declined sharply with reduced natural ventilation and light, especially in stacked dwellings. These findings mirror Gifford's (2007) critique that high-rise buildings often compromise thermal, acoustic, and psychological comfort.

In contrast, Mohit et al. (2010) showed that in Kuala Lumpur's low-cost housing, spatial satisfaction improved with better infrastructure, despite limited unit size. This suggests that spatial quality is not solely a function of area but of usability, access to light and air, and layout efficiency. Similar insights were drawn by Salleh et al. (2012), who linked perceived liveability to thoughtful spatial arrangements rather than material affluence.

2.3 RESIDENTIAL ENVIRONMENTAL SATISFACTION

RES is a multidimensional construct involving physical, social, and psychological factors. Adriaanse (2007) proposed the RESS, comprising three key dimensions: INR,

SC, and DS. This framework has been widely applied in housing studies (e.g., Galster, 1987; Mohit & Nazyddah, 2011) and informs this study's empirical approach.

Galster (1987) emphasized that housing satisfaction is not just about physical dwellings but also about neighbourhood reputation and social engagement. He critiqued traditional housing evaluations for neglecting contextual and subjective elements. Adriaanse (2007) advanced this view by validating RESS as a tool that integrates built form with social perception, particularly in low-income environments. The current study extends this framework into the Sri Lankan context, focusing on how vertical housing affects these satisfaction domains with inspirations from previous research.

2.4 THE SOCIAL DIMENSION OF INCREMENTAL GROWTH

Social cohesion is often strongest in early stages of incremental development. Turner (1976) noted that when people build their environments collectively, social capital increases. Bourdieu (1986) also emphasized the role of social capital in shaping everyday spatial practices and neighbourhood identity. In Stage 01 of incremental housing, residents often share resources, socialize in open spaces, and personalize their environments, leading to high INR and SC scores (Adriaanse, 2007; Ong'ayo, 2016).

However, as housing becomes more individualized and vertically stratified, these ties weaken. Warakapitiya et al. (2024) showed that high-rise living in Colombo led to behavioural fragmentation, with fewer shared activities and increased reliance on private, enclosed spaces. Ha (2008), in his study of Korean social housing estates, also observed that physical form directly influenced social interaction. The more rigid and stratified the environment, the lower the social cohesion.

Gilbert (2016) added that upward expansion can reflect not only a physical but also a symbolic distancing, where households seek to separate themselves socioeconomically from their neighbours. This notion is echoed in the field observations conducted by the authors at Swarna Place (this study) and corroborated by Warakapitiya et al.'s (2024) surveys, in which upper-stage residents report higher DS but lower INR and SC, suggesting a shift from community-centric to privacy-oriented values.

2.5 CONTEXTUALIZING THE STUDY IN SRI LANKA

In the Sri Lankan context, the evolution of informal housing has mirrored global patterns of incrementalism. Gamage et al. (2015) and Samaratunga and O'Hare (2013), documented the failures of top-down high-rise relocation projects like Sahaspura, where physical improvements did not translate into resident satisfaction. Warakapitiya et al. (2024) provided a nuanced analysis, showing that while behavioural adaptations occurred (e.g., space personalization, balcony use), they did not compensate for the loss of shared spaces and community ties.

Drawing on Adriaanse's (2007) Residential Environmental Satisfaction Scale (RESS) and Rashid's (2019) spatial typologies, this review critically examines how vertical layering and spatial organization influence the lived residential experience.

2.6 GAPS AND CONTRIBUTION

Despite the wealth of literature on incremental housing, few studies integrate QoS and RES frameworks to examine how vertical growth affects both physical and social dimensions of housing. While Gilbert (2016) and Gifford (2007) highlight the risks of

vertical expansion, and Adriaanse (2007) provides a robust framework for satisfaction analysis, their combined application remains limited in low-income South Asian contexts.

This study contributes by empirically assessing QoS and RES across distinct vertical development stages in a real Sri Lankan settlement. It incorporates verified tools (RESS), validated empirical methods, and critical spatial analysis, offering practical implications for policy, especially in contexts where self-built vertical housing is proliferating.

In summary, while incremental housing provides a pathway to affordability and autonomy, its long-term success hinges on maintaining spatial quality and social cohesion. A balanced approach grounded in resident engagement, environmental design, and contextual policy is essential to create not just houses, but liveable communities.

3. METHODOLOGY

3.1 RESEARCH DESIGN

This study adopts a mixed-methods case study approach to critically evaluate the evolution of spatial quality and RES in a low-income housing settlement undergoing incremental vertical development. The research focuses on Swarna Place, Colombo, Sri Lanka, as a single in-depth case, reflecting a broader typology of informal, self-built urban housing.

3.2 CASE SELECTION JUSTIFICATION

Swarna Place was selected for its unique representation of vertical incremental housing built on 2-perch government-allocated plots, developed organically over several decades. It demonstrates a range of transformation stages from single-story basic units to four-story self-extended dwellings, making it ideal to analyse spatial, functional, and social changes over time. The site includes more than 250 units, with varying architectural and socio-cultural expressions reflecting individual and collective adaptation strategies.

3.3 DATA COLLECTION METHOD

The study integrated both primary and secondary data sources:

- On-site observations and architectural mapping (plans, elevations, cognitive maps).
- 60 Resident surveys (n=60) to gather qualitative feedback on spatial use, satisfaction, and social experience.
- Semi-structured interviews with residents to understand adaptive strategies and lived experience.
- Photographic and sketch documentation of different housing types and communal spaces.
- Archival material and policy reviews to contextualize housing regulations and support mechanisms.

3.4 STAGE IDENTIFICATION AND TYPOLOGY FRAMEWORK

The identification of seven distinct incremental development stages was based on a synthesis of field observations, resident interviews, and insights from existing housing literature. Drawing inspiration from Turner's (1976) notion of "housing as a process," the following parameters were used to define development stages:

1. Vertical layers (number of storeys).
2. Structural completeness (finished roof vs slab-incomplete).
3. Layout and spatial organization (room arrangements, openings).
4. Functionality and usability (use of ground floor and upper floors).
5. Material finishes (walls, floors, roofing).
6. Facade treatments and architectural expression.

This classification was also informed by Nix et al. (2015), Rashid (2019) and Warakapitiya et al. (2024), who similarly examined the spatial transformation and layering in low-income vertical housing.

3.5 STAGE CLASSIFICATION

Table 1: Incremental stages

Stage	Description
Stage 01	Single-storey, completed roof, highly flexible space use.
Stage 02	Single-storey with slab or partial walls for upper floor preparation
Stage 03	Completed two-storey dwelling with finished roof.
Stage 04	Two-storey unit with slab or half-built third floor.
Stage 05	Completed three-storey dwelling.
Stage 06	Three-storey with slab or partial fourth-storey extension.
Stage 07	Completed four-storey building, often with modern façade elements.

The categorization follows Nix et al. (2015) and Boonyabancha (2005) who argue that while incremental development provides flexibility, unregulated vertical extensions can result in compromised living conditions and community fragmentation. From the seven identified stages of incremental development, four stages were selected for detailed analysis in this study, as they are fully constructed and align with the study's limitations.



Figure 1: Incremental development of a housing unit. (Note: Each stage includes multiple subtypes, but one representative house is illustrated here to reflect the typical incremental transformation.)

3.6 EVALUATION CRITERIA FOR QUALITY OF SPACE (QOS)

A custom evaluation framework was developed based on six key physical-spatial parameters, drawing on the work of Nix et al. (2015), Gifford (2007), and Mohit et al. (2010):

- Lighting and Ventilation (LV)
- Thermal Quality (TQ)
- Acoustic Quality (AQ)
- Spatial layout and Quality (SQ)
- Functionality (FC)
- Accessibility (AC)

Each parameter was rated using a percentage-based scale derived from resident feedback and observational scoring. The ground floor living space was the primary focus due to its multifunctional use as established in Rashid (2019) and Mohit and Nazyddah (2011).

3.7 ASSESSMENT OF RESIDENTIAL ENVIRONMENTAL SATISFACTION (RES)

To assess Residential Environmental Satisfaction, this study adopted the RESS developed by Adriaanse (2007). The RESS evaluates three domains:

1. Internal Neighbourhood Reputation (INR)
2. Social Climate (SC)
3. Dwelling Satisfaction (DS)

These were used to derive the Overall Residential Environmental Satisfaction (ORES) score for each stage. The scale's validity and multidimensionality make it a suitable tool for analysing both social and environmental dimensions of housing, as supported by Ha (2008) and Kaitilla (1993).

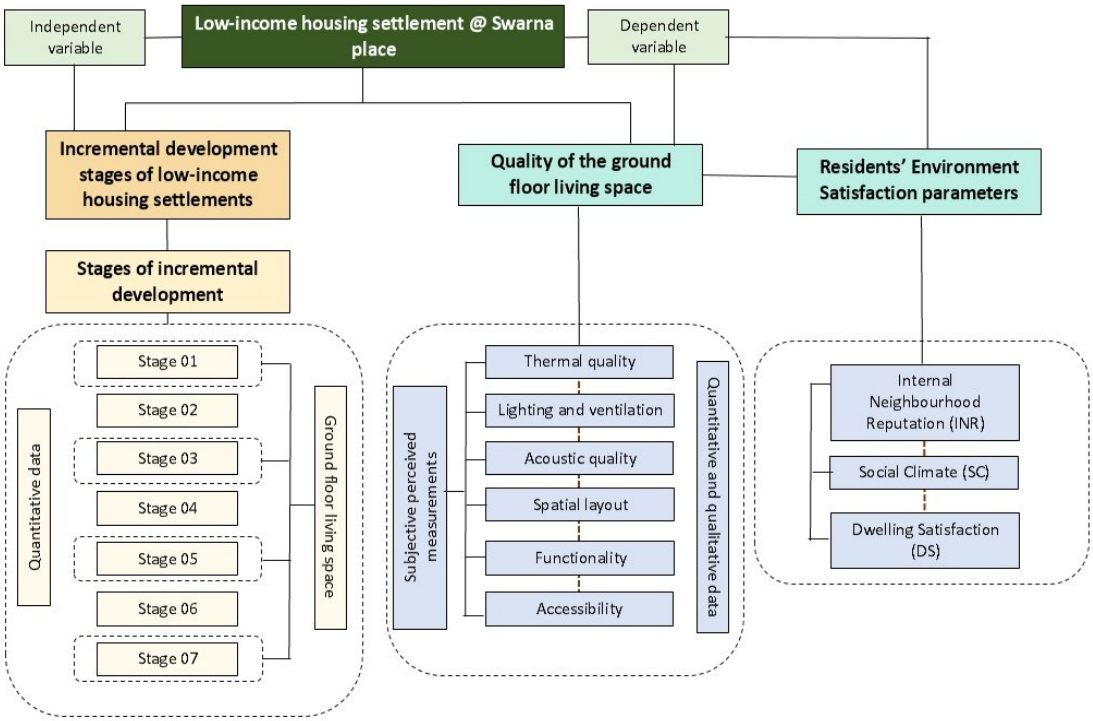


Figure 2: Independent and dependent variable

3.8 DATA ANALYSIS

- Quantitative analysis: Survey data (n=60) were processed using descriptive statistics (frequencies, means) - to identify trends across stages. Pearson correlation coefficients were calculated to quantify relationships between DS, INR, and SC.
- Qualitative analysis: Interview responses underwent - thematic coding using color-coded categorization, with emergent themes organized around three core areas: (a) spatial adaptations, (b) social cohesion, and (c) satisfaction drivers.
- Spatial analysis: On-site sketches, cognitive maps, and observational notes were compared through professional overlay techniques -. This involved physically tracing evolutionary patterns across the seven development stages using printed base drawings.
- Integrated comparison: QoS indicators and RESS scores were juxtaposed in comparative matrices developed for the study, which exposed divergences between physical upgrades and social satisfaction metrics.

4. RESEARCH FINDINGS

This study critically examined the evolution of QoS and RES across selected incremental development stages within Swarna Place, a low-income vertical housing settlement in Colombo, Sri Lanka. The findings highlight several interrelated spatial, functional, and social dynamics resulting from vertical housing growth.

- **Deterioration of Ground Floor Quality of Space:**

While incremental housing has often been associated with improved environmental quality over time (Nix et al., 2015), this study reveals a contrasting trend in vertically expanded units. As residents added floors incrementally, the ground floor living space: previously open, adaptable, and multifunctional; became increasingly constrained. The introduction of staircases, partition walls, and enclosed façades led to reduced natural lighting, poor ventilation, and decreased spatial flexibility. This aligns with Boonyabancha's (2005) warning that although incremental growth fosters autonomy, it must be balanced with regulatory and considerations of spatial quality.

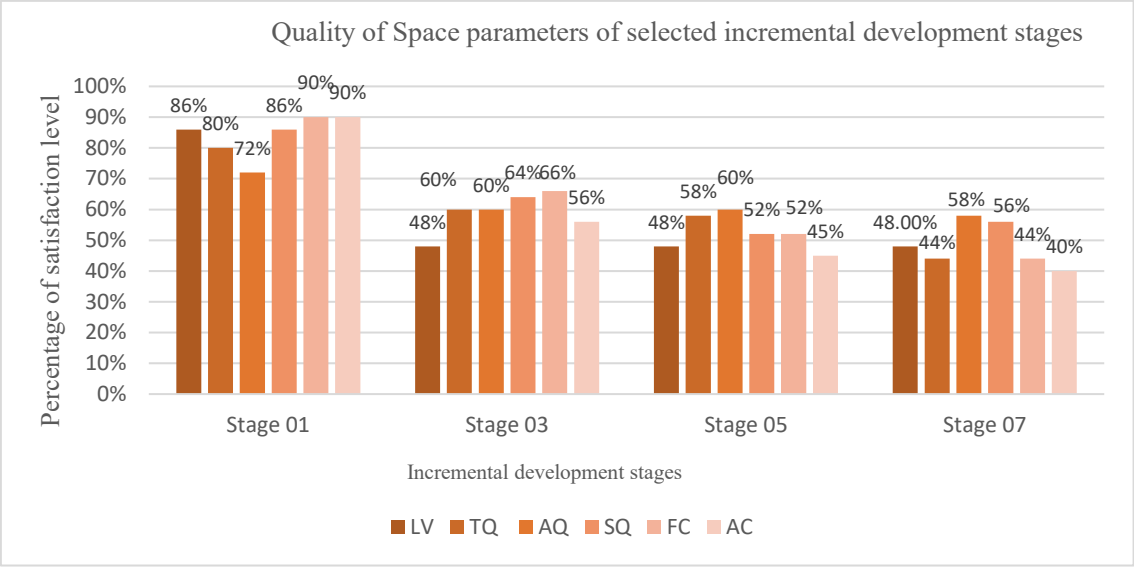


Figure 3: QoS parameters of selected 4 stages

Figure 3 illustrates how six key parameters related to the quality of space deteriorate along with the incremental development stages of Swarna Place.

- **Diverging Trajectories of Dwelling Satisfaction and Community Cohesion:**

A key observation was that DS increased steadily with each development stage, largely due to improved physical amenities, increased social status, and architectural embellishments. However, this rise in DS was inversely correlated with INR and SC; two core dimensions of the RESS framework. This inverse relationship was quantified through Pearson correlations, revealing strong negative associations between DS and both INR (r = -0.79) and SC (r = -0.82). Residents of stage 01 exhibited the highest social engagement, reporting shared boundaries, collective decision-making, and high levels of neighbourly interaction. In later stages, residents constructed more enclosed, private dwellings, reducing interpersonal connections and community identity.

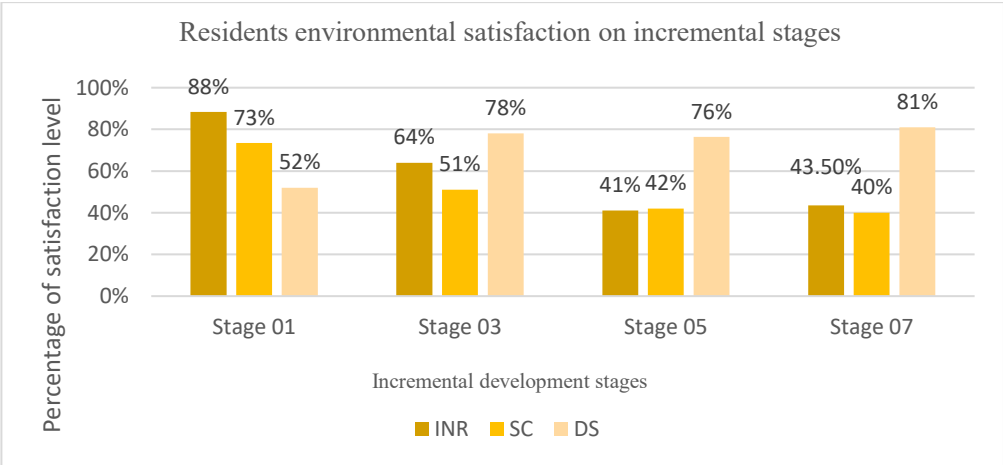


Figure 4: Residents environment satisfaction on incremental stages

Figure 4 presents the three RES parameters across the incremental stages showing that as the level of incremental development increases, the INR and SC decrease, while DS increases at higher stages.

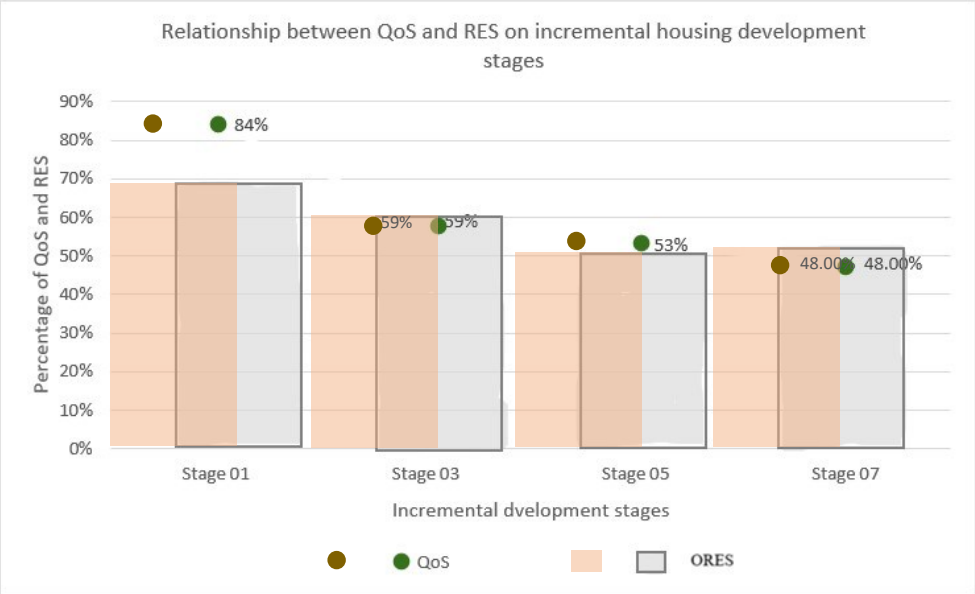


Figure 5: Relationship between QoS and RESS on incremental stages

Figure 5 illustrates the relationship between overall RES and QoS across the four stages studied. In the initial stages, both overall RES and QoS are relatively high, whereas in the later stages, a noticeable decline in both measures can be observed.

- **Loss of Space Adaptability and Functionality:**

The study further revealed a functional shift in the use of ground floor spaces. Initially, the living area served multiple roles; social gatherings, dining, studying, business operations, and sleeping; demonstrating high levels of spatial adaptability. Over time, the living space has lost its multifunctionality, becoming more rigid and defined, reflecting the prioritization of privacy and individual needs over collective usability. This mirrors observations in other South Asian contexts, where vertical infill limits flexibility and usability.

- **Intra-stage Subtypes and Spatial Diversity:**

Within each stage, multiple subtypes of housing emerged based on the configuration of staircases, window treatments, façade treatments, and layout variations. These variations underscore that while the community follows an incremental development path, it does so with high spatial heterogeneity, influenced by financial capacity, gendered spatial roles, and aspirations. However, despite this variation, feedback on spatial satisfaction was remarkably consistent within each stage, suggesting that stage-specific spatial qualities and limitations were collectively experienced and perceived.

- **Spatial Trade-offs and Vertical Densification:**

Finally, the study documented a measurable reduction in ground floor living space size and quality as vertical densification increased. The pressure to expand upward for additional bedrooms or rental income came at the cost of liveability on the ground floor contributing to reduced airflow, visual openness, and accessibility. This tension between verticality and spatial usability reflects broader critiques of unregulated high-rise developments in low-income communities.

Table 2: Summary of primary research outcomes

Finding Category	Observation	Implication
Diminishing Ground Floor Quality of space	Addition of upper floors leads to reduced lighting, ventilation, and spatial flexibility on ground floors.	Unregulated vertical growth compromises environmental comfort at the base level.
Inverse Relationship: Dwelling Satisfaction, Internal Neighbourhood Reputation Social Cohesion	DS increases over stages, while INR and SC decline.	Social cohesion weakens as privacy and architectural embellishment become prioritized.
Decline in Spatial Adaptability and Functionality	Earlier stages had multifunctional spaces; later stages show rigid, single-use layouts.	Loss of flexibility reduces the home's ability to support dynamic family needs.
Intra-stage Spatial Variations	Within each stage, variations in layout and design occur due to household-specific choices.	Despite diversity, residents share similar spatial experiences and constraints per stage.
Spatial Trade-offs in Vertical Densification	Vertical expansion reduces ground floor liveability due to space occupied by stairs and structural additions.	Tension between maximizing space vertically and maintaining functionality at lower levels.

5. CONCLUSION AND RECOMMENDATIONS

This study provides a critical empirical lens on the spatial and social implications of incremental housing in vertically expanding settlements, offering new insights into the evolving nature of spatial quality and resident satisfaction. While incremental housing enables resident-led, financially adaptive growth, this research confirms that unchecked vertical expansion can severely undermine the core qualities that make such housing sustainable; namely flexibility, adaptability, and community cohesion.

The research reveals that QoS; especially on the ground floor; deteriorates consistently with vertical growth, with the most advanced stages suffering from reduced ventilation, poor lighting, low functionality, and minimal accessibility. Although physical improvements enhance DS, they simultaneously erode INR and SC, resulting in a decline in overall RES. This divergence underscores the need to rebalance housing policy and design toward integrated solutions that maintain both spatial quality and social connectedness.

Moreover, the decreasing multifunctionality of ground-floor living spaces, a vital feature in early stages; suggests a gradual departure from the flexibility that defines successful incremental housing (Turner, 1976; Boonyabancha, 2005). Without interventions to regulate and support sustainable growth, such settlements risk transforming into densified enclaves of spatial discomfort and social fragmentation, echoing concerns about the emergence of vertical slums in the Global South.

To address these challenges, this research advocates for:

- Design guidelines that ensure flexibility and air-light-flow standards in all vertical expansions.
- Policy interventions that promote community engagement and cohesion in all stages.
- Technical support mechanisms for low-income residents to balance autonomy with spatial quality.

By advancing the understanding of how incremental growth shapes lived experience, this study contributes to a more nuanced and contextualized discourse on urban housing transformation in South Asia and beyond. It urges policymakers, urban designers, and community stakeholders to reimagine incremental housing not merely as a survival strategy, but as a platform for equity, liveability, and spatial dignity.

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TOWARDS A CIRCULAR ECONOMY: EVALUATING EFFECTIVE IMPLEMENTATION STRATEGIES FOR RECYCLING AND REUSE PROGRAMMES IN SRI LANKA'S CONSTRUCTION INDUSTRY

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ABSTRACT

Construction waste accounts for a significant portion of the total waste generated in Sri Lanka. To promote a Circular Economy (CE) in the construction industry, it is essential to adopt building procedures that minimize waste, increase the use of recycled materials in new construction, and create markets for recycled and reused materials. However, the lack of modern recycling facilities and technologies hampers the effective processing and reuse of construction materials. Additionally, there is limited market demand for recycled construction materials, primarily due to concerns about product quality and the absence of standardized products. In order to promote sustainability and reduce the industry's reliance on new materials, it is crucial to implement recycling and reuse programs. Therefore, this research aims to evaluate the effective implementation strategies for recycling and reuse programs in Sri Lanka's construction industry. The literature review highlighted these existing programs and identified the challenges and opportunities for implementing recycling and reuse initiatives in Sri Lanka's construction industry. Additionally, semi-structured interviews were conducted with 9 experts, and a questionnaire survey was administered to 48 participants to gather data. The interviews revealed strategies to address the challenges, while thematic analysis was employed to analyze the interview data, and the Relative Importance Index (RII) method was used to evaluate the effectiveness of the identified strategies. A total of 9 strategies were identified for integrating recycling and reuse programs into Sri Lanka's construction industry. The findings of this study may enable to enhance the sustainability in the construction sector by minimizing waste and promoting sustainability goals.

Keywords: *Construction Waste; Recycling and Reuse; Sustainable.*

1. INTRODUCTION

As a major global economic sector, the construction industry significantly contributes to environmental degradation through high resource consumption and waste generation.

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Globally, construction and demolition waste (CDW) accounts for 25% to 30% of all solid waste generated (Soto-Paz et al., 2023). In alignment with the UN's Sustainable Development Goals 2030, Sri Lanka aims to achieve a sustainable and prosperous nation by 2030. Sri Lanka generates (Mannamarakkalage, 2025). Sri Lanka generates 0.43 kg of waste per capita each year, which hinders the country's economic potential and its ability to achieve a sustainable future. This issue jeopardizes the nation's resources for future generations (Agarwal & Bimpli, 2025).

The global construction industry faces increasing pressure to address environmental challenges such as resource depletion, pollution, and climate change (Nilimaa, 2023; Srour et al., 2012). As construction activities intensify, so does the industry's contribution to carbon emissions and waste generation (Nilimaa, 2023). The construction industry is one of the largest emitters of greenhouse gases, accounting for 36% of global energy consumption and 37% of energy-related carbon emissions (Kalu Arachchi et al., 2025).

The construction sector's growth in developing countries is likely to increase construction and demolition waste, including concrete, wood, metal, and plastic, leading to potential environmental pollution if not managed properly (Gálvez et al., 2018). According to Kourmpanis et al. (2008), construction waste constitutes a significant portion of the total waste generated in Sri Lanka. Dumping these materials in landfills or using illegal disposal techniques generates major problems that negatively impact soil, water, and air quality (Kourmpanis et al., 2008).

Adopting building procedures that minimize waste creation in the construction industry, increasing the use of recycled materials in new construction, and finding markets for recycled and reused materials can all contribute to a CE in construction (Liyanage et al., 2022). The existing solid waste management systems in Sri Lanka are inadequate, with most construction and demolition waste being disposed of in landfills or illegal dumps (Karunasena & Amaratunga, 2016). The primary challenge of the built environment is managing construction and demolition waste that has not been disposed of properly, leading to severe environmental consequences (Agarwal & Bimpli, 2025). While Sri Lanka, particularly the Colombo Municipal Council, has initiated commendable programs recycling, these efforts are not fully effective or scalable due to systemic challenges in public participation, infrastructure, incentives, workforce management (Kaida, 2025).

There is an urgent need to learn how to reuse and recycle C&D waste, which can generate commercial opportunities, jobs, and, most importantly, promote environmental sustainability (Bansal et al., 2016). The construction industry can reduce waste and improve resource recovery by designing buildings and infrastructure for their entire life cycle, from material selection to disposal (Mollaei et al., 2023). The lack of modern recycling facilities and technologies limits the ability to effectively process and reuse construction materials (Crawford et al., 2017). Furthermore, there is little market demand for recycled construction materials due to concerns about product quality and the lack of standardized products (Geng et al., 2023).

This research aims to evaluate the effective implementation strategies for recycling and reuse programs in Sri Lanka's construction industry. Therefore, the study's aim will be achieved by accomplishing four objectives: identifying current recycling and reuse programs, assessing challenges and opportunities for implementing these programs, strategizing on overcoming challenges in implementation, and ultimately evaluating the

effectiveness of the identified strategies for implementing recycling and reuse programs in Sri Lanka's construction industry.

2. LITERATURE REVIEW

2.1 CONSTRUCTION AND DEMOLITION WASTE

The construction sector stands as one of the largest and most vital industries, being the primary user of natural resources and the leading contributor to pollution (Elgizawy et al., 2016). Construction and demolition waste encompasses materials discarded during new construction, refurbishment, and demolition processes of various structures, including buildings, roads, bridges, flyovers, and subways (Yuan et al., 2011). Beyond the direct environmental impact associated with landfilling, the creation of construction and demolition waste is tied to the depletion of natural resources and increased energy consumption (Marzouk & Azab, 2014). Hazardous substances such as asbestos, lead, and mercury, commonly present in older buildings, pose significant health risks if not managed correctly during demolition or renovation (Manoharan et al., 2021). Automated material recovery facilities have been developed to effectively sort and process construction and demolition waste. These facilities enable the reclamation of valuable materials while reducing the volume of waste directed to landfills (Mashudi et al., 2023). The average waste percentages of various materials throughout construction stages are 6.3% for the substructure, 4.8% for the superstructure, and 5.6% for finishes. In terms of concrete waste, the figures differ by building type, with high-rise structures generating 8.2%, low-rise at 5.2%, and medium-rise at 4.0% (Rathnayake et al., 2024). Globally, the construction industry is responsible for producing nearly ten billion tons of (CDW) each year, resulting in considerable financial burdens for contractors and contributing significantly to environmental degradation (Zhu & Feng, 2025).

2.2 GLOBAL PRACTICES IN CONSTRUCTION WASTE MANAGEMENT

Countries such as Germany, the Netherlands, and Denmark have been particularly successful in achieving these targets, recycling approximately 70% of all construction waste (Dytianquin et al., 2021). Germany's success can largely be attributed to its well-developed infrastructure, strong regulatory framework, and involvement of both public and private sector stakeholders (Iqbal et al., 2023). The Netherlands is implementing programs such as the use of recycled materials for road construction and modular building components that can be easily removed and reused (Van et al., 2021). Japan has effectively managed construction waste by utilizing modern material sorting and processing technologies while maintaining close coordination between government agencies, construction companies, and recycling firms (Menegaki & Damigos, 2018). The construction industry in the European Union generates 531 million tonnes of construction and demolition waste per year, accounting for around a quarter of the world's total waste. Approximately 46% of this waste is recycled across the 27 member states of the European Union (Junak & Sicakova, 2017). In countries such as the USA, Canada, Europe, Australia, India, Japan, Hong Kong, and Taiwan, several recycling projects related to construction and demolition waste have been implemented. Before the recycling of this waste, the generator must perform waste sorting (Liyanage et al., 2022).

2.3 RECYCLING AND REUSE OF CONSTRUCTION MATERIALS

Recycling involves managing waste and converting it into new products, whereas reuse refers to the practice of repurposing resources for similar or different uses without significant alterations (Minunno et al., 2020). Reusing and recycling, waste from construction and demolition can reduce the need for new materials, enabling the construction sector to contribute significantly to climate change mitigation and support sustainable development (Kourmpanis et al., 2008). These methods offer numerous environmental and economic advantages, including resource conservation, energy savings, waste reduction, and cost-effectiveness (Abera, 2023). Nevertheless, to fully realize these benefits, the construction industry must tackle issues related to material quality, infrastructure, and market demand (Storey, 2014).

2.4 CURRENT RECYCLING AND REUSE PRACTICES IN SRI LANKAN CONSTRUCTION INDUSTRY

Current practices mostly involve recycling construction and demolition waste into materials like aggregates and reusing structural components such as steel and concrete (Karunasena & Amaratunga, 2016). Concrete, for instance, is often demolished but not widely recycled, and this trend highlights the limited focus on reuse and recycling in the country's construction industry (Wimalarathna et al., 2023). Some construction companies have implemented basic waste separation programs, sorting materials such as metals, wood, and concrete for reuse or recycling (Kumarasinghe & Sylva, 2024). However, wood is frequently burned, and landfills, often filled with construction waste, continue to be heavily utilized in Sri Lanka (Ramos & Martinho, 2023).

The application of CE principles can help address these issues by promoting the reduction, reuse, and recycling of construction materials, which can extend the lifespan of products (Ghufran et al., 2022). CE strategies also have the potential to reduce raw material usage, preserve material resources, and lower the carbon footprint of construction projects (Adekunle et al., 2023). Additionally, digital tools improve record-keeping and coordination between stakeholders, leading to better material management (Liyanage et al., 2022).

Furthermore, construction projects that adopt circular techniques, such as wastewater reuse and rainwater collection, can significantly reduce the demand for freshwater, thus enhancing overall environmental sustainability (Wimalasena et al., 2025). A significant example of sustainable building practices in Sri Lanka is the "Jetwing Lighthouse Hotel," which incorporates passive cooling, solar energy utilization, and water reuse systems, demonstrating how CE principles can be effectively integrated into building design (Kalu Arachchi et al., 2025). The use of modular building methods and prefabrication can also optimize resource consumption by reducing offcuts and construction waste, leading to budgetary savings (Wimalasena et al., 2025). Bansal et al., (2016) highlights global technologies for recycling construction and demolition waste, focusing on separation techniques such as eddy current magnetic separation, air shifting, dry density separation, and spiral separation to eliminate contaminants like wood, gypsum, and plastics. These processes yield high-quality recycled materials, while rock breakers and mechanical hammers further reduce debris for use in non-structural applications like kerb stones, paving blocks, and tiles.

2.5 OPPORTUNITIES TO IMPLEMENT RECYCLING AND REUSE PROGRAMMES IN SRI LANKA

2.5.1 Environmental

Recycling one ton of concrete waste can save approximately 900 kg of CO2 emissions, contributing to more sustainable construction practices (Al-Sharif et al., 2024). Recycling materials in construction can significantly lower its carbon footprint, supporting global climate change efforts (Labaran et al., 2022). Research suggests that recycling CDW could cut the carbon footprint of building operations by up to 50% (Wimalasena et al., 2025). Additionally, recycling CDW can alleviate the environmental burden of landfilling and generate economic returns by producing goods that are in demand (Liyanage et al., 2022).

2.5.2 Economic

One of the most apparent benefits is the financial savings derived from using recycled and reused materials (Wimalasena et al., 2025). By incorporating these materials, construction organizations can reduce procurement costs and decrease dependence on expensive virgin materials for new projects (Amarasinghe et al., 2024). Furthermore, the demand for sustainable building materials rises, industries focusing on recycling, processing, and selling repurposed building materials have significant growth potential (Knoth et al., 2022).

According to the literature review findings, identified opportunities are given in Table 1.

Table 1: Opportunities to implement recycling and reuse programmes

Opportunities	Reference
Reduction of CO_2 emissions	(Al-Sharif et al., 2024)
Lower demand for virgin materials, conserving natural resources	(Knoth et al., 2022; Rathnayake et al., 2024; Wimalasena et al., 2025)
Cost savings	(Wimalasena et al., 2025)
Growth of the recycled material market, creating business opportunities	(Knoth et al., 2022)
Decreased environmental pollution	(Lamma & Waleed, 2021; Liyanage et al., 2022)
Improved air and water quality, reducing health risks	(Hajam et al., 2023)

2.6 CHALLENGES TO IMPLEMENTING RECYCLING AND REUSE PROGRAMMES IN SRI LANKA

Implementing recycling and reuse programmes in Sri Lanka faces several challenges (Victar & Waidyasekara, 2024). Addressing these challenges requires strategic investments in technology, financial support, and awareness initiatives to promote sustainable construction practices (Rathnayake et al., 2024; Victar & Waidyasekara, 2024). According to the literature review, identified challenges are given in Table 2.

Table 2: Challenges to implement recycling and reuse programmes

Challenges	Reference
Lack of advanced technology and knowledge	(Karunasena & Amaratunga, 2016; Rathnayake et al., 2024; Victar & Waidyasekara, 2024)
Significant initial investment in technology, equipment, and training	(Athapaththu & Karunasena, 2016; Coelho & De Brito, 2013)
High costs of building recycling facilities	(Coelho & De Brito, 2013; Liyanage et al., 2022)
Lack of knowledge and understanding of recycling and reuse benefits	(Al-Raqeb et al., 2023; Liyanage et al., 2022)
Difficulty in adopting new practices due to workflow changes	(Al-Raqeb et al., 2023; Ghufran et al., 2022)
Limited market demand for recycled materials	(Geng et al., 2023)
Limited infrastructure and resources for waste segregation, collection, and processing	(Rathnayake et al., 2024; Victar & Waidyasekara, 2024)
Fluctuating raw material prices	(Ghufran et al., 2022)

3. METHODOLOGY

3.1 RESEARCH PROCESS

Given the complexity of the subject, a mixed-methods approach was adopted, combining qualitative exploration and quantitative evaluation to ensure a holistic understanding of the research problem (Williams, 2007). This methodological framework enhances data collection and analysis, capturing both numerical trends and in-depth contextual insights (Dawadi et al., 2021). It also helps to validate and enrich findings by integrating multiple data sources, leading to more reliable and well-rounded conclusions (Dawadi et al., 2021). Pragmatic research philosophy was chosen, allowing the integration of quantitative methods, such as surveys, to measure industry challenges, alongside qualitative methods, such as interviews, to explore practical barriers (Khatri, 2020). The study employed a deductive approach, enabling statistical analysis of industry trends while incorporating qualitative insights.

The study commenced with an extensive literature review, which identified research gaps, defined the problem, and established key objectives. The review examined existing recycling practices, industry challenges, and potential opportunities. To refine and validate these findings, semi-structured interviews were conducted with key stakeholders, providing deeper insights into the practical barriers and opportunities within the sector. Subsequently, a questionnaire survey was administered to a broader group of industry professionals to collect quantitative data. The final phase involved statistical and thematic analysis of the collected data, ensuring a comprehensive evaluation of industry trends and stakeholder perspectives.

3.2 DATA ANALYSIS

3.2.1 Qualitative Data Analysis

The first phase involved conducting semi-structured interviews with a purposively selected sample in Sri Lanka's construction industry. Semi-structured interviews provide a balance of consistency and adaptability, while unstructured interviews offer greater depth and openness but less control and comparability (Ruslin et al., 2022). These interviews aimed to gather data on the existing recycling and reuse programmes, challenges to implementation, and strategies for improvement. Responses from the interviews were analysed using thematic analysis to identify key themes and patterns related to recycling and reuse programmes.

3.2.2 Expertise Core Data Analysis

The semi-structured interview was conducted with nine experts, and Table 3 represents the professional experience of the respondents who participated in the interviews.

Table 3: Expert core data analysis

Years of Experience	Professions	No. of Experts
5 - 10 years	Project Quantity Surveyor	1
	Planning Engineer	1
	Senior Civil Engineer	1
10 - 20 years	Project Manager	1
	Chartered Quantity Surveyor	1
20- 30 years	Senior Quantity Surveyor	1
	General Manager - MEP Services	1
More than 30 years	Chartered Quantity Surveyor	1
	Chartered Civil Engineer	1

3.2.3 Quantitative Data Analysis

The questionnaire survey was collected from a total of 48 participants. It is commonly used in research to collect information through structured or semi-structured questions, ensuring consistency in analysis (Kuphanga, 2024). This survey employed a non-probability sampling method. Non-probability sampling involves selecting participants based on specific criteria or relevance, not random selection, with the aim of gaining deeper insights rather than broad generalizations (Taherdoost, 2016). In this study, a five-point Likert scale was used. RII values were used to rank the effectiveness of identified strategies. RII provides a clear indication of the priority or significance of different variables, making it useful in analysing survey or questionnaire data (Tarek et al., 2022). The formula for finding RII for each factor is as follows:

$$RII = \frac{\sum w}{A \; x \; N} \qquad Equation\,(1)$$

Where, w = Weighting for each factor by the respondent (No. of responses x weight), A = Highest weight, and N = Total number of respondents

3.2.4 Demographic Survey Data Analysis

Out of 48 respondents to the questionnaire survey, 64% were from construction companies, 34% from consultancy firms, and 2% from the activated carbon industry. The demographic survey data analysis is represented in Figure 1.

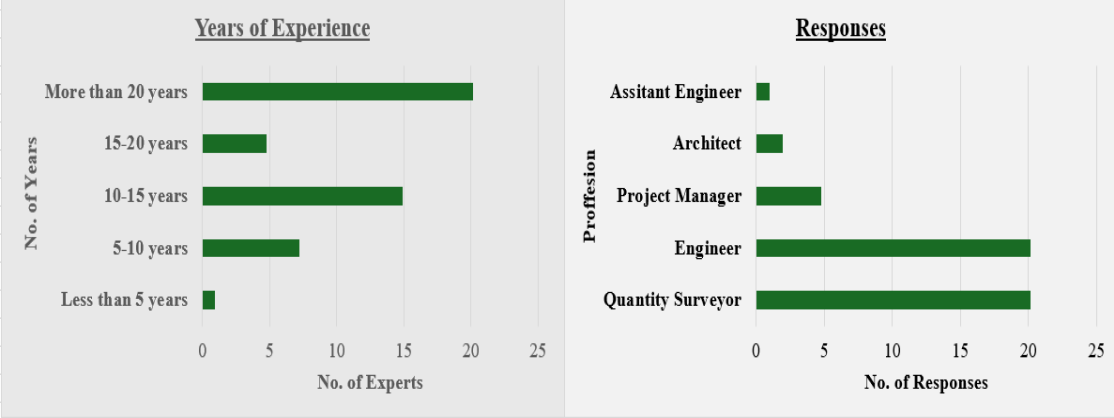


Figure 1: Demographic data analysis

4. RESEARCH FINDINGS

4.1 MATERIAL POTENTIAL AND INDUSTRY SUPPORT FOR RECYCLING AND REUSE IN THE SRI LANKAN CONSTRUCTION INDUSTRY

Participants indicated that while small-scale recycling efforts exist, they are not widely integrated into project workflows. A key challenge emphasized by all participants is the absence of a comprehensive recycling and reuse system in the industry. Insights gathered from interviews are represented in Table 4.

Table 4: Material potential for recycling and reuse

Material	Insights gathered from interviews	No. of responses	Literature review
Steel	Considered a suitable material for recycling.	9	✓
Timber	Can be effectively recycled and reused.	9	✓
Roof Tiles	Have the potential to be recycled.	2	
Concrete	Primarily repurposed for backfilling rather than being recycled.	2	✓

All interviewees highlighted steel and timber as the most commonly recycled materials, a finding also supported by the literature review. Two interviewees noted that concrete is rarely fully recycled and is mainly used for backfilling, while another two identified roof tiles as a commonly reused material, particularly in renovations.

However, one interviewee noted that the growing adoption of BIM (Building Information Modelling) could improve material management and support future recycling initiatives. Another interviewee highlighted that the GBCSL (Green Building Council of Sri Lanka) has introduced a certification system to promote the use of recycled materials in construction projects.

4.2 OPPORTUNITIES AND CHALLENGES IN IMPLEMENTING RECYCLING AND REUSE PROGRAMMES IN SRI LANKA'S CONSTRUCTION INDUSTRY

Insights gathered from both interviews and the literature review highlight key challenges and opportunities in implementing recycling and reuse programs represented in Table 5.

Table 5: Opportunities and challenges for recycling and reuse programmes

Considered key criteria	Insights gathered from the interviews	Interviews										Literature review
		R1	R2	R3	R4	R5	R6	R7	R8	R9	Total	
Opportunities	Environmental and economic benefits	✓		✓	✓	✓		✓			5	✓
	Green certification and market differentiation				✓		✓	✓			3	
	Job creation				✓						1	✓
Challenges	Lack of technology			✓	✓	✓		✓	✓	✓	6	✓
	Financial constraints	✓		✓		✓		✓	✓		6	✓
	Regulatory and governmental barriers	✓	✓	✓		✓	✓				5	
	Lack of public awareness		✓	✓				✓			3	✓
	Insufficient infrastructure		✓			✓			✓		3	✓

Key challenges identified include a lack of advanced recycling technology, noted by five interviewees. Financial constraints were mentioned by four, citing high initial investments for facilities and transportation. Two highlighted public awareness gaps, while regulatory barriers were noted by two, including a lack of government incentives and weak frameworks, as mentioned by four. Insufficient infrastructure, such as inadequate waste collection, was a concern for three interviewees, and one interviewee mentioned that tight project timelines hinder recycling integration. These findings echo the literature review, which identifies these obstacles as critical limitations.

The interviews and literature review highlight key opportunities, including reduced costs, enhanced sustainability through lower carbon emissions, and decreased landfill waste. Additionally, recycling practices can create jobs in waste management and processing, and help companies attain green building certifications, attracting eco-conscious clients. Addressing challenges related to technology, finance, regulation, and awareness can further boost recycling adoption in the sector.

4.3 STRATEGIES FOR OVERCOMING RECYCLING AND REUSE CHALLENGES

Interviewees suggested strategies to tackle challenges in recycling and reuse programs, which were then distributed via a questionnaire survey. Data from the survey were analysed using the RII method to rank the effectiveness of these strategies in the Sri Lankan construction industry.

This analysis included a comparison of each strategy's RII with the mean RII ($\bar{X}$ = 0.7955), indicated by the (X-$\bar{X}$) column, which shows how each strategy's score deviates from the average significance level. A total of 9 strategies with average RII values above 0.7955 were identified as the most effective strategies, as illustrated in Table 6.

Table 6: Proposed strategies

	Strategies	Semi-Structured interviews										Questionnaire survey		
		R1	R2	R3	R4	R5	R6	R7	R8	R9	Total	RII	Rank	(X-$\bar{X}$)
S1	Training and education	✓		✓				✓	✓		4	0.8667	1	0.0711
S2	Investment in technology and infrastructure	✓		✓		✓		✓		✓	5	0.8208	2	0.0253
S3	Development of Recycling Infrastructure						✓			✓	2	0.8208	2	0.0253
S4	Government support for companies	✓	✓	✓	✓	✓	✓	✓	✓	✓	9	0.8167	3	0.0211
S5	Partnering with investors who are interested in green technologies.	✓									1	0.8083	4	0.0128
S6	Establishing clear quality control standards for recycled materials	✓	✓	✓	✓	✓	✓	✓	✓	✓	9	0.8042	5	0.0086
S7	Public-Private Partnerships to fund recycling initiatives	✓	✓	✓	✓	✓	✓	✓	✓	✓	9	0.7958	6	0.0003
S8	Setting green certification standards	✓	✓	✓	✓	✓		✓	✓		7	0.7958	6	0.0003
S9	Creating a Recycling and Reuse Department								✓		1	0.7958	6	0.0003

	Strategies	Semi-Structured interviews										Questionnaire survey		
		R1	R2	R3	R4	R5	R6	R7	R8	R9	Total	RII	Rank	(X-$\bar{X}$)
S10	Encourage companies to adopt circular economy practices						✓				1	0.7875	7	-0.008
S11	Hiring experts						✓				1	0.7833	8	-0.012
S12	Demonstrating the long-term cost savings							✓			1	0.7792	9	-0.016
S13	Attracting foreign investments and partnerships with international firms				✓		✓				2	0.7708	10	-0.025
S14	Reduced landfill fees for companies				✓						1	0.7458	11	-0.05
S15	Incorporation of Modular Construction Methods				✓	✓					2	0.7417	12	-0.054

According to the analysis, the most effective strategies for advancing recycling and reuse in Sri Lanka's construction industry focus on education, investment, regulation, and collaboration. Training and educational programs can raise awareness among industry professionals about the benefits and best practices of recycling. Investing in technology and developing recycling infrastructure will enhance the efficiency and feasibility of waste processing.

Government support for companies that produce high-quality recycled materials, along with clear quality control standards, can boost confidence in using these materials. Encouraging public-private partnerships and collaborating with green investors can provide the necessary funding and expertise to expand recycling initiatives.

Additionally, implementing green certification standards that promote recycling will incentivize companies to adopt sustainable practices. Establishing an internal Recycling and Reuse Department within companies can ensure a structured approach to sustainability efforts. By collectively implementing these strategies, the construction industry can drive long-term progress in sustainability.

5. CONCLUSIONS

This research emphasizes the urgent need for systematic recycling and reuse initiatives within Sri Lanka's construction industry. The study shows that despite increasing awareness, the adoption of these practices is still impeded by technological, financial, regulatory, and infrastructural challenges. However, there are promising opportunities available, including economic benefits, job creation, and green certifications, which could motivate companies to invest in recycling efforts. To address these challenges, the study identifies nine strategies. The construction industry must prioritize strategic investments in technology, enhance public-private partnerships, and implement clear policies to support sustainable waste management. Additionally, government incentives and regulatory frameworks should be strengthened to encourage companies to incorporate recycling practices into their operations. Furthermore, increasing awareness and providing technical training will facilitate the transition toward a more sustainable construction sector. By tackling these obstacles and capitalizing on available opportunities, Sri Lanka can progress towards a more sustainable and environmentally responsible construction industry.

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TOWARDS A COMPUTERISED MAINTENANCE MANAGEMENT SYSTEM FOR HEALTHCARE FACILITIES IN SOUTH AFRICA

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ABSTRACT

Healthcare facilities constitute one of the essential infrastructures in any community. It plays a critical role in achieving Sustainable Development Goal (SDG) No. 3, which aims to enhance the health and well-being of individuals. Nevertheless, the efficient upkeep of healthcare facilities in South Africa has encountered several obstacles, and one potential solution is the implementation of computerised maintenance management systems (CMMS). This study explored the benefits of the deployment of CMMS for healthcare facilities in South Africa. A quantitative methodology required data collection through a structured questionnaire distributed to professionals within the built environment. The collected data was analysed via exploratory factor analysis, utilising principal component analysis as the extraction method. The study's outcome identified four components as the benefits of the deployment of CMMS for healthcare facilities in South Africa: maintenance efficiency and facilities uptime, asset and resource management, regulatory compliance and safety assurance, and sustainability adherence and strategic insights. In conclusion, the study offered suggestions that could facilitate the effective integration of computational systems like CMMS to maintain healthcare facilities in South Africa.

Keywords: *Benefits; CMMS; Developing Country; Facilities; Healthcare.*

1. INTRODUCTION

Healthcare delivery is a fundamental provision of any decent society. Prowle and Araali (2017) noted that in most developing countries, there is a growing need for healthcare services arising from the surge in population. This also reflects the surge in healthcare facilities needed to attend to the teeming population. The maintenance management of healthcare facilities is critical in delivering healthcare needs (Lavy & Terzioğlu, 2023). In most developing countries, such as South Africa, there has been a strain on utilising healthcare facilities due to increased healthcare needs. According to Yousefli et al.

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(2017), this underscores the need for efficient maintenance management of healthcare facilities. Also, in most developing countries, due to poor maintenance planning and management, most healthcare facilities are attributed with downtime (Arab-Zozani et al., 2021). A major contributor to the non-implementation of maintenance management is the lack of or missing data. Furthermore, Ikuabe et al. (2023) noted that, resulting from outdated systems, there is a significant bottleneck towards the efficient management of facilities. Hence, there is a need to navigate to a system that can deliver efficient maintenance management to deliver the requisite functions of healthcare facilities. Implementing the computerised maintenance management system (CMMS) is one such system.

The computerised maintenance management system (CMMS) is a digital platform that assists in maintenance and asset management of an organisation's facilities (Wienker et al., 2016). Rastegari and Mobin (2016) state that it is an enabling, technology-driven system that helps in functions such as scheduled maintenance, asset management, and production & tracking of issued work orders. Moreover, CMMS is featured as a digital platform used to plan and supply parts of facilities, while also driving the proper keeping of records of facilities (Alemayehu et al., 2023; Stazic et al., 2023). Generally, the system helps gather and collect maintenance records and data to project the effectiveness and efficiency of maintenance management (Alemayehu et al., 2023). The deployment of CMMS for healthcare facilities can help mitigate some of the challenges experienced in the maintenance management of facilities. Furthermore, by employing strategic maintenance management of healthcare facilities, there is a high tendency to reduce medical incidents propagated by faulty facilities and equipment (Li et al., 2023). Also, the Joint Commission on Accreditation of Healthcare Organisations issued a certified revised programme to drive the maintenance of healthcare facilities (Joint Commission, 2014). Moreover, from a South African perspective, no study has explored the benefits of the deployment of CMMS for healthcare facilities. Hence, on this basis, the current study strives to evaluate the benefits of the deployment of CMMS for healthcare facilities in a South African context. The study's outcome will make theoretical and practical contributions towards the upscaling of maintenance management practices of healthcare facilities using innovative solutions.

2. REVIEW OF RELATED STUDIES

Healthcare facility maintenance in South Africa faces challenges including aging infrastructure, limited budgets, regulatory compliance demands, and the need for uninterrupted services (Lebea et al., 2024). These constraints often lead to reactive rather than preventive maintenance approaches, compromising safety, hygiene, and operational efficiency, while also increasing long-term costs and affecting patient care quality and staff productivity. Due to the purpose of use, maintaining healthcare facilities is very important. This is reinforced by the sustainable and life expectancy attainments, characterised by well-maintained facilities. Beniacoub et al. (2021) noted that CMMS seeks to help deliver the mandates as mentioned earlier, aided by its computational capabilities. CMMS are automated in that they provide predictive maintenance, which therefore plays a vital role in ensuring that adequate and quick maintenance is easily achieved (Gorski et al, 2022). When a fully detailed maintenance strategy (e.g. scheduled inspection) for all equipment is pre-loaded in the CMMS, maintenance is executed, which reduces possible breakdowns on such equipment. CMMS also facilitates the collection

and storage of data. Aliyu et al. (2023) noted that the system is not only deployed for storing data but can also store large amounts of data. Thus, enhancing maintenance planning of healthcare facilities. Moreover, a critical use of the CMMS in a healthcare set-up is the drive for preventive maintenance strategies (Wienker et al., 2016). Due to the reliance of healthcare facilities on high-value and complex equipment, the use of CMMS can foster optimised preventive maintenance techniques that can serve in the long term. The system enables maintenance personnel to set up and automate maintenance functions using facilities' historical data or manufacturer recommendations (Besiktepe et al., 2020). A fundamental derivation from the deployment of the CMMS is the optimisation of asset management (Jonassen, 2024). Also, due to the limited resources and tight budgets operated by most healthcare institutions, the use of CMMS tends to make facilities very efficient. This is actualised through centralised databases that assist in tracking and conducting a comprehensive assessment of the facilities lifecycle (Ismail, 2019). This covers maintenance history, performance metrics, warranty periods, and purchase dates. Besiktepe et al. (2020) stated that well-maintained equipment provides a high probability of such equipment operating and performing to its full capacity without failure, and becomes a dependable tool in times of need, and can offer service delivery to patients (improving health and safety). Healthcare facilities are subject to stringent regulations from health authorities and accreditation bodies, and CMMS aids in actualising regulatory compliance (Wienker et al., 2016). The regulation covers maintenance process documentation, enforced routine inspections, and traceable maintenance actions.

3. METHODOLOGY

The study aims to evaluate the benefits of the deployment of CMMS for healthcare facilities in South Africa. A questionnaire survey was employed for data collection using a quantitative research approach. The ability to reach out to a large number of respondents while also considering the quantifiability of the data is the reason for the choice of the data collection instrument (Nardi, 2018). Using a Likert scale of 1 to 5, the questionnaire captured fourteen benefits identified from literature and presented to the study's respondents for rating based on their significance. These respondents were facilities managers, construction managers, quantity surveyors, and architects. The research area is Gauteng province in South Africa. The choice of the study area is driven by its characteristics of having a large pool of professionals and having a significant number of healthcare facilities in the country. The sampling techniques deployed for the study are purposive and snowball sampling techniques. Professionals with knowledge and experience in healthcare facilities management were identified and participated in the survey; thereafter, referrals were given to professionals with similar expertise and experience. Sixty-five questionnaires were filled out and deemed appropriate for analysis after collection. Cronbach's alpha was used to assess the validity and reliability of the research instrument. An alpha value of 0.896 was given, which gives a good validity and reliability of the study's instrument as it is above the threshold of 0.7 and closer to 1.00 (Tavakol & Dennick, 2011). The method of data analysis used for the study is exploratory factor analysis (EFA) employing the principal component analysis as the technique for data extraction, as employed by Ikuabe et al. (2021) and Maphongwane et al. (2024). This technique helped in clustering variables with similar attributes, thereby leading to a reduction in the number of variables.

4. FINDINGS

The use of EFA in this study is driven by the need to identify clusters of measurement variables with similar dimensions. This clustering process resulted in a more streamlined and comprehensible framework by reducing the number of variables. The initial phase involved evaluating the appropriateness of the gathered data from the study participants. The outcome indicated an inter-item correlation ranging from 0.20 to 0.50, which is deemed suitable (Phelan & Wren, 2007). The data's factorability was assessed using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. According to Pallant (2005), a dataset is considered suitable for EFA if it is significant ($p < 0.05$). The results displayed in Table 1 reveal a KMO value of 0.826, while Bartlett's test shows significance with a p-value of 0.000. This result exceeds the 0.6 threshold recommended by earlier studies (Ikuabe & Oke, 2019; Ibrahim et al., 2024). This finding confirms that the retrieved data is suitable for conducting EFA.

Table 1: KMO and Bartlett's Test

KMO and Bartlett's Test Results		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.826
Bartlett's Test of Sphericity	Approx. Chi-Square	1207.496
	Df	115
	Sig.	0.000

The rotated component matrix results and the percentage of variance accounted for by the analysed variables are shown in Table 2. The measurement variables converged through six iterations by applying principal component analysis (PCA) as the extraction method with varimax rotation. The results revealed four components with an eigenvalue ≥ 1.00, explaining a cumulative variance of 72.97%. The initial component is linked to four variables with factor loadings between 0.885 and 0.635, accounting for 53.72% of the variance and is referred to as Maintenance Efficiency and Facilities Uptime. The second component comprises four variables with factor loadings that range from 0.777 to 0.581, representing 11.36% of the variance and is labelled Asset and Resource Management. The third component includes three variables with factor loadings from 0.679 to 0.518, contributing to 4.64% of the variance and is identified as Regulatory Compliance and Safety Assurance. The fourth component comprises three variables, with factor loadings between 0.622 and 0.508, accounting for 3.25% of the variance and is named Sustainability Adherence and Strategic Insights.

Table 2: Rotated component matrix

Benefits	**Component**				**Extracted Communalities**	**% of Variance**
	1	**2**	**3**	**4**		
Maintenance Efficiency and Facilities Uptime						
Automated Work Order Scheduling	0.885				0.533	53.72
Reduced Equipment Downtime	0.814				0.628	
Preventive Maintenance Optimisation	0.722				0.615	
Real-time updates	0.635				0.507	

Benefits	Component				Extracted Communalities	% of Variance
	1	2	3	4		
Asset and Resource Management						
Lifecycle Asset Tracking		0.777			0.738	11.36
Inventory Management		0.716			0.777	
Minimised Emergency Repairs		0.649			0.829	
Capital Planning		0.581			0.715	
Regulatory Compliance and Safety Assurance						
Regulatory and Standards Compliance			0.679		0.661	4.64
Improved Safety			0.542		0.593	
Support for Quality Assurance			0.518		0.724	
Sustainability Adherence and Strategic Insights						
Environmental Sustainability				0.622	0.566	3.25
Enhanced Decision-Making				0.547	0.599	
Analytical Reporting and KPIs				0.508	0.682	

Extraction Method: Principal Component Analysis
a.4 components extracted

5. DISCUSSION

The results of the study affirm that the implementation of CMMS in healthcare facilities provides notable advantages. The system increases the scheduling and execution rates of preventive and corrective maintenance activities. This is corroborated by Beniacoub et al. (2021), who noted that CMMS improves facility reliability by minimising unplanned downtime. Also, the system's automated work order generation and monitoring in real-time systems markedly reduced response times, thus improving overall efficiency. For asset and resource management, CMMS enables enterprises to track asset lifecycles effectively, supporting equipment replacement and budgeting decision-making. CMMS also improves resource planning based on performance data and maintenance costs, as Jonassen (2024) asserted. The system's ability to create audit-ready regulatory compliance and safety assurance documentation was highly appreciated. This is corroborated by the study of Wienker et al. (2016), who noted that CMMS facilitates compliance by capturing all maintenance activities in logs, documents, and records. Furthermore, regarding sustainability adherence and strategic insights, the study found that CMMS promotes environmental sustainability by reducing paper use and conserving energy. Moreover, the system's analytics and reporting capabilities helped develop more effective strategies, which Wienker et al. (2016) also noted regarding the role of CMMS in performance evaluation and ongoing enhancement.

6. CONCLUSION AND RECOMMENDATIONS

The research revealed the outcomes of evaluating the benefits of deploying CMMS in healthcare facilities in South Africa. A review of existing literature was done, which facilitated the identification of these benefits. The identified benefits were then rated by the study's respondents according to their significance using a Likert scale. The gathered data underwent analysis through exploratory factor analysis, employing principal component analysis as the method for extraction. The results from this analysis identified four components as the benefits of using CMMS in South African healthcare facilities.

These are maintenance efficiency and facilities uptime, asset and resource management, regulatory compliance and safety assurance, sustainability adherence and strategic insights. The enhancement of maintenance management systems within healthcare facilities is crucial for improving the delivery of healthcare services. Implementing CMMS can help mitigate some challenges associated with traditional maintenance management systems, especially as facilities aim to upscale maintenance practices. Consequently, based on the study's findings, it is recommended that healthcare organisations develop the necessary technical skills to utilise CMMS effectively. Additionally, government financial assistance in the form of subsidy regimes could help address the costs involved in implementing the system. Furthermore, fostering a cultural shift among stakeholders is essential to encourage the adoption of advanced computational systems for more efficient maintenance management.

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TOWARDS SUCCESSFUL IMPLEMENTATION OF OFFSITE CONSTRUCTION IN SRI LANKA: BARRIERS AND STRATEGIES

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ABSTRACT

The construction industry has significantly progressed by incorporating modern construction technologies. Offsite building is growing in popularity, yet it continues to face resistance from the built environment market and the construction industry. Offsite construction (OSC) is gaining recognition globally as a sustainable, efficient, and innovative alternative to traditional construction methods. In Sri Lanka, despite the evident benefits but OSC adoption remains limited due to several barriers. This research aims to investigate and identify strategies to overcome the barriers that hinder the successful implementation of OSC in building projects in Sri Lanka. Accordingly, the literature review highlighted the feasibility of OSC for the Sri Lankan construction industry and the advantages and barriers of OSC in the Sri Lankan context. Moreover, semi-structured expert interviews were conducted with 10 experts to gather data, and thematic analysis was used to analyze the collected interview data. Findings reveal that the primary barriers include high initial capital costs, lack of skilled labour, insufficient governmental support, limited public awareness, and a reliance on conventional construction practices. Additionally, logistical challenges, such as transporting prefabricated components, and the absence of standardized design codes further constrain OSC implementation. Despite these obstacles, the study emphasizes the transformative 5 potential strategies proposed for promoting the adoption of OSC in building projects in Sri Lanka. This strategy strives to empower Sri Lanka towards a more innovative, productive, and sustainable construction industry

Keywords: *Construction Industry; Offsite construction (OSC); Strategy*

1. INTRODUCTION

The rapid development of the construction industry has brought about critical issues such as resource depletion, environmental pollution, and ecological damage (Liu and Abidin, 2024). In the Sri Lankan context, construction material wastage is notably high during both construction and demolition processes (Bimsara et al., 2024). Given the significant

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environmental pressures faced by the industry, there is an increasing urgency to adopt more eco-friendly construction methods (Liu & Abidin, 2024).

The construction industry has made significant progress with the incorporation of modern construction technologies (Wasana, et al., 2019). Off-site building can be thought of as a viable solution for the challenges connected to the conventional construction techniques currently employed in the construction industry (Wasana et al., 2019). The offsite building is becoming more popular, but it still faces resistance from the built environment market and the construction industry (Razkenari et al., 2020).

Also, the construction industry is competitive, with cost as the main focus for contractors. To stay relevant, they must continually reduce project costs while maintaining quality. (Sandamini & Waidyasekara, 2022). Jayasena et al. (2023) stated the adoption of OSC techniques, such as prefabrication, to improve efficiency and reduce construction waste. Prefabricated construction provides a new direction for transforming and upgrading the construction industry (Jin et al., 2018). It is stated that the industry's performance might be improved via collaboration among all the stakeholders and the use of new construction building materials, such as off-site manufacturing, to reduce construction costs (Dharmendra & Thusyanthan, 2021)

Sanjeepan (2017) suggests that Sri Lanka's construction industry should focus on off-site construction methods to attain these advantages. In Sri Lanka, the construction industry mainly uses traditional onsite methods, but recent advancements in OSC have led to more case studies and research. Still, there is a lack of review papers examining various aspects of offsite buildings (Razkenari et al., 2020). Sri Lanka is slow to adopt prefabricated construction due to inherent barriers. As a developing economy, Sri Lanka significantly lags in adopting prefabricated construction technologies compared to developed and industrialized economies (Jayawardana et al., 2023). OSC offers significant benefits for Sri Lanka's construction industry, but low adoption due to persistent barriers. Investigating these barriers and developing effective strategies is essential to unlock OSC's potential and guide industry growth. Therefore, this research aims to identify strategies to overcome the barriers that hinder the successful implementation of OSC in building projects in Sri Lanka. Firstly, the research identified the feasibility and suitability of OSC in the Sri Lankan context. Secondly, it examined the potential benefits associated with the implementation of OSC in local building projects. Thirdly, the study investigated the key barriers hindering the adoption of OSC within the construction industry. Ultimately, the research will propose strategies for promoting the adoption of OSC in building projects in Sri Lanka.

2. LITERATURE REVIEW

2.1 OVERVIEW OF OSC

OSC consists of creating building components and modules in a controlled environment, transporting them to the construction site, and assembling or installing them on site (Assaad et al., 2022). The OSC method is classified into volumetric systems, panel systems, hybrid systems, and sub-assemblies and components (Gunawardena et al., 2016; Sanjeepan, 2017)

OSC presents a compelling opportunity for the construction industry in Sri Lanka, as it enhances economic feasibility and overall efficiency (Gunarathne et al., 2023). Many

government reports emphasize the importance of addressing issues within the traditional construction industry. They propose adopting innovations based on a modern and sophisticated technique known as OSC. This approach is seen as a revolutionary and sustainable solution to the challenges the industry faces (Abanda et al., 2017). According to Jayasena et al. (2023) findings OSC technique is one of the suitable strategies to overcome challenges in construction innovation projects in Sri Lanka. These methods can significantly enhance the efficiency of the construction process while minimizing waste, thereby addressing key challenges in the industry (Jayasena et al., 2023).

2.2 BENEFITS OF OSC

OSC techniques have emerged as a promising solution to address many challenges in the Sri Lankan construction industry. These techniques offer numerous advantages, ranging from cost savings to environmental benefits.

Sanjeepan (2017) highlights that OSC provides multiple benefits, including cost reductions, increased productivity, enhanced quality control, and a lower environmental footprint. Similarly, Rahimian et al. (2017) emphasize that offsite manufacturing conducted in a controlled environment contributes to faster construction speeds, improved product quality, reduced costs, and decreased on-site labour requirements. The advantage of faster construction is particularly significant. According to Hong et al. (2018), volumetric construction techniques can improve construction schedule efficiency by up to 50%, a remarkable contribution to addressing delays commonly observed in traditional construction. Worker safety is another critical area where OSC demonstrates significant impact. Offsite prefabrication can reduce the occurrence of safety incidents by 80% to 85%, thereby minimizing risks and enhancing worker safety (Navaratnam, 2022). The factory-centric nature of volumetric construction naturally reduces on-site hazards, as noted by Balasbaneh and Ramli (2020) who emphasize the importance of safety in construction projects.

The quality of final construction products is also notably improved through OSM. Gan et al. (2018) and Peltokorpi et al. (2018) support the claim that OSM not only speeds up construction but also improves the quality of the final product while substantially reducing construction costs. Gan et al. (2018) add additional importance to the benefits of OSC, emphasizing that it not only expedites the construction process but also improves the overall standard of the completed work. This is a critical component since the long-term operation and durability of structures are dependent upon the level of quality of the construction process. In the long run, projects involving essential infrastructure and urban growth may become more financially feasible and environmentally friendly as building prices decrease (Peltokorpi et al., 2018).

Environmentally, OSC aligns well with Sri Lanka's sustainability goals. According to Sandamini and Waidyasekara (2022) and Razkenari et al. (2020), OSC has environmental benefits that are under the country's sustainability targets. These advantages include decreased waste, pollution, and depletion of resources. They mark a substantial advancement in Sri Lanka's construction industry's transition to a greener and more sustainable one (Sandamini & Waidyasekara, 2022).

2.3 BARRIERS OF OSC

Sanjeepan (2017) stated that given issues with industry capacity, public perception, and attitude, as well as off-site construction's higher cost compared to conventional building, off-site construction has seen little usage within the construction industry.

Gan et al. (2018) highlight inadequate policies and regulations, lacking knowledge and skills, dominated traditional project approach, and poor standardization as the most pressing problems. According to Uthpala and Ramachandra (2015), the cost of OSC is a major barrier, with OSC projects costing 7% to 10% more than conventional building projects due to the speedier construction and higher-quality off-site construction. Cost factors for prefabricated buildings are complex, involving technology, policy, market conditions, materials, and management. A major challenge is high capital costs, often resulting from poor coordination, weak supply chain integration, and complicated connections (Liu & Abidin, 2024).

According to the literature review findings, barriers to OSC in the Sri Lankan context are given in Table 1.

Table 1: Identified barriers to OSC in Sri Lanka from literature review

Barriers	Source
Lack of experienced collaboration groups	3,6,13
Lack of manufacturers and suppliers of prefabricated components	1,3,6
Transportation of prefabricated elements and access to the building site	2,3,13
Lack of experienced contractors on prefabrication	6
Poor integration for the supply chain	6
Longer lead-in time for OSC components	4,6
Low productivity	1
High-skill demands for labour	3,7,6
Increase in complexity for maintenance	1,6
High initial & capital cost	3,6,9,10,11,12,13
Longer capital payback period	3,6,9,12
Increased cost due to higher quality/rapid construction	3
Lack of design codes and standards for prefabricated components	4,8,7,6,12
Lack of governmental regulations and incentives	8,6
Lack of technologies and testing institute to prefabricated components	2
The owner’s negative perception	1,2,3,4,6
Lack of awareness of prefabrication by the market and public	2,3,11
Dependence of traditional construction method	1,2,3,5,7,12
Poor quality impression	1,2,7,6
Lack of confidence of the industry in offsite production	6,13
Project planning and coordination	1,3,4,9
Uncertainty of market demand	1

	Barriers		Source
1.	(Jayasena et al., 2023)	8.	(Blismas et al., 2005)
2.	(Kamar et al., 2009)	9.	(Hwang et al., 2018)
3.	(Pan & Sidwell, 2011)	10.	(Razkenari et al., 2020)
4.	(Sanjeepan, 2017)	11.	(Rahimian et al., 2017)
5.	(Pan et al., 2008)	12.	(Gan et al., 2018)
6.	(Zhai et al., 2014)	13.	(Dharmendra & Thusyanthan, 2021)
7.	(Mao et al., 2015)		

3. METHODOLOGY

This study adopts a qualitative, inductive approach to investigate the strategies to overcome the barriers that hinder the successful implementation of OSC in building projects in Sri Lanka. Qualitative research explores the meanings and perceptions of individuals or groups by gathering and analyzing textual data through methods such as surveys, interviews, focus groups, and observations (Borrego et al., 2009).

3.1 DATA COLLECTION PROCESS

Data collection integrates a systematic literature review and semi-structured interviews. Interviews are considered one of the best selection techniques as its goes up to the depth of opinion of the interviewees (Kallio et al., 2016). This will involve conducting semi-structured interviews with diverse stakeholders involved in building projects in Sri Lanka, such as architects, engineers, contractors, and workers.

3.2 DATA ANALYSIS PROCESS

Semi-structured interviews were chosen as they allow flexibility to explore participants' experiences in-depth while maintaining consistency across interviews (Kallio et al., 2016). This approach is common in qualitative research where participants are selected based on their expertise and relevance to the study (Etikan, 2016). A semi-structured interview was conducted with ten interviewees in the local construction industry. A sample of 10 participants was adequate to reach data saturation, ensuring rich and relevant insights without unnecessary repetition (Guest et al., 2006). The interview was designed to investigate local practices, ensuring that the responses collected would offer valuable insights into the local construction industry. Interview responses data were analyzed using thematic analysis. A qualitative data analysis method involves identifying recurring ideas in a data set. Typically, a researcher conducting thematic analysis will work with interview data and attempt to derive themes inductively (Jason & Glenwick, 2015).

3.2.1 Expertise Core Data Analysis

Table 2 represents the demographic data analysis of the semi-structured interviews.

Table 2: Demographic data analysis

Profession	No. of Interviewees	Years of experience
Senior Project Manager	4	More than 15 years
Site Manager	3	More than 12 years
Senior Quantity Surveyor	1	More than 15 years

Profession	No. of Interviewees	Years of experience
Senior Architect	1	10 Years
Civil Engineer	1	15 Years

4. RESULTS AND DISCUSSION

A literature review was conducted to identify the potential advantages and barriers of off-site construction. Semi-structured interviews were conducted with ten experts from the Sri Lankan construction industry to further explore the benefits and challenges of OSC, while also identifying practical strategies to overcome the barriers associated with its implementation. Responses were provided to address the needs of the local construction context, emphasizing their relevance to the practice of off-site construction in the Sri Lankan context.

4.1 RESPONSES OF THE INTERVIEWEES FOR THE ADVANTAGES OF OSC

From the insights gathered in the interviews and the literature review, the compelling advantages of OSC are thoroughly explored. According to semi-structured interview findings, the advantages of OSC data analysis are given in Table 3.

Table 3: Identified Advantages of OSC

	Identified benefits of OSC	Literature review	Interview responses
1	Time saving (Speed & Efficiency)	✓	10
2	Reduced wastage	✓	7
3	Cost Reduction	✓	6
4	Quality Improvement	✓	4
5	Improve health and safety	✓	4
6	Environmental Benefits	✓	4
7	Addressing Shortage of Skills	✓	2
8	Productivity Improvement	✓	1

The majority of interviewees, approaching 100%, agreed that offsite building excels at saving time on construction projects. Interviewees explored this is achieved by manufacturing components in controlled environments and assembling them on-site, ensuring adherence to schedules and leveraging economies of scale. Cost reduction is another notable advantage, primarily driven by minimized labour requirements, reduced material waste, and the efficiency of precast construction, which offers up to 40% savings compared to traditional methods.

OSC also promotes quality improvement through prefabrication, standardized processes, and rigorous inspection and testing, ensuring consistency across projects. The approach addresses the shortage of skilled labour by shifting much of the work to controlled environments, reducing reliance on on-site labour. Safety is significantly enhanced, as the controlled production environment minimizes accident risks compared to traditional on-site construction.

Environmental benefits are also prominent, including reduced waste, noise pollution, and a lower carbon footprint. Components manufactured with precision eliminate excessive material usage, while resource efficiency conserves energy and materials. These advantages position OSC as a transformative approach for improving efficiency, sustainability, and safety in the construction industry while addressing key challenges.

4.2 OPPORTUNITIES AND CHALLENGES IN IMPLEMENTING RECYCLING AND REUSE PROGRAMMES IN SRI LANKA'S CONSTRUCTION INDUSTRY

The findings from the interviews and literature review reveal several significant barriers to the adoption of off-site construction. Interview responses indicated that the most critical challenges are the lack of awareness and understanding of off-site construction benefits and the high initial and capital costs involved. Additionally, 60% of respondents highlighted the lack of confidence and experience among contractors and designers, alongside a notable gap in skilled labour availability. Financial concerns, such as the extended capital payback period, were noted by 40% of participants, further emphasizing the economic challenges faced by stakeholders. According to the semi-structured interview findings, the barriers of OSC data analysis are given in Table 4.

Table 4: Identified barriers for OSC

	Identified barriers for OSC	Literature review	Interview responses
1	Lack of awareness and understanding	✓	10
2	High initial and capital cost	✓	10
3	Limited availability of specialized equipment		6
4	Lack of confidence	✓	6
5	Lack of experienced contractors	✓	6
6	Lack of experienced design consultancy and designers		6
7	High skill demands for labor	✓	6
8	Lack of experienced collaboration groups	✓	4
9	Longer capital payback period		4
10	Lack of practice and experience in local projects		3
11	Lack of technologies and testing	✓	3
12	Transportation issues	✓	3
13	Dependence of traditional construction method	✓	3
14	Project scheduling issues		3
15	Lack of governmental regulations and incentives	✓	2
16	Lack of local Research and Development institutes and services		2
17	Uncertainty of market demand	✓	2
18	Lack of manufacturers & suppliers	✓	2
19	Unpredictable planning decisions		2
20	The fragmented nature of the construction industry		2

	Identified barriers for OSC	Literature review	Interview responses
21	Lack of design codes and standards	✓	2
22	Poor quality impression	✓	2
23	Off-site construction techniques limit design options		2
24	Project planning and coordination	✓	1
25	Poor integration for the supply chain	✓	1
26	Additional maintenance cost for heavy machinery		1
27	Inability to make changes in the field		1
28	Risk management and liability		1

These findings align with literature findings, identifying key systemic barriers such as the lack of design codes and standards for prefabricated components, insufficient governmental regulations and incentives, and the negative perceptions of project owners. It also underscores a persistent dependence on traditional construction methods, which hinder the industry's transition to modern practices. Additional challenges include supply chain inefficiencies, logistical constraints in transporting prefabricated components, and high technological costs.

These results highlight the interconnected nature of the barriers, where knowledge gaps, financial limitations, regulatory shortcomings, and skill deficiencies collectively impede the adoption of off-site construction. Addressing these challenges requires a multi-faceted approach, as discussed in the literature, with particular attention to overcoming the barriers identified in the interviews.

Taking these complex issues into consideration is essential to coordinating an effective shift to OSC techniques in the Sri Lankan setting. Taking a closer look at the money side of things, careful planning is needed to reduce the large in advance and capital costs of offsite building and create an environment that makes adoption easier. In order to guarantee compliance in the construction sector and to offer a strong basis for standardized procedures, regulatory frameworks must be developed and refined at the same time.

Essentially, this all-encompassing approach highlights the need for a holistic strategy while acknowledging the interconnectedness of these issues. Sri Lanka can only effectively navigate and embrace the transformative potential of OSC methodologies by making a concentrated effort to address the financial, regulatory, perceptual, skill-related, logistical, and technological aspects.

4.3 STRATEGIES FOR PROMOTING OSC IN SRI LANKAN BUILDING PROJECTS

The adoption of OSC in Sri Lanka faces several barriers and to overcome these obstacles, targeted strategies are essential. Addressing these barriers with tailored strategies will pave the way for the growth of OSC in Sri Lanka's building sector. The majority of interviewees identified several important strategies for the successful implementation of off-site construction projects in Sri Lanka. These include awareness and education, development and research, public acceptance and perception, financial incentives, and

projects for demonstration. According to the semi-structured interview findings, proposed strategies and strategy incentives to overcome the barriers are given in Table 5.

Table 5: Proposed strategies

Proposed strategy	Strategy incentives	Barriers
Awareness and Education	Conduct training, workshops, and awareness campaigns targeting industry stakeholders	Lack of awareness[1], lack of confidence[4], lack of experienced contractors[5], high skill demands[7], lack of collaboration groups[8], traditional methods[13], project, Project scheduling issues[14] coordination[24], risk management[28], Fragmented industry[20], supply chain issues[25], planning unpredictability[19]
Development and Research	Invest in local Research and Development, establish institutes, and innovate with new technologies	Limited equipment[3], lack of design consultancy[6], lack of prefab testing institutes[11], transportation issues[12], lack of local Research and Development[16], lack of manufacturers and suppliers[18], design codes[21], field changes[27], limit design options[23]
Public Acceptance and Perception	Promote successful projects to gain public trust and improve market acceptance	Uncertainty in market demand[17], poor quality impressions[22]
Financial Incentives	Provide subsidies, tax benefits, grants, and low-interest loans to reduce financial burdens	High initial costs[2], longer payback periods[9], lack of regulations[15], additional machinery maintenance costs[26]
Projects for Demonstration	Encourage pilot projects to build local expertise	Lack of practice and experience in local projects[10]

According to the insights from interviewees, institutions of higher learning should integrate off-site construction methods into their courses. Research and development initiatives should allocate funds to develop locally adapted off-site construction technologies and foster collaborations between academics, research facilities, and the construction sector. To address misconceptions and highlight the advantages of off-site construction, such as economic and environmental benefits, public awareness campaigns should be launched to build trust within communities. Financial incentives like tax breaks, grants, and specialized loans should be provided to developers and contractors adopting off-site methods, supported by partnerships with financial institutions. Additionally, successful off-site construction projects should be showcased as prototypes to demonstrate the method's viability and benefits, attracting stakeholders and emphasizing cost reduction, enhanced quality, and decreased construction time.

5. CONCLUSIONS

This study provides critical insights into the implementation of OSC in Sri Lanka by highlighting both common global barriers and unique local challenges. While many identified barriers, such as high initial costs, lack of skilled labour, and inadequate regulatory support, mirror those found in international contexts, the Sri Lankan setting is further constrained by deeply rooted preferences for traditional construction methods and limited awareness among stakeholders. These context-specific challenges stem from a combination of cultural resistance, insufficient local manufacturing capabilities, and policy gaps.

Despite these barriers, the study also reveals key enablers of OSC adoption in Sri Lanka, including its potential to reduce construction time, improve safety, and support environmental sustainability, benefits consistent with global findings. However, the success of OSC in Sri Lanka depends heavily on strategic, locally adapted interventions that build confidence and capabilities within the industry.

The study contributes to the body of knowledge by bridging global OSC discourse with the underexplored Sri Lankan context. It proposes a targeted framework of five practical strategies, awareness and education, research and development, public perception enhancement, financial incentives, and demonstration projects, tailored to Sri Lanka's socio-economic and industrial environment. These insights not only guide local practitioners and policymakers but also offer a reference model for other developing countries facing similar implementation challenges in modernizing their construction sectors

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UNLOCKING EFFICIENCY IN TIMBER FRAME CONSTRUCTION: A COMPARATIVE STUDY OF ON-SITE VS. OFF-SITE APPROACHES IN SCOTLAND

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ABSTRACT

This study evaluates the effectiveness of on-site versus off-site timber frame construction (TFC) for low-rise housing in Scotland, specifically addressing sustainability, cost, time efficiency, and quality control to support the Scottish government's target of delivering 110,000 affordable homes by 2032. Data were collected using a mixed-methods approach, comprising a quantitative survey of 100 construction professionals and qualitative interviews with two senior industry managers. The quantitative data were analysed using statistical methods, including frequency and mean analysis, while the qualitative data were analysed using thematic analysis. The findings reveal that off-site offers advantages in terms of time efficiency and quality control, reducing on-site labour and ensuring consistent production. However, high initial costs and logistical challenges hinder widespread adoption, particularly in remote areas. On-site TFC remains more adaptable and cost-effective in such regions, benefiting from readily available labour and material flexibility. Sustainability outcomes varied based on material usage and transportation, with off-site reducing waste but often using less eco-friendly insulation. While 80% of respondents favoured off-site for quality control, concerns about insulation settlement and moisture risks existed. Accordingly, the choice between on-site and off-site methods depends on project scale, location, and budget. Off-site is better suited for large-scale developments, while on-site methods remain practical in rural areas. This study contributes by highlighting the importance of context-specific considerations in choosing construction methods and supports the strategic alignment of TFC practices with Scotland's housing targets.

Keywords: *Cost and Time Efficiency; Off-Site Prefabricated Construction; On-Site Timber Frame Construction; Sustainability; Quality Control.*

1. INTRODUCTION

The UK construction industry faces persistent challenges, particularly in the domestic housing sector, where the supply of affordable homes fails to meet increasing demand. The UK Government has set a target of constructing 300,000 new homes annually in

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England to address this shortfall; however, only approximately 233,000 homes were completed in 2021/22 (UK Parliament, 2023). Similarly, Scotland has established its housing targets to deliver 110,000 affordable homes by 2032, averaging approximately 12,222 homes annually, with at least 70% designated for social rent (Scottish Government, 2025a). The housing crisis in both contexts is driven by population growth, unsuitable housing stock, and economic constraints (UK Parliament, 2023; Scottish Government, 2025a).

This research investigates the effectiveness of on-site and off-site prefabricated TFC methods specifically for low-rise domestic dwellings in Scotland, assessing their potential to contribute to meeting the Scottish Government's housing targets. A significant proportion (77.9%) of the UK population resides in houses or bungalows, reinforcing the need for efficient construction methods (ONS, 2023). While on-site TFC is widely utilised, closed-panel off-site manufacturing is increasingly adopted due to advantages related to labour availability, material supply, and regulatory support (Duncheva & Bradley, 2019). Scotland, notably, exhibits high adoption rates of TFC, accounting for 85% of the housing market, compared to only 23% in the rest of the UK (Structural Timber Association, 2023).

Both on-site and off-site construction methods offer distinctive advantages. Traditional on-site timber frame systems typically serve as load-bearing structures requiring additional insulation and finishing. In contrast, prefabricated off-site panel systems are highly engineered, pre-assembled, and enable faster erection with superior thermal efficiency, achieving U-values as low as 0.10 W/m²K compared to approximately 0.15 W/m²K for on-site construction (Structural Timber Association, 2023). Despite these recognised benefits, existing research rarely evaluates how specific geographic, economic, and logistical contexts within Scotland influence the comparative effectiveness of these timber construction methods, highlighting a critical knowledge gap.

Addressing this gap, this study aims to evaluate and compare the effectiveness of on-site versus off-site TFC methods in Scotland, specifically assessing their relative performance against sustainability, cost, construction time, and quality control criteria, to determine their potential to support Scotland's target of delivering 110,000 affordable homes by 2032. The paper is structured sequentially to ensure logical coherence; Section 2 reviews literature and identifies research gaps, shaping the research aim and methodology (Section 3). Findings from surveys and interviews are presented (Section 4), informing a discussion (Section 5) linked to theory and practice. Section 6 provides actionable conclusions and recommendations for Scotland's housing sector.

2. LITERATURE REVIEW

TFC has a long-standing presence in the building industry, particularly praised for sustainability benefits stemming from its near carbon-neutral profile (Palma & Steiger, 2020). The UK's housing crisis has renewed interest in off-site prefabrication methods as potential solutions due to their efficiency, speed, and reduced dependency on skilled labour (Menendez et al., 2011; Shibani et al., 2021). Despite these recognised benefits, adoption across the UK remains uneven, with only 9% in England versus 92% in Scotland (DEFRA, 2025), highlighting regional variances influenced by economic, geographic, and logistical contexts. However, existing literature frequently overlooks detailed, context-specific comparisons between on-site and off-site timber frame methods within

Scotland, particularly regarding their practical viability, sustainability, cost-effectiveness, and quality control. Recent studies, such as those by Mackenzie and Bell (2025), emphasise the growing need for localised research to enhance the understanding of regional construction contexts. Although numerous studies broadly address the advantages of prefabrication, they rarely investigate how unique regional factors, such as geographic location, availability of skilled labour, transport infrastructure, and local economic conditions, directly influence method selection and effectiveness. This gap limits the practical utility of existing research for Scottish policymakers and construction professionals facing the specific challenges of achieving ambitious housing targets in diverse Scottish contexts.

Construction is vital to the UK economy, employing 231,000 people in Scotland in 2021 and generating £13.3 billion in output (CIOB, 2024). As of 2025, Scottish construction output is projected to reach £14.1 billion, driven largely by ongoing housing and infrastructure investments (Scottish Government, 2025a). The government has pledged £44 billion in housing investment (Department for Business and Trade, 2019). Investments in manufacturing aim to boost speed, safety, and productivity, though skills shortages remain, despite apprenticeship growth from 22,500 in 2018/19 to 33,600 in 2022/23 (CIOB, 2024). Off-site prefabrication, valued at £6 billion, makes up less than 6% of UK construction (George et al., 2022). A 2023 NBS survey showed that over half of professionals had used off-site methods (NBS, 2023). Reported benefits include faster build times, better material control, and reduced reliance on skilled labour, supporting sustainability goals (NBS, 2023).

Globally, countries like Sweden, Japan, and New Zealand have embraced off-site TFC, often achieving higher efficiencies than the UK (Smith, 2010). A recent comparative analysis by O'Connor and Mitchell (2025) underlines that targeted policy interventions and robust supply chains remain essential for successful adoption, highlighting lessons Scotland could integrate into its housing strategies. These comparisons highlight the importance of systemic adoption, local manufacturing support, and cultural acceptance in successful implementation.

2.1 GOVERNMENT INCENTIVES FOR MODERN CONSTRUCTION METHODS

Government intervention plays a crucial role in promoting off-site construction. The Science and Technology Select Committee's report, Off-site Manufacture for Construction: Building for Change (2018), identified several industry challenges, including low productivity, structural fragmentation, narrow profit margins, limited training, an ageing workforce, and a poor industry image (UK Parliament, 2018). Furthermore, the Department for Business, Innovation and Skills (2013) reinforced commitments to prefabrication through funding, regulatory reforms, and enhanced industry collaboration to address persistent productivity and skills challenges. To address these issues, the Infrastructure and Projects Authority (IPA) released the Transforming Infrastructure Performance report (2017), which prioritises investment, productivity improvements, and maximising infrastructure outcomes (Infrastructure and Projects Authority, 2017). In addition, the Industrial Strategy White Paper (2017) set ambitious targets for the construction sector, such as a 33% reduction in lifecycle costs, a 50% cut in construction time and greenhouse gas emissions, and a 50% reduction in the trade gap for construction materials (HM Government, 2017).

2.2 COMPARATIVE ANALYSIS OF ON-SITE VS. OFF-SITE TFC

2.2.1 Sustainability

The built environment sector is a major contributor to greenhouse gas emissions, accounting for 37% globally and 40% in the UK. This is mainly due to the cement and metal production (United Nations Environment Programme, 2023). Moreover, the industry generates 60% of the UK's waste and emits 50 million tonnes of CO_2 annually (Government Commercial Function, 2021). Recent sustainability audits in Scotland emphasise the pressing need for construction innovations that reduce emissions and waste, placing prefabrication prominently in the policy discourse (Scottish Government 2025b). With the growing concerns in sustainable and environmentally responsible building, prefabricated construction methods provide sustainability benefits by minimising waste and improving energy efficiency (Pons, 2014). Even though there are benefits to prefabricated construction, Liu et al. (2022) argue that challenges like high carbon emissions from element manufacturing persist.

On-site timber construction, on the other hand, offers much greater material flexibility and often relies on local resources, reducing transportation-related emissions (Nikologianni et al., 2022). Timber construction also supports carbon sequestration, preventing approximately 3.9 tonnes of CO_2 emissions per tonne of wood used. Moreover, Scotland's 2023 carbon reduction laws promote sustainable materials like timber, which can be recycled more efficiently than some prefabricated components (Hart et al., 2019).

2.2.2 Cost

Cost remains a critical factor in construction decisions. The UK construction industry, valued at £138 billion, employs over 3.1 million people (ONS, 2025). Inflation, supply-chain issues, rising material costs, and geopolitical tensions have notably increased delays and expenses (Crichton, 2025). Off-site TFC is increasingly recognised as offering substantial cost-saving potential, particularly through reducing on-site construction durations, minimising waste, streamlining material management, and mitigating risks such as theft and damage (J-Engineering, 2024). Consequently, prefabrication tends to be highly cost-effective, particularly for repetitive construction formats such as flats and multi-unit developments. Despite these advantages, Current estimates indicate upfront costs for prefabricated methods remain around 7-10% higher than conventional approaches (Connected Places Catapult, 2019). However, recent industry perspectives increasingly recognise that these initial costs are offset through lifecycle efficiencies, enhanced quality control, and reduced operational costs over time (J-Engineering, 2024).

2.2.3 Time Efficiency

One of the most significant advantages of off-site timber construction is its ability to significantly reduce project timelines, with some estimates indicating up to a 50% reduction compared to traditional methods (Hashemi, 2013). Faster completion lowers costs and allows developers to allocate resources more efficiently to other projects. Recent evaluations by McGregor and Sinclair (2025) confirm these time efficiencies, particularly in large-scale residential projects across Scotland.

2.2.4 Quality Control

Quality control is a crucial consideration in construction and is particularly challenging in on-site construction, where human errors and weather exposure can lead to costly delays (Carnegie Mellon University, 2014) . Scotland's unpredictable climate poses risks to prefabricated timber frame buildings during transport and erection. New studies have recommended enhanced logistics strategies to minimise these risks, emphasising controlled transport and rapid assembly processes to improve quality outcomes (Scottish Timber Industry Association, 2025).

3. RESEARCH METHODOLOGY

This study employed a mixed-methods approach, combining both quantitative and qualitative research to evaluate the application of on-site and off-site TFC. This approach comprehensively integrates numerical data with contextual insights (Creswell & Plano Clark, 2023). The quantitative component offered measurable data for statistical analysis, enabling the identification of trends and general patterns (Bryman, 2016), while the qualitative component captured the in-depth experiences and views of industry practitioners. Primary data were collected via a structured questionnaire sent to 120 experienced construction professionals, including site managers, architects, contractors, and surveyors, yielding 100 responses. Descriptive statistical methods, such as frequencies and percentages, ensure analytical rigour and identify key trends. Given the study's exploratory nature, these methods provided a straightforward yet robust foundation for understanding industry perceptions across sustainability, cost, time, and quality control dimensions. Additionally, semi-structured interviews were conducted with two industry experts (with six decades of experience) from a UK housing development firm to supplement the survey findings with practical insights and sector-specific reflections. The primary reason for selecting two interview participants in this study is that the value of these interviews lies in the quality and specificity of the information obtained rather than the quantity, enabling focused and highly relevant insights. Additionally, practical considerations such as time constraints, resource availability, and the limited availability of qualified experts justify limiting the interviews to two participants.

Additionally, the validity of the survey findings was enhanced through triangulation with qualitative interview data. A snowball sampling technique was employed to recruit survey participants. This method, which combines elements of convenience and purposive sampling, was selected for its efficiency in accessing qualified respondents while ensuring the inclusion of information-rich cases (Parker et al., 2019). Table 1 presents the demographic profile of participants, including their professional roles, years of industry experience, and levels of exposure to different TFC systems.

Table 1: Background information of survey respondents

Respondents' attributes	No. of respondents
Profession in the organisation	
Architectural Technicians	57
Building Standards Surveyors	24
Contractor	04

Respondents' attributes	No. of respondents
Site Agent/ Manager	09
Others (Engineers, Quantity surveyors and project managers)	14
Years of experience in the construction industry	
0-5 years	12
5-10 years	14
10-15 years	06
15- 20 years	14
More than 20 years	62

The questionnaire survey was conducted using Microsoft Forms, which enabled the efficient collection of responses while ensuring participant anonymity. This digital platform also facilitated streamlined data management and visualisation (Evans & Mathur, 2005). The questionnaire design combined multiple-choice questions for statistical analysis with open-ended questions to capture qualitative insights, aligning with best practices in mixed-methods research (Creswell & Plano Clark, 2023).

4. RESEARCH FINDINGS

The primary aim of this research was to evaluate and compare the effectiveness of on-site versus off-site TFC methods in Scotland against key criteria such as sustainability, cost, time efficiency, and quality control. Findings from the questionnaire survey and interviews are presented thematically below.

4.1 QUESTIONNAIRE SURVEY FINDINGS

4.1.1 Experience in TFC Methods

Respondents were asked to report their experience with various low-rise domestic construction methods. Results indicated that 66% of participants had extensive experience with on-site TFC, whereas approximately 26% reported experience with off-site prefabricated timber frame systems. This distribution suggests a prevailing industry preference for on-site TFC in Scotland's low-rise domestic housing sector. A smaller group (8%) had experience across multiple construction types, including modular, masonry, and a combination of all methods. These findings are summarised in Table 2, which presents the number of respondents indicating familiarity with each construction method.

Table 2: Respondents' experience in TFC

Low-rise domestic frame construction	Respondents' most experienced
On-site timber frame	66
Prefabricated timber kit	26
Masonry construction	05
Modular construction	01
All of the above	02

4.1.2 Industry Perceptions of the Initial Cost of On-site and Off-site Timber Construction

Respondents expressed divided opinions regarding the cost-effectiveness of on-site versus off-site timber construction. A majority (59%) perceived on-site construction to be more cost-effective, attributing this to lower upfront costs, greater on-site flexibility, and the use of readily available labour and materials. Conversely, 41% of respondents viewed off-site prefabrication as a strategic investment, noting that while initial costs are higher, these are often offset by labour efficiencies, reduced construction time, and improved quality control throughout the project's life.

Key barriers to adopting off-site methods were identified as the higher capital investment required at the outset, along with additional transportation costs, complexity in panel design, and a reliance on specialised equipment, such as cranes, for on-site assembly. These factors continue to influence industry preferences and decision-making, particularly in small- to medium-scale domestic construction projects.

4.1.3 Sustainability Considerations

More than 75% of respondents perceived off-site prefabrication as the more sustainable construction method. Key reasons cited included reduced material waste, improved quality control in factory settings, and enhanced airtightness, all contributing to better energy efficiency. These findings align with broader industry perspectives on the environmental benefits of off-site prefabrication in modern timber construction.

However, a subset of respondents argued that on-site construction could be more sustainable in specific contexts. This view was based on the use of locally sourced materials, reduced transportation requirements, and lower reliance on synthetic or industrially processed materials. Additionally, some participants highlighted that off-site panels often include additional layers, such as insulation sandwiched between two sheets of Oriented Strand Board (OSB), which can increase material usage. In contrast, on-site timber frame walls typically require only a single OSB sheathing layer, which can potentially result in lower overall material consumption.

These contrasting views suggest that the sustainability of timber construction methods may be context-dependent, influenced by factors such as material sourcing, project scale, and regional practices.

4.1.4 Quality Control and Build Time

The findings indicate that approximately 79% of construction professionals believe prefabricated or closed panel systems offer superior quality control compared to on-site methods. Respondents highlighted that factory-controlled environments enable more consistent workmanship and reduce the likelihood of defects due to weather, labour variability, or material handling on site. In contrast, around 21% of participants supported open panel systems, emphasising the benefits of on-site flexibility, particularly where design modifications are needed during construction phases.

Regarding build time, the majority of respondents recognised that off-site construction significantly reduces on-site assembly duration, thereby shortening overall project schedules. Specific advantages cited included *"speed of manufacture and erection" and achieving "wind and watertight stage more quickly."* However, many also cautioned that longer lead times for design finalisation, factory production, and delivery logistics can

offset these advantages. Additionally, a few respondents noted that delays in factory scheduling or site readiness can compromise the efficiency gains typically associated with off-site approaches.

4.1.5 Challenges and Benefits of Construction Methods

Survey respondents highlighted challenges and benefits associated with on-site and off-site TFC methods. Approximately 28% of professionals identified longer build times as a significant issue associated with on-site construction. A further 27% raised concerns regarding weather-related delays, material wastage, and inconsistent build quality, factors often linked to site-dependent variability and manual errors. These challenges were commonly perceived to undermine schedule certainty and long-term performance, especially in projects exposed to Scotland's unpredictable weather conditions.

In contrast, off-site prefabrication methods were positively viewed by a large proportion of participants, with over 75% indicating that off-site methods provide better control over quality, reduce site disruption, and improve overall construction safety. In particular, over 65% of respondents noted the efficiency of prefabrication, especially the speed of on-site assembly and ease of coordination among trades. However, nearly 32% of professionals expressed reservations about off-site techniques, particularly concerning logistical constraints (e.g. transporting large components to remote sites), higher upfront capital costs, and limited design flexibility once the manufacturing process is underway.

Despite these limitations, many favoured off-site TFC for its sustainability advantages, reduced waste, and enhanced ability to meet performance standards such as airtightness and thermal insulation. A notable 45% of respondents mentioned faster project delivery as a critical benefit of off-site methods, especially when integrated with advanced planning and digital coordination.

Overall, the findings revealed that while off-site construction offers considerable benefits in quality, safety, and sustainability, its success depends on careful early-stage planning and efficient logistics. Meanwhile, on-site construction remains valuable in contexts where adaptability, traditional craftsmanship, or low capital cost is prioritised. Based on the questionnaire responses, approximately 2% of participants explicitly advocated for hybrid solutions, referring to the benefits of combining on-site and off-site construction methods to suit project-specific requirements.

4.1.6 Addressing the Housing Shortage

According to the survey, approximately 60% of respondents identified off-site prefabrication including timber frame, modular systems, and closed panel construction as the most suitable solution to address the UK's housing shortage. These methods were complimented for their scalability, potential for mass production, and capacity to accelerate housing delivery while maintaining quality standards. Specific comments noted the advantages of decentralised production and faster on-site assembly, which could significantly reduce programme durations and ease pressure on skilled labour availability.

Despite this preference, around 10% of participants suggested a hybrid approach, combining off-site efficiency with the flexibility of traditional construction methods, particularly in rural or logistically complex sites. Additionally, 18% of responses reflected uncertainty or emphasised non-technical solutions, such as government

investment, policy reform, and increased funding for affordable housing as necessary complementary strategies.

Furthermore, several professionals highlighted a persisting barrier in public perception, noting that some potential occupants remain hesitant to adopt modern prefabricated homes, often due to concerns around appearance, robustness, or resale value. This highlights the need for education, marketing, and policy alignment to build confidence in modern construction techniques as viable long-term housing solutions.

4.2 INTERVIEW FINDINGS

To complement the survey data, interviews were conducted with two site managers from a major UK housing developer with over six decades of experience in TFC. Their insights provided practical perspectives on construction efficiency, sustainability, cost management, and quality control in the Scottish housing sector.

Both interviewees emphasised the efficiency of TFC in Scotland's variable climate. Interviewee I stated that *"using open-panel timber kits constructed by our sister company allows internal work to start immediately once the building is wind and watertight,"* offering a clear advantage over off-site systems or double-block masonry which require longer lead times. Similarly, Interviewee II highlighted that "*pre-assembled kits help maintain progress even in poor weather*," thereby reducing delays and keeping projects on schedule.

Sustainability was described as a key consideration in construction decisions. Both managers noted efforts to reduce environmental impact using recycled materials, energy-efficient products, and strict waste management. Interviewee I explained, "*we install energy-efficient systems and enforce waste policies to encourage recycling*," while Interviewee II added, "*these practices significantly reduce our carbon footprint and promote greener construction*."

Cost and time management were also central themes. While acknowledging slightly higher upfront costs, Interviewee I observed that "*faster build times balance the expense, leading to more handovers and improved efficiency*." Interviewee II echoed this view, noting that "*balancing affordability and high standards is essential for successful delivery*."

Quality control was rigorously enforced through inspections by internal teams, building control, and National House Building Council (NHBC) regulators. Both interviewees described structured quality procedures. Interviewee I noted, "*we use photographic records, regular toolbox talks, and detailed snagging inspections by senior management*," while Interviewee II stressed that *"ongoing supervision and compliance checks ensure the final product is safe, durable, and built to last."* Overall, the interviews reinforced the view that TFC especially when supported by integrated supply chains and experienced site teams offers a practical, efficient, and quality-focused approach suited to the demands of the modern UK housing sector.

5. DISCUSSIONS

5.1 SUSTAINABILITY

Sustainability continues to be a defining objective in construction, particularly as the built environment seeks to align with global carbon reduction goals. Both on-site and off-site TFC methods offer environmental benefits. Off-site prefabrication is frequently perceived as more sustainable due to controlled production and minimised waste. According to Hart et al. (2019), timber construction prevents approximately 3.9 tonnes of CO_2 emissions per tonne of wood used, reinforcing the environmental advantages of timber-based systems.

Survey findings show that approximately 75% of respondents believed off-site construction contributed positively to sustainability due to reduced site waste and lower emissions from fewer deliveries. However, respondents also pointed out that prefabricated systems often require additional materials (e.g., extra OSB sheathing and polyurethane insulation), which may offset some environmental gains. Conversely, on-site TFC allows for using locally sourced materials and mineral wool insulation, which is perceived as more environmentally friendly, echoing conclusions drawn by Nikologianni et al. (2022), who advocate for place-based sustainability practices.

Interview insights further support this dual perspective; both participants highlighted the importance of energy efficiency and material sustainability, regardless of the method used. Ultimately, deciding which system is more sustainable appears to depend on contextual factors such as material sourcing, transportation logistics, and climatic conditions.

5.2 COST

Cost is a major consideration influencing strategic procurement and operational decision-making in construction. While prefabrication offers long-term savings, especially in large-scale developments due to its efficiency and repeatability, initial investment remains a barrier. Shahzad et al. (2015) assert that off-site construction can reduce life-cycle costs, particularly in mass housing projects.

In the present study, 44% of respondents recognised off-site prefabrication as a cost-effective option. However, challenges persist that limit local manufacturers in northern regions of Scotland, resulting in higher transport costs and often making traditional on-site construction more viable in remote areas. Interview data reinforced this nuance; large developers prioritise cost control and economies of scale, whereas smaller firms often opt for customisation, even if it comes at a higher price.

5.3 TIME

Time efficiency is another pivotal factor in construction delivery. Off-site prefabrication is credited for significantly reducing on-site construction time. Hashemi (2013) supports this by noting that timber frame systems require fewer person-hours than masonry construction. About one-third of survey respondents cited time savings as a key advantage of off-site prefabrication.

However, off-site prefabrication is not without its time-related challenges. Respondents highlighted long lead times, manufacturing bottlenecks, and the need for specialised equipment such as cranes. Moreover, limited local expertise in some regions slows the

adoption of these systems. Traditional TFC, by contrast, allows immediate site mobilisation post-approval and is often favoured for projects requiring greater adaptability. Interview responses echoed this sentiment, emphasising that while prefabrication speeds up certain phases, the overall benefit hinges on precise coordination and upfront planning.

5.4 QUALITY CONTROL

Quality control remains crucial for project success. Survey data showed 80% favoured prefabrication due to factory environments reducing variability and errors (Frühwald Hansson, 2011). However, concerns existed about insulation shifting and moisture ingress during transport (Mjörnell & Olsson, 2019). Interviews suggested that on-site methods, such as inspections, digital records, and skilled oversight, could match prefabrication quality. Off-site methods excel in precision and consistency, while on-site approaches offer flexibility for complex projects. Urban developers may prefer off-site for efficiency, whereas rural projects benefit from on-site adaptability. Policymakers should support logistics and training for off-site adoption, and educational bodies should align curricula with Modern Methods of Construction.

Several limitations should be acknowledged. Firstly, the limited qualitative sample (two interviews) restricts generalisability; future research should include more diverse experts for richer insights. Secondly, quantitative analysis was mainly descriptive due to the exploratory design and modest sample size (n=100). Although reliability was confirmed, future studies should employ advanced statistical methods for stronger validation.

6. CONCLUSIONS

This study evaluated on-site versus off-site TFC methods for low-rise housing in Scotland. Using quantitative data from 100 professionals and qualitative insights from industry interviews, the findings highlighted distinct method-specific advantages influenced by location, scale, and logistics. Off-site methods offered superior quality control, efficiency, and reduced waste but were constrained by higher initial costs and logistical complexities. Conversely, on-site methods were preferred for cost-effectiveness, adaptability, and reduced transport impacts in rural contexts. The key theoretical contribution addresses how contextual factors such as geographic, economic, and logistical factors influence TFC method selection and effectiveness. Practically, the study guides policymakers and developers in strategically aligning construction methods with Scotland's housing targets, recommending targeted investment to overcome barriers to off-site adoption. Ultimately, a hybrid approach, integrating the strengths of both methods, could maximise overall effectiveness. Future research should broaden the geographic scope and explore commercial sector applications to enhance sustainability and efficiency further.

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UNPACKING AGILE PROJECT MANAGEMENT IN INDIAN CONSTRUCTION: ADOPTION BARRIERS, INDUSTRY READINESS AND SUSTAINABILITY VIEWPOINT

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ABSTRACT

The construction industry faces mounting challenges in controlling the complexity, size, and dynamic nature of contemporary projects. Conventional project management approaches lack the flexibility and adaptability to address these challenges. Agile Project Management (APM) has been proposed as an alternative, with a focus on flexibility, teamwork, and iterative development. This present research examines the impediments to APM adoption through a systematic literature review and a questionnaire survey with industry experts. The impediments identified were grouped into four categories: Organizational Barriers, Team and Collaboration Barriers, Process and Communication Barriers, and Technical and Integration Barriers. The data gathered were analyzed using statistical methods, including descriptive analysis, Cronbach's alpha for reliability analysis, and the Relative Importance Index (RII) for ranking key factors. The results identify deficiency in agile expertise, complex interdisciplinary coordination, and client resistance to agile transition as the foremost challenges. Among all the barrier groups, the Team and Collaboration barriers group possesses the maximum RII score, which means the most critical issues in cross-functional coordination and communication. In spite of the limited experience of the respondents with APM, there is a distinct recognition of its need for the efficiency of projects and the improvement of outcomes. Additionally, the current study also discusses the sustainability aspect of APM in construction. The research concludes that effective APM adoption in construction is contingent on focused interventions, including specialist training programs, organizational reorganization, and hybrid project management models integrating agile principles and conventional milestone-based methods.

Keywords: *Agile Project Management; Construction Challenge; Implementation Barriers.*

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1. INTRODUCTION

Construction is a vital economic sector, central to employment generation and infrastructure. It provides jobs for more than 180 million individuals and contributes approximately 10% to 13% GDP of any nation. Urbanization and population growth stimulate demand for megaprojects, hence boosting the sector. However, megaprojects are generally faced with large uncertainties and complexities (Pitsis et al., 2018). Industry fragmentation causes coordination issues and communication delays, hence necessitating more adaptive project management to enhance responsiveness and efficiency.

India's construction sector is growing at a fast pace, with a projected growth of 11.2% in 2024 to INR 25.31 trillion, boosted by urban development and infrastructure growth. Some of the significant projects are Bharatmala, Chenab Bridge, Mumbai Trans Harbour Link, and the Mumbai-Ahmedabad High-Speed Rail (MAHSR) project. The need for sustainable infrastructure and housing for the common man is on the rise, putting pressure on the construction companies to move in a timely and efficient manner. NITI Aayog reports that more than 70% of the infrastructure projects are delayed and over-budget due to ineffective planning and inflexible implementation. The sector also has its hierarchical culture and resistance to change, which are not conducive to new project management methods (Wilson, 2018). Therefore, there is an increasing need for adaptable and collaborative methods to enable the team to respond to the evolving project requirements.

Conventional project management techniques, especially the waterfall technique, have been extensively used in the construction industry but lack the dynamic nature of mega projects. The techniques follow a linear and sequential strategy where phases of the project (planning, design, execution, and closure) are fixed at the initial stage, and it is challenging to change once the execution stage has begun. Thus, when unexpected issues occur, such as material shortages, design changes, or unexpected site conditions, the inflexibility results in delays in the project, cost overrun, and inefficiencies (Moshood et al., 2024). To address these challenges and weaknesses of the traditional project management approaches, the construction industry seeks new project management systems that emphasize flexibility, collaboration, and continuous improvement (Levitt, 2011). Agile Project Management (APM), originally developed in the software sector of the 21st century, has drawn considerable attention as an effective tool to enhance flexibility, stakeholders' collaboration, and risk management in construction (Ciancarini et al., 2022). Agile tools such as Scrum and Kanban emphasize strong emphasis on iterative planning, ongoing updating of project objectives, and effective management of workflow, which makes them most suitable for complicated and uncertain construction environments (Sudipta, 2021).

Though APM has been effectively applied in IT, manufacturing, and product development, its use in construction, particularly in India, is still in its infancy (Kashikar et al., 2016). Identifying India-specific barriers is useful for effective implementation of agile project management in Indian megaprojects construction. The present study, therefore, aims to explore and analyse potential barriers to adopting APM in the construction megaprojects, particularly in the Indian context. Through literature review, expert opinions, and survey-based statistical analysis, the present research explores APM's implementation challenges, and the appropriate project management approach needed to propel construction megaprojects.

2. LITERATURE REVIEW

The word agility is derived from the Latin word 'agere', which means "to drive, act," implying a sense of ownership, and the ability to drive something forward (White, 2013). Other definitions mention "ready ability to move with quick, easy grace" (Kerievsky, 2023). Additionally, the definition refers to having a quick, resourceful and adaptable character. According to the Project Management Body of Knowledge (PMBOK), agile is an iterative approach to incremental delivery of value and responding to shifting requirements. According to White (2013), agility has three characteristics important to project management in this new business world:

- Sense of ownership and authority,
- Quick and easy changes of direction, and
- Resourceful and adaptable

2.1 TRADITIONAL PROJECT MANAGEMENT APPROACH AND ITS CHALLENGES

The Traditional Project Management (TPM) or Waterfall model is a linear and sequential approach as shown in the Figure 1 of project management with a strict structure and approach, and sequential project life-cycle planning (Mohammed & Karri, 2020).

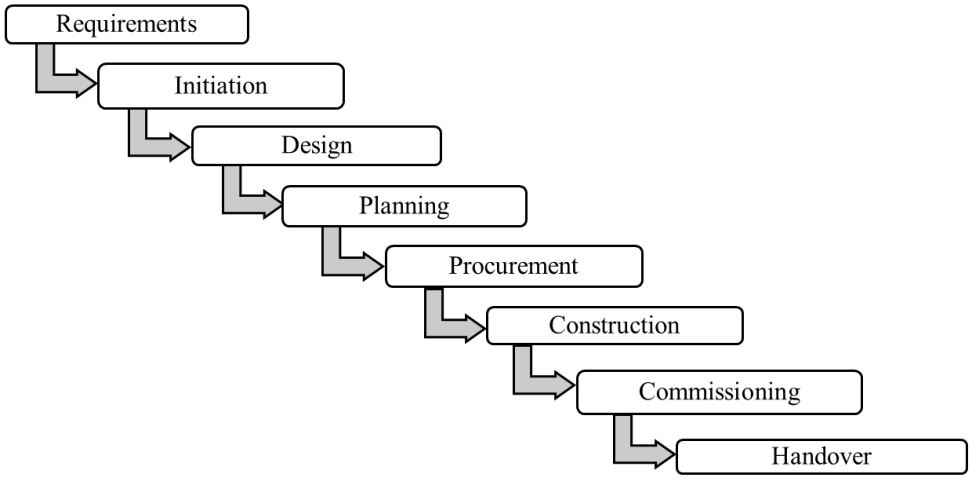


Figure 1: Traditional project management

This model has been faulted for its shortcomings in handling contemporary projects. Its greatest weakness is inflexibility, which hinders the ability to accommodate new requirements or environments. Additionally, TPM lacks provisions for fostering cooperation among stakeholders in a project, which is a requirement for big, multidisciplinary projects. Reliance on extensive documentation brings inefficiency, devouring time and resources without increasing agility. TPM also lacks in risk management due to its sequential nature, which does not leave space for iterative evaluation and adjustments. These flaws stress the need for more cooperative and adaptable approaches, such as APM, to handle the changing needs of contemporary construction projects.

2.2 POTENTIAL OF AGILE PROJECT MANAGEMENT IN CONSTRUCTION AND ITS APPLICABILITY

Limited literature has examined the suitability of APM for application in construction projects (Mohammed & Karri, 2020; Dallasega et al., 2019). Stare (2014) points out that some APM practices can be implemented even in traditionally managed projects, although great obstacles still exist for their implementation in the construction stage. In the Indian context, researchers found that APM can minimize time overruns in megaprojects by dividing work into smaller, manageable pieces, enhancing delivery reliability in an industry where almost 90% of government infrastructure projects experience delays.

The application of APM tools such as daily scrum can enable subcontractors to set day-by-day objectives and monitor progress. Mohammed and Karri (2020) illustrated that sprint planning resolves delays effectively, as evidenced by a case study on the construction of a 2-BHK flat. Likewise, other studies revealed that Agile enhances planning, scheduling, and motivating the team and diminishes uncertainty in projects. APM has shown the potential to reduce delays by 70% to 80%, drawing on case studies in Kerala and Tamil Nadu. It was also found agile strategies for dealing with client-initiated changes and price variations of materials, highlighting their function in improving flexibility and risk management in construction projects. While all these studies indicate the implementation and usefulness of APM practices in the construction industry, systemic, full-scale, and sustainable implementation of APM remains a challenge.

2.3 AGILE AND SUSTAINABILITY

APM offers a paradigm shift in the facilitation of sustainability in the construction industry through the utilization of iterative feedback loops, adaptive planning, and collaborative stakeholder engagement. Linear traditional approaches, such as the waterfall model, are likely to hinder sustainability initiatives since they are rigid in their timelines and offer little scope for improving resource efficiency or reducing waste during project execution. In contrast, APM's emphasis on self-correcting teams and continuous improvement aligns with the dynamic demands of sustainable construction, thus allowing real-time adjustments to energy efficiency targets, material reuse practices, and societal equity measures. Empirical studies reveal that APM frameworks, such as Scrum, not only enhance productivity but also foster environmental consciousness—a primary consideration in an industry that is responsible for 40% of global energy consumption. APM practices, therefore, foster sustainability in the construction industry.

2.4 FACTORS IMPEDING THE IMPLEMENTATION OF AGILE PROJECT MANAGEMENT (APM) IN CONSTRUCTION

Though there are considerable and larger benefits of implementing APM, there are several obstacles to the construction industry's adoption of APM, especially in developing nations such as India. Systematic literature review and interviews with industry experts were conducted to identify the factors impeding the implementation of APM revealed 18 critical factors. The identified factors and their respective sources are summarized in Table 1, providing a detailed reference for understanding the barriers to APM implementation.

Table 1: Identified barriers

No.	Factors	Sources
1	Resistance within organization	Hansenne & Hibner (2011)
2	Insufficient leadership support	Input from industry experts
3	Lack of training	Fazal-Baqaie & Engels (2016); Ciric et al., (2018)
4	Lack of resources	Input from industry experts
5	Complex interdisciplinary coordination	Stare (2014)
6	Absence of cross-functional teams	Xu (2009)
7	Deficiency in agile expertise	Ozorhon et al. (2022)
8	Client collaboration challenges	Nerur et al. (2005);
9	Client resistance to agile transition	Hansenn & Hibner (2011)
10	Continuous stakeholder engagement	Hohl et al. (2018)
11	Alignment of client requirements with agile processes	Fazal-Baqaie & Engels (2016); Ciric et al., (2018)
12	Iterative planning difficulties	Nuottila et al. (2016)
13	Efficient data management	Graudone & Kirikova (2023); Marnada et al. (2022)
14	Integration of agile sprints with traditional milestones	Input from industry experts
15	Software integration challenges	Fazal-Baqaie & Engels (2016); Ciric et al., (2018)
16	Documentation and reporting management	Graudone & Kirikova (2023); Marnada et al. (2022)
17	Quality assurance integration	Nuottila et al. (2016)
18	Adherence to regulatory compliance	Taylor (2016)

3. METHODOLOGY

A comprehensive literature review was conducted to explore available research on APM in construction. The barriers identified in the literature review are contextualised to the Indian context through expert interviews. Questionnaire survey data collection is then utilized to assess industry-related issues. Collected data are analysed using statistical methods, i.e., descriptive statistics, Cronbach's alpha, and Relative Importance Index (RII), to rank the identified barriers. The research process is illustrated in Figure 2, which depicts the methodological framework of the study.

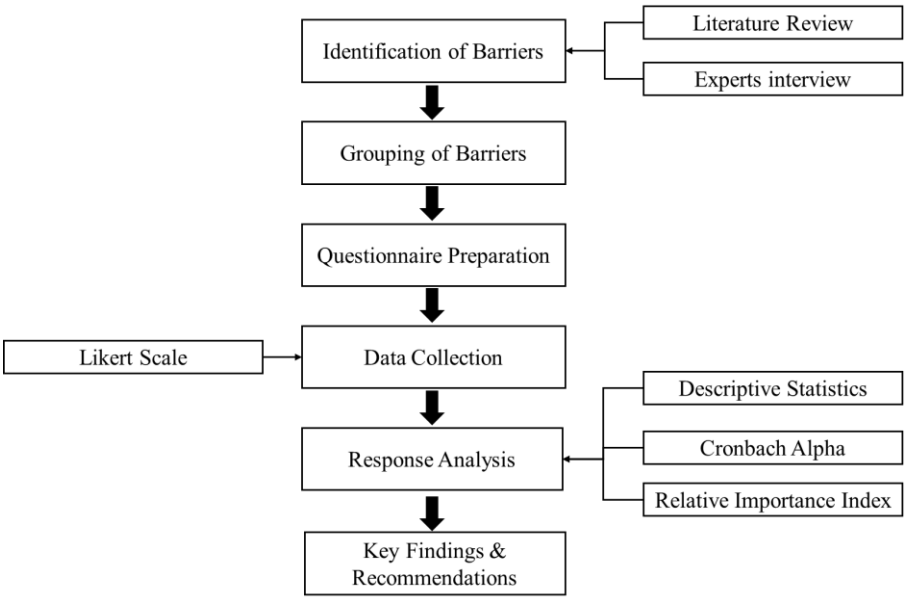


Figure 2: Flow of Research

3.1 DATA COLLECTION

To facilitate data collection for this research, a questionnaire survey was utilized to ascertain and quantify the main drivers of the implementation of APM in heavy civil infrastructure projects. The survey was carried out on a 10-point Likert scale to provide an in-depth analysis of the main challenges as well as industry perceptions in applying APM. The survey was specifically crafted to capture diverse feedback, including the respondents' expertise in APM, relevant certifications, real-world application of APM in projects, and their perspectives on the necessity of APM in the Indian construction sector. To obtain credible and industry-related data, the survey was circulated among the targeted set of agile experts, senior project planning experts, and mid-level project planning experts. 53 responses were obtained, which provided us with a robust set of data to further analyse.

3.1.1 Demographics of respondents

The respondents' designations were categorized into three primary groups: Senior Roles, Mid-Level Roles, Technical Roles, and Other Roles based on their responsibilities and level of involvement in project management processes.

Senior roles include General Manager, Technical Director, Sr. Manager Planning, etc, Mid-Level roles include Project Manager, Planning Manager, Senior Consultant, etc, Technical roles include Construction Manager, Sr. Engineer, Tunnel Supervisor, etc. Other roles include Academicians, Sr. Research Associate (R&D), etc.

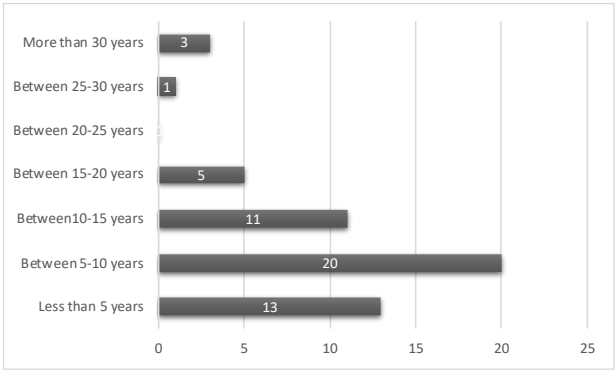


Figure 3: Experience level of respondents

The participants who responded to the survey were classified according to the number of years of working experience, which is presented in Figure 3. The average experience of the respondent is 10.5 years in project planning and APM practices.

3.2 DATA ANALYSIS

For the analysis of the data received in the questionnaire survey, three major types of statistical approaches have been used as follows.

3.2.1 Descriptive Statistics

Descriptive statistics is responsible for summarizing and defining the main characteristics of a dataset, giving a brief and clear description of the collected data. Descriptive statistics are particularly important in the identification of patterns, trends, and distributions of the data, thus becoming part of the analytical process of this study (Loeb et al., 2017). Providing a general summary of the data, descriptive statistics set the foundation for deeper inferential analysis and the creation of useful knowledge.

3.2.2 Cronbach Alpha

Cronbach's Alpha is a statistical measure used to evaluate the internal consistency and reliability of a survey instrument, particularly for scales such as Likert scales.

Cronbach's Alpha is calculated using the formula:

$$\alpha = \frac{N \times \bar{c}}{\bar{v} + (N-1) \times \bar{c}} \qquad Equation\ (1)$$

Where: N = Number of items in the scale, $\bar{c}$ = Average covariance between item pairs, $\bar{v}$ = Average variance of individual items

3.2.3 Relative Importance Index

The Relative Importance Index (RII) method is a statistical tool used to rank factors based on their relative importance as perceived by respondents (Johnson & LeBreton, 2004).

The RII is calculated using the formula:

$$RII = \frac{\sum W}{A \times N} \qquad Equation\ (2)$$

Where: W: The weight assigned to each response (based on a Likert scale), A: The highest weight in the scale, N: The total number of respondents. The RII value ranges from 0 to 1, where higher values indicate greater relative importance.

4. RESULTS AND DISCUSSIONS

To initiate the data analysis of the questionnaire survey responses, a reliability test was conducted to determine the Cronbach's Alpha value.

Table 2: Reliability test

Section	Number of items	Reliability (Cronbach's Alpha)
Organizational	5	0.763
Team and Collaboration	5	0.728
Process and Communication	5	0.827
Technical and Integration	5	0.841
All Items	20	0.918

The results indicated that the Cronbach's Alpha for individual groups as well as the overall dataset exceeded 0.7, confirming the internal consistency and reliability of the collected data.

4.1 RANKING OF BARRIERS IMPEDING AGILE IMPLEMENTATION

The present study identifies 20 critical factors influencing the challenges in APM adoption in construction through a comprehensive literature review and expert consultations. These factors have been systematically categorized into four key groups: Organizational Barriers, Team and Collaboration Barriers, Process and Communication Barriers, and Technical and Integration Barriers, as outlined in Table 3.

Table 3: Ranking of barriers

ID	Item	RII	Group rank	Overall rank
Organisational Barriers				
OR1	Resistance within organization	0.658	5	*15*
OR2	Insufficient leadership support	0.666	4	*14*
OR3	Lack of training	0.734	1	*6*
OR4	Rigid organizational hierarchies	0.705	2	*10*
OR5	Lack of resources	0.673	3	*12*
Team and Collaboration Barriers				
TC1	Complex interdisciplinary coordination	0.756	2	*2*
TC2	Absence of cross-functional teams	0.737	4	*4*
TC3	Deficiency in agile expertise	0.771	1	*1*
TC4	Client collaboration challenges	0.735	5	*5*
TC5	Client resistance to agile transition	0.745	3	*3*
Process and Communication Barriers				
PC1	Continuous stakeholder engagement	0.724	1	*7*
PC2	Alignment of client requirements with agile processes	0.684	2	*11*
PC3	Iterative planning difficulties	0.635	4	*18*
PC4	Risk identification and management	0.605	5	*20*

ID	Item	RII	Group rank	Overall rank
PC5	Efficient data management	0.669	3	*13*
Technical and Integration Barriers				
TI1	Integration of agile sprints with traditional milestones	0.715	1	*8*
TI2	Software integration challenges	0.709	2	*9*
TI3	Documentation and reporting management	0.658	3	*16*
TI4	Quality assurance integration	0.637	4	*17*
TI5	Adherence to regulatory compliance	0.611	5	*19*

The RII findings reveal the most critical issues in implementing APM in construction projects, which closely corroborate with the literature. The highest-ranked issue, Deficiency in Agile Expertise (RII: 0.772), highlights the imperative requirement of skilled individuals. Elseknidy et al. (2024) stated that the lack of experienced practitioners is a significant challenge, which requires specialized training and knowledge transfer programs to bridge the gap. Similarly, Complex Interdisciplinary Coordination (RII: 0.757) reflects the challenge of managing multi-disciplinary teams and workflows. Studies emphasized that coordinated working across disciplines is necessary but challenging in the context of advanced construction projects.

Client Resistance to Agile Transition (RII: 0.745) and Collaboration Challenges (RII: 0.745) necessitate the education of stakeholders in agile processes. Absence of Cross-Functional Teams (RII: 0.738) indicates conventional models that do not support empowered, collaborative teams necessary for APM (Elseknidy et al., 2024). Lack of Training (RII: 0.734) necessitates training programs to develop competency and confidence in agile practices. Technical concerns are significant, with Agile Sprints integration (RII: 0.715) and Software Integration (RII: 0.709) capturing the need for hybrid solutions to balance agile and traditional milestones. Studies pointed out real-time collaboration tools to bridge the gaps. Organizational issues such as Rigid Hierarchies (RII: 0.706) hinder APM flexibility, prompting Elseknidy et al. (2024) to recommend structural reforms to improve agility. Resource constraints, data management, and regulatory compliance are areas that reflect technical issues that require strategic attention. The findings corroborate the global literature's perspective that technical and cultural issues must be addressed to achieve successful APM implementation in construction.

4.2 COMPARATIVE GROUP-WISE ANALYSIS OF BARRIERS

In Figure 4(a), the Organizational Barriers category shows moderate RII values, ranging from 0.658 (OR1) to a peak of 0.734 (OR3). Figure 4(b) highlights the Team & Collaboration barriers, with consistently higher RII values—most notably TC3 (0.772) and TC1 (0.757). These results underscore the critical importance of interdisciplinary collaboration, communication flow, and stakeholder engagement as central enablers of agile integration. Figure 4(c) illustrates the Process and Communication challenges, with the highest RII for PC1 (0.725), emphasizing the need for aligning agile processes with existing project workflows. In Figure 4(d), Technical and Integration barriers such as TI1 (0.715) and TI2 (0.709) point to significant challenges in synchronizing traditional planning systems with agile methodologies, especially in large-scale projects. Together,

the radar charts enable side-by-side comparison of the four barrier categories, clearly demonstrating that Team and Collaboration issues (Figure b) are perceived as the most critical group, followed by Technical Barriers. This visual analysis reinforces the need for strategic efforts to improve team coordination, cross-functional communication, and integration frameworks to facilitate APM adoption in construction projects.

4.3 CURRENT SCENARIO OF THE INDIAN CONSTRUCTION INDUSTRY ON AGILE PROJECT MANAGEMENT APPROACH

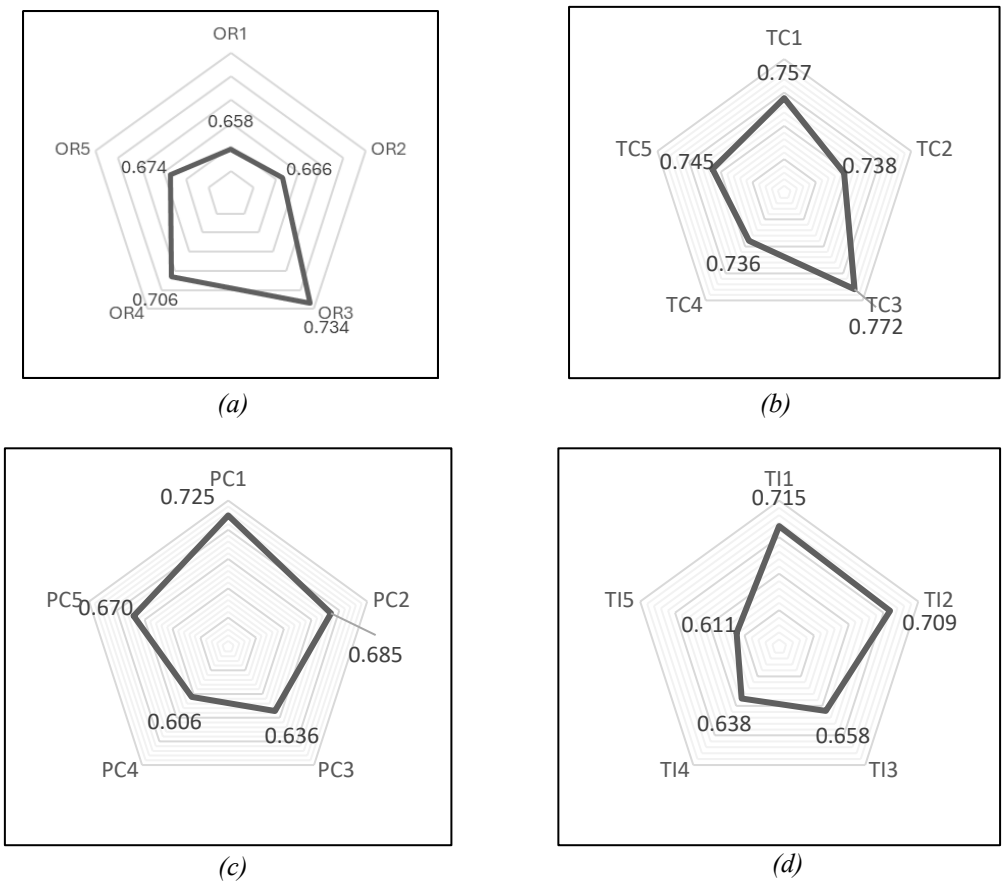


Figure 4: Radar Chart (a) Organisational (b) Team and collaboration (c) Process and communication (d) Technical and integration

The result of the survey from Figure 5 (a) indicates that 72% of the respondents had no exposure to APM at any time, while only 28% of the respondents had any type of exposure. Similarly, Figure 5 (b) indicates that 83% of the respondents are not certified in APM, while 17% of the respondents are certified. These results indicate a lack of awareness and systematic training in APM among the professionals working in the construction industry. This scenario indicates the need for systematic APM training programs and combined industry initiatives to enhance awareness and application in the Indian construction industry. The results of the survey presented in Figure 5 (c) indicate that there is a high perceived need for APM application in the construction industry, as 58% of the respondents agreed and 19% strongly agreed on its importance and a vast 19% of respondents remained neutral, while a tiny minority of 2% disagreed or strongly disagreed, indicating some hesitation or lack of awareness. Though there is awareness, the practice of effective usage of APM in real construction projects is lacking, as in Figure

5 (d), 72% of respondents indicated no application, and only 28% confirmed its application. The findings indicate the urgent need for industry-wide efforts for the facilitation of the use of APM through systematic training, awareness building, and pilot application in construction projects.

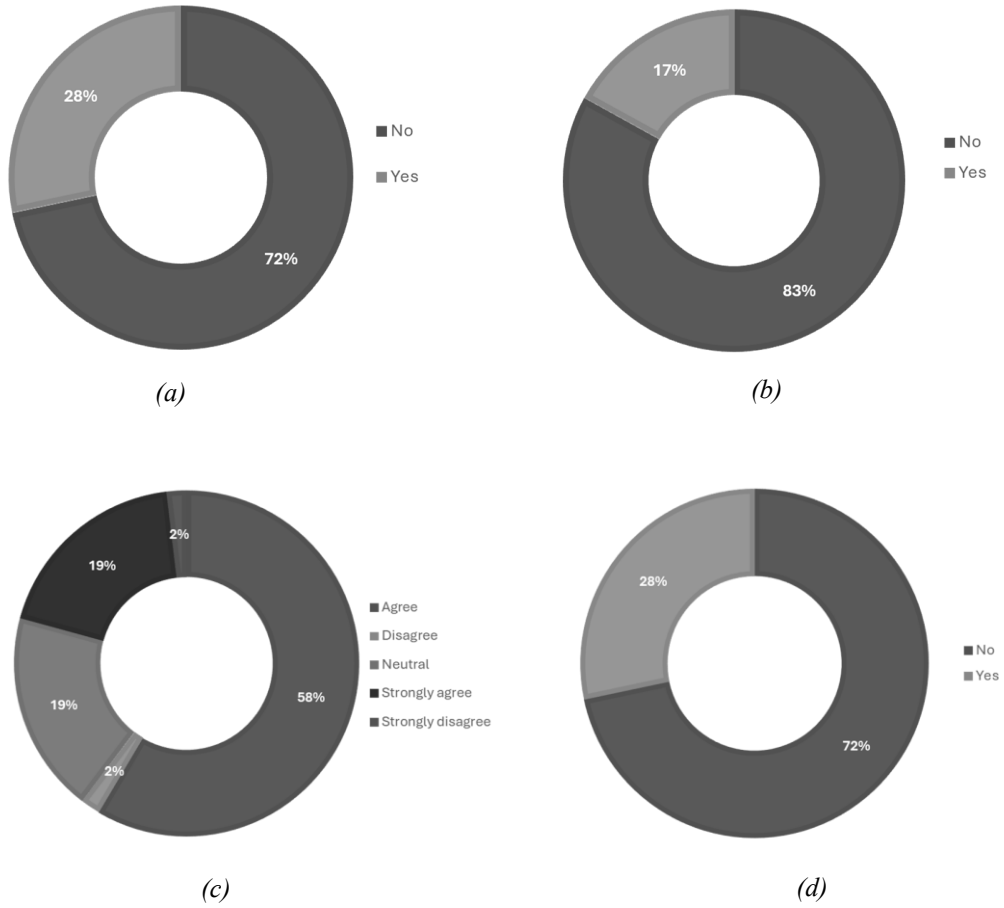


Figure 5: (a) Experience in APM (b) Certifications in APM (c) Necessity of APM implementation (d) Application of APM in live project

5. SUSTAINABILITY IMPLICATIONS

APM is a valuable approach to enhancing sustainability within the construction sector through facilitating flexibility, teamwork among stakeholders, and efficient resource use. The Agile Building Adaptation (AgiBuild) model, for instance, facilitates planning approaches centered on users and responsive, thus allowing construction teams to adapt more effectively to changing circumstances and facilitating innovation and enhanced performance in building adaptation processes—factors key to delivering more sustainable construction results (Ng et al., 2023). The present research, which indicates challenges in implementing APM within large-scale civil infrastructure projects, indicates that the absence of agile expertise, inadequate interdisciplinary collaboration, and resistance to change are among the most daunting challenges. Such challenges also reflect significant challenges in attaining sustainable project delivery, where agility and responsiveness to changing needs are of utmost importance. APM fosters a culture that is supportive of

ongoing learning and iterative development, thereby making it highly effective in meeting the dynamic and changing nature of sustainability goals in the construction industry. Since sustainability requires ongoing compliance with environmental regulations, societal expectations, and technological advancements, Agile's emphasis on frequent feedback mechanisms, shared planning, and prompt decision-making offers a framework that supports the tripartite model of sustainability—economic, environmental, and social considerations (Moshood et al., 2024). The findings of this study significantly emphasize that Team and Collaboration Barriers, which have been reported as the largest challenge among all groups, are not only adverse to the practice of APM but also prevent the integration of sustainability goals that involve interdisciplinary collaboration and open communication. Moreover, the fragmented character of construction projects—characterized by heterogeneous sources of data, isolated teams, and diverse stakeholder needs—requires a project management paradigm that is adaptive but structured. APM, through its iterative nature and adaptive planning loops, is especially apt to enable sustainability initiatives across all stages of projects. The incorporation of agile methods into construction planning can enable teams to quickly overcome material inefficiencies, design changes, or regulation updates, thereby enhancing both project results and sustainability performance. To this end, the present research highlights that overcoming the hindrances to APM not only enables more efficient implementation of agile methods but also provides the potential to integrate sustainability as an integral operating objective within construction project management.

6. CONCLUSIONS

The study brings out discussions in relation to the use of APM in large-scale civil infrastructure projects in the face of its commonly known theoretical advantages. The study recognizes that organizational resistance, combined with a lack of suitable training programs, prevents extensive use of APM, thus limiting its practical use in the industry. Strong leadership commitment is found to be a critical factor in overcoming resistance to change, building a culture of flexibility, and driving innovation in organizations. One of the most important critical hindrances to APM implementation is the absence of real-time coordination among cross-functional teams, highlighting the importance of formal agile activities, including daily stand-ups, to facilitate synchronization and workflow effectiveness. Additionally, stakeholder participation is a conventional issue, primarily because of hierarchical structures that restrict dynamic communication. These can be resolved by moving towards more inclusive and flexible communication systems that facilitate active participation by all stakeholders. Lastly, the study emphasizes that scaling APM for large-scale complex infrastructure projects requires a hybrid approach—one that combines Agile's iterative flexibility with the milestone-driven stringency of traditional project management. A balanced approach can close the gap between structured implementation and agility, and APM can be both feasible and effective for large-scale construction projects. These also emphasise the need for a hybrid framework that complements agile methodologies and tools with a waterfall approach for better project efficiency.

Although this research is carried out with a limited dataset, particularly in the context of the Indian context, the data is collected with targeted project planning and agile experts and acts as a solid starting point for understanding APM adoption issues in construction megaprojects. Similar studies can be conducted in other geographical contexts to confirm

or modify the outcomes of this study. Also, since the study largely records perceived barriers and not actual steps of implementation in the real world, future work using case studies and longitudinal measures can extend these results to present a more comprehensive picture of APM's construction impact.

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URBAN SYMBIOSIS IN MUNICIPAL SOLID WASTE MANAGEMENT AND REDUCTION: INSIGHTS FROM A BIBLIOMETRIC REVIEW

G.G.N. Chandani[1] and A.S.W. Karunarathna[2]

ABSTRACT

Municipal solid waste (MSW) output has escalated to critical levels due to the fast expansion of urban populations and industrial activity. This poses serious risks to environmental sustainability due to resource inefficiencies, greenhouse gas emissions, and increased landfilling. By encouraging interorganisational cooperation and resource sharing among urban systems to improve waste reduction and material recovery, urban symbiosis presents a viable remedy. The purpose of this study is to investigate how urban symbiosis might enhance MSW management through a thorough bibliometric analysis. The study analyses patterns of international collaboration, evaluates the topic's development, and identifies the most significant sources and authors. 50 journal articles published between 2015 and 2025 were analysed using a bibliometric approach. Systematic keyword searches were used to retrieve relevant articles from Scopus. To find research hotspots, top journals, top authors, and country-by-country contributions, a manual content analysis was used. Collaboration networks and keyword co-occurrence maps were created using VOS viewer software. While the concept of urban symbiosis has been increasingly applied in the context of industrial ecology and circular economy, existing literature remains fragmented with limited cross-sectoral integration. Most studies focus on isolated case applications without exploring broader synergies or long-term sustainability outcomes. This study presents a consolidated body of knowledge that documents the historical and thematic development of urban symbiosis in MSW management. The findings serve as a valuable resource for researchers, urban planners, and policymakers seeking to advance resilient and resource efficient urban waste systems.

Keywords: *Municipal Solid Waste (MSW); Municipal Solid Waste Management (MSWM); Urban Symbiosis.*

1. INTRODUCTION

The global generation of MSW has increased dramatically because of the rapid urbanization of the world and changing patterns of consumption (Saja et al., 2021). Cities are particularly under pressure to contain waste sustainably given the limited space available, the density of the population, and the need to mitigate negative impacts on the environment. The management of waste continues to follow decades old practices such

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as landfilling and incineration which pose serious risks to the environment and to health (Kaza et al., 2018). Incinerating waste releases gas and contributes to air pollution along with creating greenhouse gases, while landfills lead to the decaying of land, groundwater contamination, and methane emissions. These methods also incur high operational costs that cities do not have in reserve, posing extensive financial hurdles (Blair & Mataraarachchi, 2021).

In many developing counties, a large part of municipal waste is uncollected and dumped inappropriately leading to steadily increasing urban pollution and worsening public health (Agamuthu & Babel, 2023). Developing countries are not the only ones facing challenges of growing per capita waste generation, intricate waste streams, and inadequate recycling systems; high earning countries also face similar challenges. Without appropriate long-term resolutions in place, systems that work in silos remain ineffective (Awino & Apitz, 2024). The lack of integrated, circular strategies that address waste generation, reduction, and recovery as part of a larger urban system is a crucial gap in practice and research that is highlighted by this disjointed approach (Kotyal, 2023). Considering growing environmental pressures and urban resource constraints, it is becoming increasingly apparent that traditional linear waste management models are no longer practical (Kotyal, 2023).

Considering this, urban symbiosis presents a viable and comprehensive substitute. Urban symbiosis, which has its roots in industrial symbiosis, promotes cooperation between communities, businesses, and governments to exchange materials, energy, and byproducts in ways that maximize resource efficiency and minimize waste (Nugroho et al., 2025). Cities can shift from disposing of waste to circulating resources thanks to these synergies, which decreases their reliance on landfills while producing benefits for the economy and environment (Edmond et al., 2025). By encouraging innovation, strengthening urban resilience, and promoting circular economy practices, urban symbiosis supports global sustainability goals. Its use in municipal solid waste management is still restricted and poorly understood, though (Wilson et al., 2012). The infrastructure, institutional coordination, and policy frameworks necessary to execute such integrated approaches are still lacking in many cities (Nugroho et al., 2025). This emphasises how important it is to comprehend urban symbiosis as a method for managing and reducing MSW. To solve today's waste issues and create more sustainable, effective, and connected cities, it is imperative to investigate how it can be more effectively integrated into urban systems (Edmond et al., 2025). Therefore, the main objective of this study is to analyse international research trends, key contributors, collaboration networks, and thematic developments related to urban symbiosis in the context of MSW management, to identify research gaps and inform future strategies for resilient and resource efficient urban waste systems.

2. LITERATURE REVIEW

2.1 URBAN SYMBIOSIS

Urban symbiosis is a cooperative interaction between diverse urban actors (such as homes, businesses, and institutions) that involves the exchange of resources and services for the mutual advantage of both parties to maximize resource efficiency, water efficiency, and sustainability (Yatawatta, 2023). The concept was equivalent to the concept of Industrial Symbiosis. "Industrial symbiosis engages traditionally separate

industries in a collaborative approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products" (Mulder, 2016). As an extension of urban symbiosis, studies synergies between urban and industrial areas by turning municipal solid waste into industrial space and employing industries to supply living resources, such as waste heat and hot water (Sun et al., 2017).

2.2 THE CONCEPT OF URBAN SYMBIOSIS FOR MUNICIPAL SOLID WASTE REDUCTION AND MANAGEMENT

Municipal solid waste (MSW) is waste collected by local municipalities. The main part of MS comes from households, but waste from commerce and trade, offices and institutions are also included in municipal solid waste (Cvetković et al., 2014). Its main components include kitchen waste, wastepaper, waste plastic, waste fabric, scrap metal, scrap glass, and scrap furniture (Zhao, 2021). The increasing amount of MSW brought on by population expansion, urbanization, and shifts in consumer behaviour is posing a significant threat to urban areas worldwide. The take-make-dispose paradigm of traditional linear waste management systems is becoming less and less sustainable (Kellner, 2021). One potential remedy is the idea of urban symbiosis. Reimagining cities as interconnected ecosystems where waste, energy, materials, and resources continuously flow among stakeholders including municipalities, industries, homes, and service providers is the foundation of urban symbiosis, which has its roots in industrial ecology and circular economy ideas (Momirski et al., 2021).

Urban symbiosis transforms waste into valuable inputs for other sectors. Compost and biogas can be produced from organic waste from food markets for local businesses or urban farming. In a similar vein, construction and demolition waste can be recycled for infrastructure projects, which lessens the need for virgin materials and landfills (Kaza et al., 2018). Working together and pooling resources is essential to developing effective, closed-loop systems (Momirski et al., 2021). Urban symbiosis for municipal solid waste management (MSWM) emphasises integrated approaches that coordinate collection of waste, recycling, and treatment. Waste streams are more efficient when residential regions are connected to adjacent commercial or industrial zones (Fraccascia, 2018). Recycling hubs that serve a variety of stakeholders can reduce processing and transportation costs while increasing material recovery. Composting and anaerobic digestion systems are examples of waste-to-resource networks that can transform biodegradable trash into fertilisers or renewable energy, boosting regional economies and sustainability (Oberoi, 2020).

Strategic facility co-location strengthens urban symbiosis. Locating waste treatment plants near manufacturing hubs or residential areas enables efficient energy recovery and material reuse. Waste-to-energy plants can supply electricity and heat to nearby users, while material recovery facilities provide recycled inputs for manufacturers, creating economic and environmental benefits (Fraccascia, 2018). Technology plays a critical role in urban symbiosis, with smart waste management systems and digital platforms ensuring real-time monitoring, transparency, and efficient resource matching. Collaboration among municipalities, private enterprises, and communities is essential to developing supportive infrastructure and governance mechanisms (Kellner, 2021). By integrating waste as a resource into regenerative urban systems, urban symbiosis offers a transformative approach to municipal waste management, fostering sustainable and circular cities for the future (Mulder, 2016).

3. RESEARCH METHODOLOGY

This study applied a bibliometric analysis approach to explore the relationship between urban symbiosis and municipal waste reduction and management. Bibliometric analysis offers a quantitative method for examining research trends, key contributors, and emerging themes within a specific field, enabling a structured understanding of scholarly development over time. To gather relevant literature, the Scopus database was selected due to its broad indexing of peer-reviewed journals across scientific disciplines. The search was conducted using the combined keywords "municipal waste reduction," "urban symbiosis," and "waste management", with the following query: TITLE-ABS-KEY (“municipal waste" OR "municipal solid waste" OR "municipal solid waste management" OR "municipal solid waste reduction" AND "urban symbiosis”).

The timeframe for this search spanned from 2015 to 2025, ensuring coverage of a complete decade of academic research on the topic. The initial search returned 81 records, which were then screened for relevance. Articles were filtered by publication year and refined to include only journal articles, reducing the number to 54. A final language filter was applied to retain only publications in English, resulting in a dataset of 50 articles that served as the basis for the analysis. The selected articles were analysed using two primary bibliometric indicators. First, keyword co-occurrence was examined to uncover dominant themes and conceptual interconnections across the dataset. Second, publication distribution was evaluated to track changes in research output over time, as well as to identify the most active journals, prolific authors, and leading countries contributing to the field. These indicators provided a comprehensive view of how scholarly attention to urban symbiosis in the context of municipal waste management has developed over the years.

4. RESULT AND DISCUSSION

The paper's main study findings are presented in this section on two main areas: (i) outcomes of bibliometric analysis, and (ii) industrial symbiosis for municipal solid waste reduction and management. The bibliometric analysis identified the most influential publications, authors and south Asian countries in the field of industrial symbiosis, highlighting the growing interest in this area of research.

4.1 OUTCOME OF BIBLIOMETRIC ANALYSIS

The primary stage in gathering information about the involvement of urban symbiosis in municipal solid waste reduction and management was a systematic study based on Scopus. Bibliometric analysis was performed on the data acquired between 2015 and 2025. The outcomes were categorized into four main headings: (i) evolution of the number of journal articles published, (ii) leading journals that published articles related to industrial symbiosis and municipal solid waste reduction and management (iii) analysis of the leading authors in this field, and (iv) analysis of leading south Asian countries of journals that published articles on the topic. This analysis offers insightful information about the patterns and trends in this field of study, emphasizing the increasing interest in the concept of industrial symbiosis to reduce and manage municipal solid waste.

4.2 GROWTH OF JOURNAL PUBLICATIONS ON URBAN SYMBIOSIS FOR MUNICIPAL SOLID WASTE REDUCTION AND MANAGEMENT

A total of 50 papers published between 2015 and 2025 were examined in this review, which concentrated on the involvement of urban symbiosis in municipal solid waste management and reduction. Figure 1 shows the evolution of the number of journal articles published on this topic in the Scopus database. According to the database, there were just 01 articles published in 2015; and by 2016 it has been increased to 4 articles. This early growth may reflect the emergence of global interest in sustainable urban planning and resource efficiency following the 2015 Paris Agreement and the adoption of the UN Sustainable Development Goals (SDGs) (United Nations, 2015). According to the analysis there were no any articles in 2017. however, the number of publications peaked in 2018 with total 9 articles as illustrate in the figure. This spike likely reflects increased global discourse on circular economy principles, along with a growing push for sustainable urban development policies in both developed and developing countries (Geissdoerfer et al., 2017). In 2019 and 2020 there were 3 and 4 articles published, respectively. grew to 6 sources in 2021 before being lowered to 3 articles in 2022. The marginal output during these years may be linked to broader research disruptions and shifting priorities due to the COVID-19 pandemic, which affected many research activities worldwide (Miki et al., 2020). But the following years showed a strong recovery, with 7 publications each in both 2023 and 2024. In 2025, the output slightly decreased to six. Overall, the data reveals a pattern of fluctuating research productivity with a general upward trend in publications on urban symbiosis in municipal solid waste reduction and management from 2015 to 2025, highlighting renewed consistency and growth in publication output. This resurgence could be driven by increasing policy mandates for sustainable cities, greater public awareness of climate resilience, and advances in digital tools for symbiotic urban design. Overall, the data reflects a fluctuating but generally upward trajectory in research activity. The trend highlights increasing academic and practical interest in the role of urban symbiosis for MSW reduction, especially considering global sustainability challenges and policy shifts over the past decade.

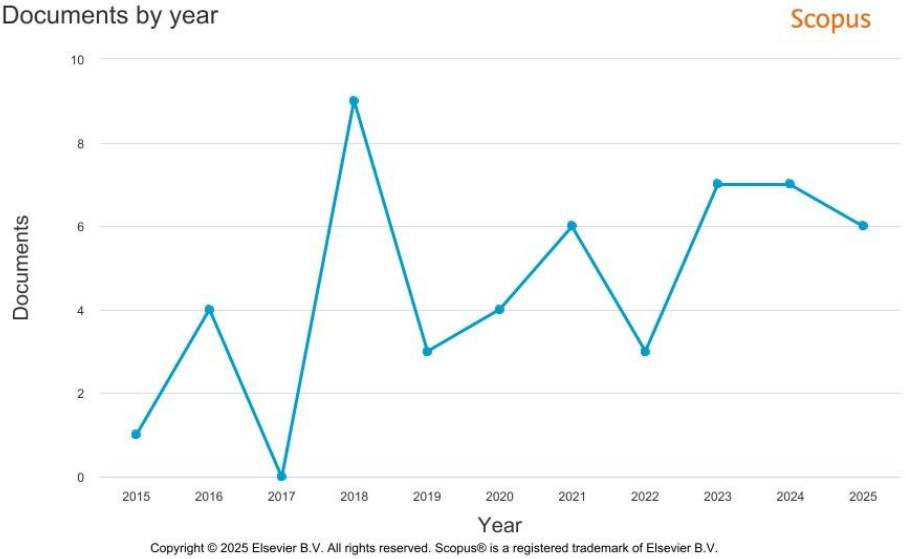


Figure 1: Publication distribution through 2015-2025
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4.3 LEADING JOURNALS PUBLISHED URBAN SYMBIOSIS IN MUNICIPAL SOLID WASTE REDUCTION AND MANAGEMENT

Nowadays, concept of urban symbiosis is considered a novel idea, with only a limited number of journals dedicated to publishing research on the topic. The top journals that published papers on urban symbiosis in municipal solid waste management and reduction between 2015 and 2025 are shown in Figure 2. The data shows that over the period, the Journal of Cleaner Production published the most papers (nine) on this subject. Resources, Conservation and Recycling, Sustainability (Switzerland), Environmental Science and Pollution Research, Science of the Total Environment, Waste Management are some more prestigious journals that have published a significant number of articles.

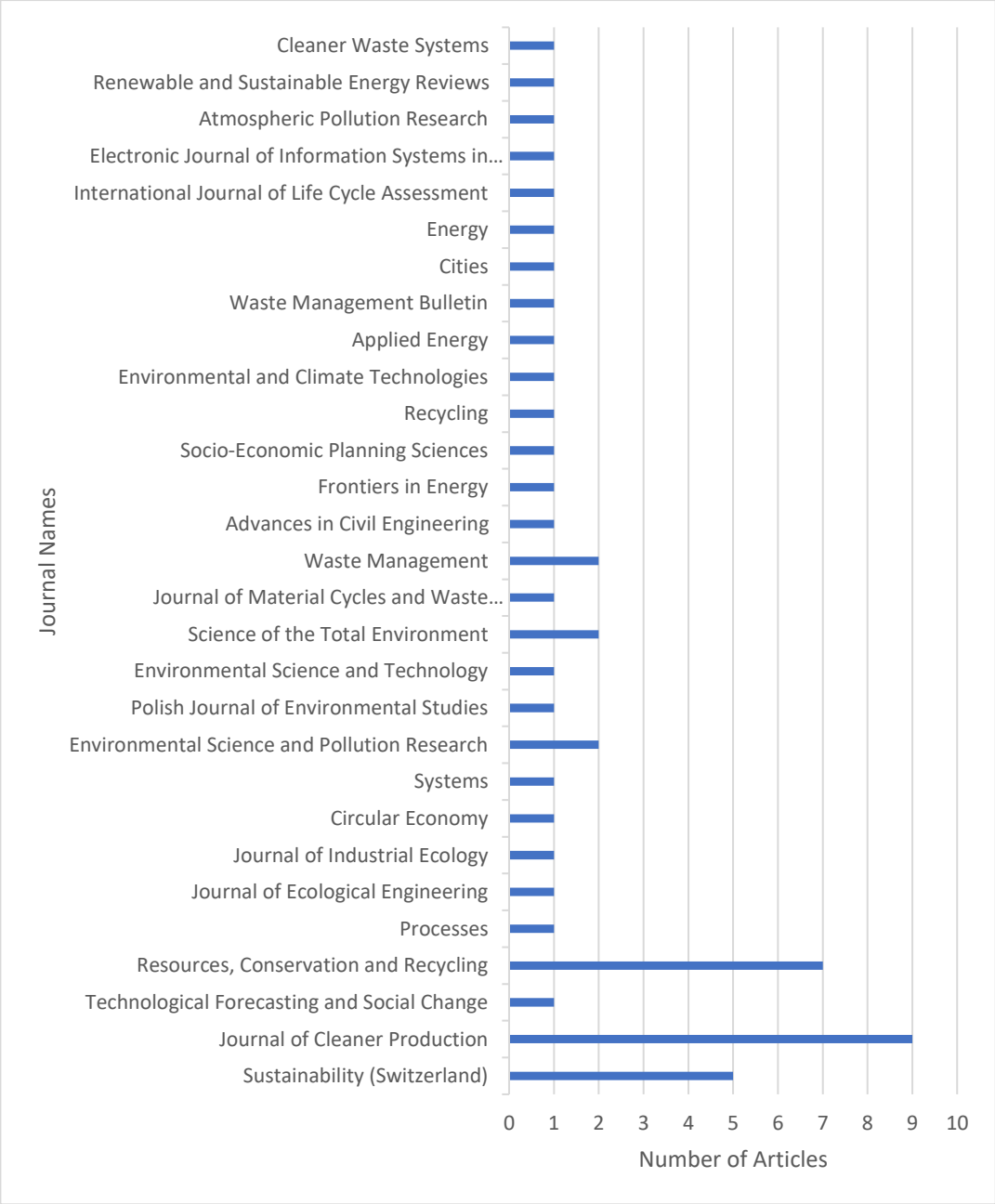


Figure 2: Leading journals that published most articles
Source: Produced by authors from data retrieved from Scopus®

This dominance of journals such as the Journal of Cleaner Production and Resources, Conservation and Recycling reflects the interdisciplinary nature of urban symbiosis, which intersects sustainability science, environmental engineering, and industrial ecology. These journals have a strong emphasis on life cycle thinking, circular economy models, and integrated approaches to environmental management which align closely with the principles of urban symbiosis (Geissdoerfer et al., 2017).

Furthermore, the prominence of these journals suggests that the academic community increasingly recognizes the role of urban symbiosis in addressing complex urban waste challenges. High-impact journals in environmental science and waste management, such as Science of the Total Environment and Waste Management, have published studies that frame urban symbiosis as a scalable, systems-based solution for sustainable city infrastructure (Dong et al., 2016).

The fact that relatively few journals contribute to this research body also indicates that urban symbiosis is still an emerging subfield. Its presence in established journals hints at growing legitimacy and relevance, potentially forecasting wider adoption in policy, planning, and urban innovation discourse in the coming years.

4.4 LEADING AUTHORS IN CONCEPT

The prominent authors who have aided in urban symbiosis in municipal solid waste management and reduction are showcased in Figure 3. According to a Scopus data study, Fujii M published the most publications (seven) and author Geng Y published six papers on this topic between 2015 and 2025. Both authors Dong H and Fujita T published five articles. Ohnishi, S. and Sun, L. have each contributed 4 publications, reflecting a consistent output in the field. Dong, L. follows with approximately 3 articles, while Li, Z., De Clercq, D., and Liu, J. each have published two articles in Scopus and have all made noteworthy contributions.

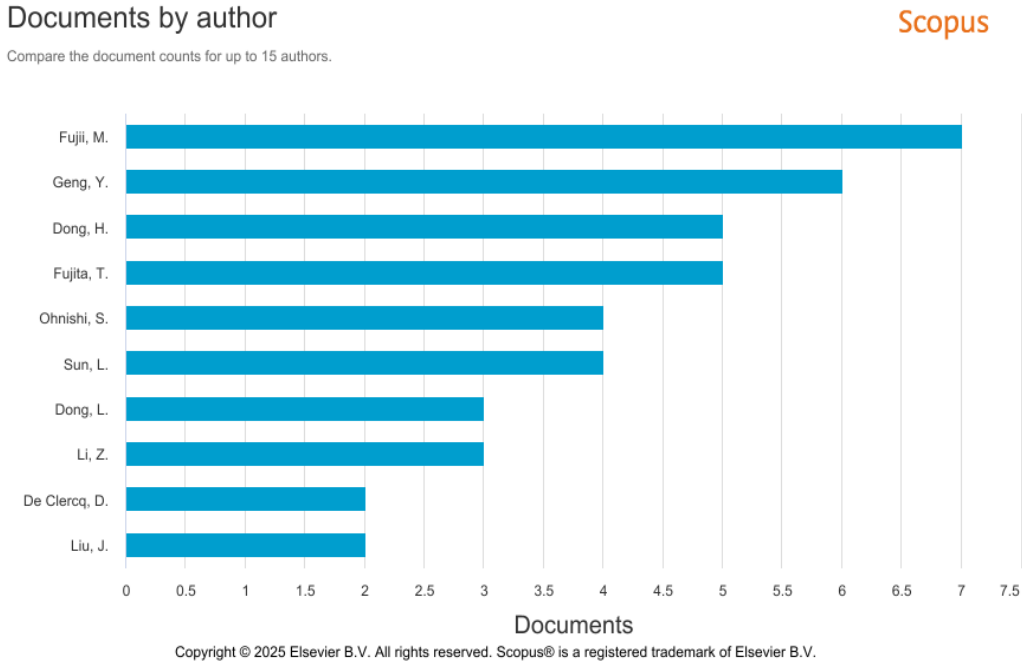


Figure 3: Leading authors in the field
Source: Scopus®. Copyright © 2025 Elsevier B.V. All rights reserved

4.5 PUBLICATIONS BY COUNTRY OR TERRITORY

The uppermost journal countries that have contributed the most articles regarding urban symbiosis in municipal solid waste management and reduction during the span of years from 2015 to 2025 are represented in Figure 4. Figure 4 displays the situation that China and Japan published the most articles regarding the combination of urban symbiosis, municipal solid waste management and reduction among the countries which published from 2015 to 2025. The Italy and United State America came in third place as country that produced a journal on urban symbiosis in municipal solid waste management. Along with the Czech Republic, Pakistan, Poland, Slovenia, South Africa and United Kingdom are the other significant countries that takes journal articles on urban symbiosis and municipal solid waste management as the major topic.

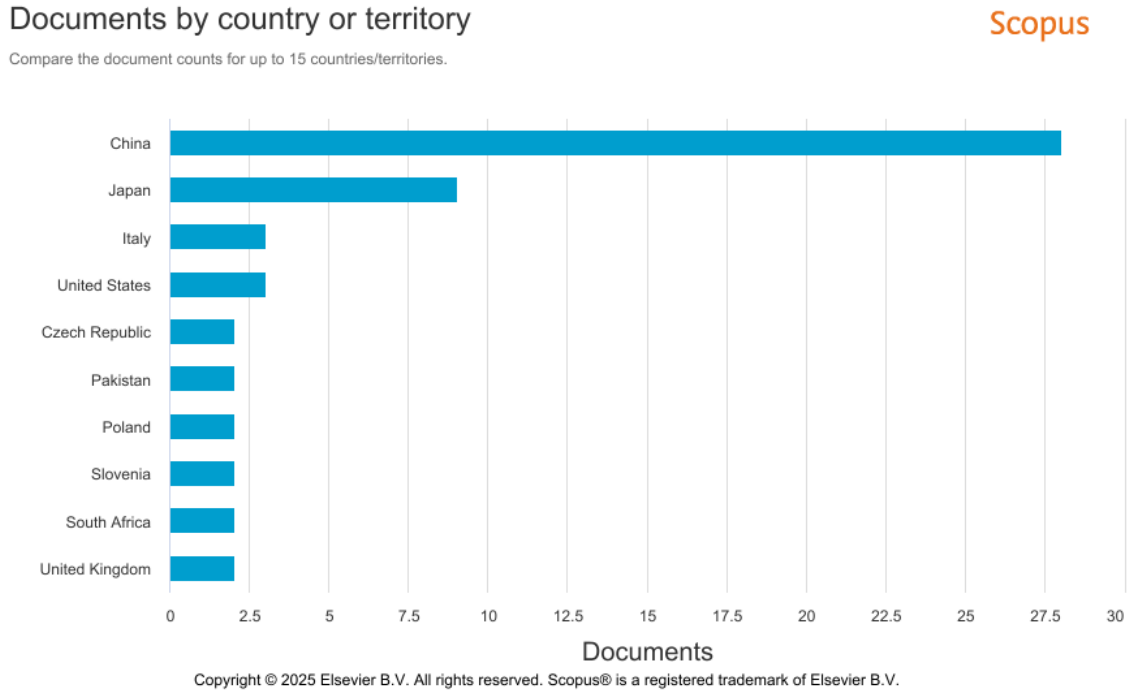


Figure 4: Documents by countries
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4.6 MAPPING OF THE KEY WORDS OCCURRENCE IN RESEARCH

A total of 29 keywords were retrieved from the 50 articles using VOSviewer software. The selection of these keywords was based on their occurrence in a minimum of four publications. The frequency of a keyword in a document reflects its overall scope, while cooccurrence highlights how often two keywords appear together in a title, abstract, or keyword list. The findings of this study depict Figure 5. The illustration shows the frequency of co-occurring terms in the publications through the size of nodes. The thickness of the linking lines represents the strength of relationships. The proximity of nodes in the figure shows a strong linkage between them. According to the visual network map, these keywords may be categorised into four clusters.

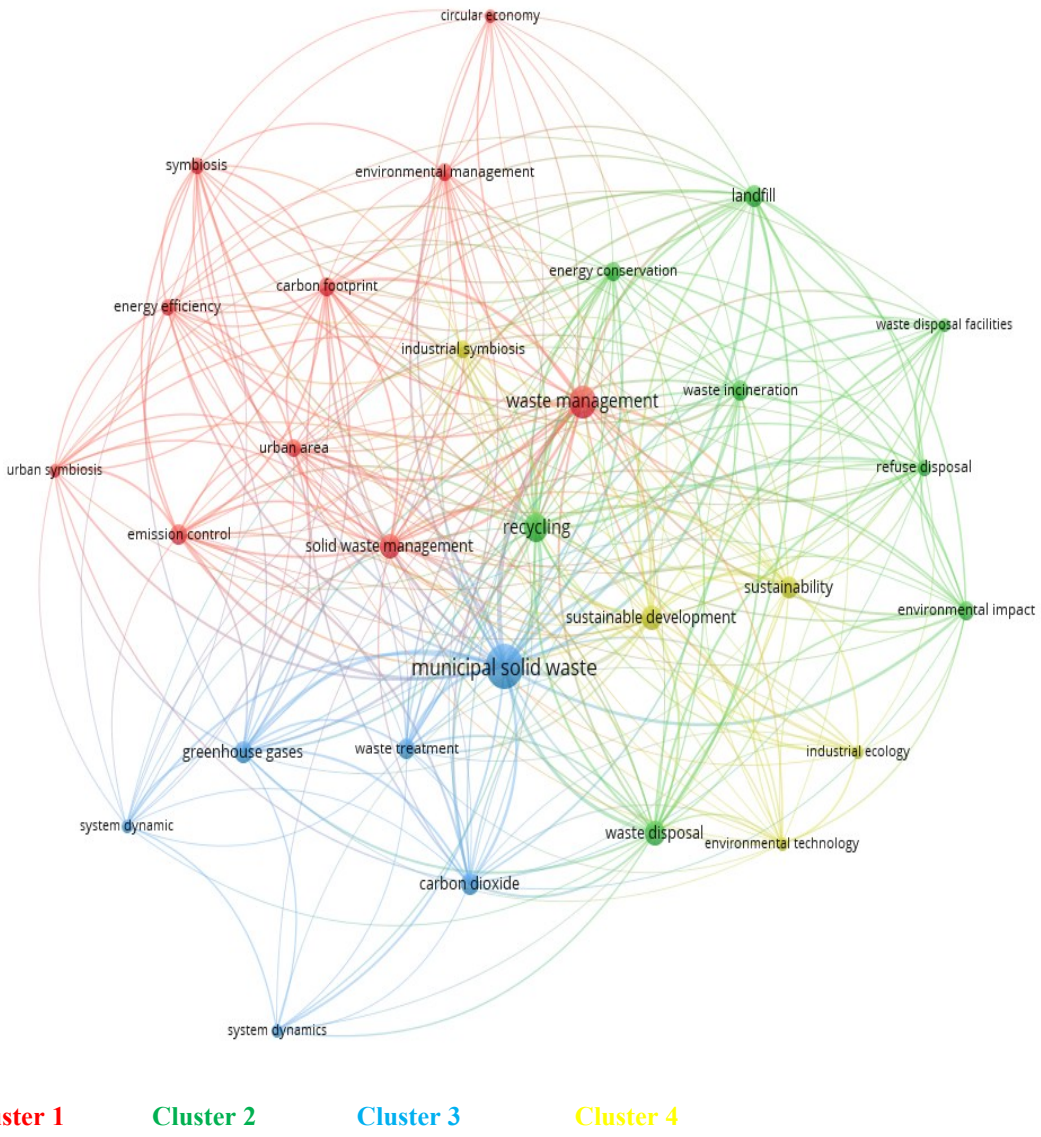


Figure 5: Key words occurrence analysis

According to Figure 5, The co-occurrence network diagram reveals four distinct thematic clusters within the field of waste management and sustainability, each represented by different colours. The cluster 1 (red) emphasizes systems thinking and resource optimization, highlighting concepts such as circular economy, symbiosis (both urban and industrial), energy efficiency, and emission control. These terms reflect a strategic approach to minimizing environmental impact through integrated environmental management. The cluster 2 (green) canters around traditional waste disposal methods, including landfill, incineration, and refuse facilities. This group of terms captures the infrastructure focused, end-of-pipe solutions that are still widely employed in many waste management systems today. The cluster 3 (blue) shifts focus toward the scientific and quantitative assessment of waste related impacts, featuring terms like municipal solid waste, greenhouse gases, carbon dioxide, and system dynamics. This cluster underscores

the importance of modelling and analysing emissions and environmental consequences associated with waste. Finally, the cluster 4 (yellow) aligns closely with the broader goals of sustainability, incorporating terms such as sustainable development, industrial ecology, environmental technology, and environmental impact. This cluster reflects a holistic and interdisciplinary approach aimed at embedding sustainability principles within waste management strategies. Collectively, these clusters illustrate the multidimensional nature of municipal solid waste management research, encompassing technical, environmental, economic, and systemic perspectives.

4.7 ADOPTING URBAN SYMBIOSIS FOR MUNICIPAL SOLID WASTE REDUCTION AND MANAGEMENT

The concept of urban symbiosis is central to the study, where the interactions between urban waste management and industrial processes can lead optimize waste management and resources to reduced environmental impacts and enhanced resource efficiency between various sectors. Examples of successful urban symbiosis include using waste heat from industrial processes for district heating and repurposing solid waste as fuel in energy intensive industries (Tröger et al., 2023).

Recent journal articles suggest that adopting the concept of urban symbiosis can be an effective approach to manage and reduce municipal solid waste in urban areas. To enhance urban symbiosis, several strategic approaches can be implemented. As example, prioritizing the recycling of materials such as slag, fly ash, and scrap steel is crucial for maximizing resource savings and reducing CO2 emissions (Lu et al., 2020). This approach should be complemented by fostering integration between urban waste management and industrial resource needs, allowing for efficient exchanges of by products and waste (Kuznetsova et al., 2019). Furthermore, a recent review by Dong et al. (2016) highlighted the potential of urban symbiosis for municipal solid waste management in China. According to the study, to promote resource efficiency and reduce waste outputs, a symbiosis network designed that connects multiple industries and urban areas to facilitate the exchange of materials and waste. Moreover, identifying and implementing waste reuse initiatives coupled with establishing energy recovery systems to harness waste energy from industrial processes, will significantly reduce reliance on fossil fuels while enhancing overall energy efficiency (Taouahria, 2024).

Urban symbiosis presents numerous benefits in the realm of waste management, fundamentally transforming how waste is perceived and utilized. One of the primary advantages is the reduction of greenhouse gas emissions, as utilizing municipal solid waste as a resource can significantly lower emissions by converting waste into energy or valuable products, thus decreasing reliance on landfills and fossil fuels(Dong et al., 2016). Additionally, urban symbiosis promotes efficient resource use by allowing waste from one process to serve as raw material for another, optimizing material consumption and minimizing waste generation (Sun et al., 2020). utilize both fossil and recycled resources, allows for better optimization of existing industrial facilities (Smith et al., 2015). This not only helps in reducing waste but also in maximizing the efficiency of resource use, leading to a more sustainable industrial ecosystem (Sun et al., 2020). The financial implications of converting waste into energy or products, enhancing economic viability and creating new business opportunities through synergies between different waste-to-energy or waste-to-product systems (Fei et al., 2021). Urban symbiosis can be tailored to fit the specific socioeconomic conditions of different cities. cities with varying waste

management practices and economic situations, allowing for localized strategies that can effectively address waste management challenges (Fujii et al., 2016). By integrating waste management into industrial processes, urban symbiosis contributes to the development of sustainable practices that align with global efforts to reduce carbon emissions and promote low-carbon industries (Fei et al., 2021). Lastly, effective waste management through urban symbiosis can lead to improved public health outcomes by reducing risks associated with waste accumulation and enhancing sanitation efforts in urban areas (Berg et al., 2018). Overall, urban symbiosis offers a comprehensive approach to waste management that addresses environmental concerns while promoting economic growth and community well-being (Dong et al., 2016).

Implementing urban symbiosis faces several significant barriers. One major challenge is the insufficient infrastructure in many cities, particularly in Africa, where inadequate public service management and failing systems limit the effectiveness of urban symbiosis initiatives(Tsai et al., 2020). Additionally, the high costs associated with advanced waste treatment technologies pose a financial barrier, especially in developing regions, preventing the adoption of necessary systems for resource recovery (Chin et al., 2023). The excessive generation of waste further complicates matters, as existing MSWM infrastructure often struggles to manage increasing volumes, leading to environmental issues like plastic waste leakage. Moreover, the lack of holistic approaches to monitoring and managing MSWM on a global scale makes it difficult to establish effective urban symbiosis frameworks that require coordinated efforts across various sectors (Appio et al., 2019). There is also a limited body of research and knowledge on MSWM in a circular economy, which hinders the identification of best practices and indicators essential for successful implementation. The complexity of integrating various types of materials and operations poses a challenge. Urban symbiosis requires the seamless integration of different flows, including materials and energy, which can be difficult to achieve(Sun et al., 2018). Finally, regional disparities in research output, with areas like Africa and North America having fewer studies compared to Europe and Asia, create additional barriers to effectively implementing urban symbiosis in less-studied regions (Tsai et al., 2020). These challenges underscore the complexities involved in fostering urban symbiosis and highlight the need for targeted strategies to overcome them.

5. CONCLUSIONS

In recent years, there has been a growing interest in the concept of urban symbiosis for municipal sloid waste management and reduction. The results of this bibliometric analysis show a significant increase in publications that address this intersection, especially between 2017 and 2025. This indicates that there is an increasing need to find long-term solutions to reduce the negative environmental effects of urbanization and infrastructure. Prominent journals have become important venues for sharing research on this subject, suggesting that the academic community is working together to increase knowledge and comprehension in this area. Furthermore, nations like China, Japan, and Italy have contributed significantly to the body of knowledge on the concept urban symbiosis for MSWM. The concept of urban symbiosis offers significant potential to enhance waste reduction, resource recovery, and circularity in urban systems by promoting inter industry collaboration and material exchange. By optimizing flows of energy, materials, and information across sectors, urban symbiosis supports more resilient, efficient, and sustainable urban environments. However, challenges persist in

achieving widespread implementation, including regulatory barriers, lack of infrastructure, high cost of waste treatment technologies, and the need for stronger cross-sectoral coordination. Overcoming these challenges will require interdisciplinary collaboration, supportive policy mechanisms, and targeted investment in scalable symbiotic solutions. In conclusion, urban symbiosis holds substantial promise in reshaping municipal solid waste management practices. Continued innovation, stakeholder engagement, and policy alignment are essential to fully realize its transformative potential in building sustainable cities for the future.

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UTILIZATION OF TEXTILE INDUSTRY BY-PRODUCTS TO DEVELOP AND OPTIMIZE GEOPOLYMERIZED MUD CONCRETE FOR SUSTAINABLE CONSTRUCTION

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ABSTRACT

The industrial sector generates large quantities of by-products daily, posing environmental challenges due to disposal issues and global warming. To address this issue, researchers have successfully incorporated these by-products into sustainable building materials. Geopolymerized Mud Concrete is an existing eco-friendly concept that introduced an alternative stabilizer for Mud Concrete by utilizing fly ash, which is generated from the coal combustion process. This study focuses on developing and optimizing the Geopolymerized Mud Concrete mix using textile industry by-products, highlighting its potential as a sustainable alternative to Cement-Based Concrete. The mix design was prepared using soil, wood ash, textile wastewater, and NaCl. Wood ash served as the aluminosilicate source for geo-polymerization, while textile wastewater was used as an alkaline activator instead of commercial NaOH. Both materials were collected from the textile manufacturing industry. The feasibility of textile wastewater as an alkaline activator was assessed through FTIR analysis. Additionally, SEM-EDX was performed to analyse morphology, particle size, and elemental composition of wood ash which affects the strength variation. The study aimed to optimize key parameters, including moisture content, wood ash content, and textile wastewater concentration (pH value) based on the 7, 14, and 28-day compressive strength values of the mix. The results showed that the optimum wood ash content was 20%, and the optimum moisture content ranged from 20% - 22% from the dry weight of the mix. The optimum textile wastewater concentration was shown at pH 12. Furthermore, the findings confirmed that the unconfined compressive strength of the developed concrete mix met the standard requirements for earth-based masonry units.

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Keywords: *Geopolymerized Mud Concrete; Sustainable Construction; Textile Industry; Textile Wastewater; Wood Ash.*

1. INTRODUCTION

The building construction sector has increasingly adopted the concept of sustainability in response to its significant greenhouse gas (GHG) emissions and energy consumption throughout the building life cycle, including material production, transportation, construction, operation, maintenance, and end-of-life stages (Fei et al., 2021; Zuo et al., 2012). However, the construction sector remains the largest emitter of GHGs, accounting for approximately 37% of global emissions, and consuming 40% of global energy (United Nations Environment Programme, 2023;). These challenges are further intensified by factors such as global population growth, rising living standards, and increasing electricity demand (United Nations Environment Programme, 2023; Yan et al., 2010). While improvements in building envelopes and energy systems have reduced operational carbon emissions (those from heating, cooling, and lighting), embodied carbon emissions associated with the production and deployment of materials like cement, steel, and aluminum remain high (Aperador & Bautista-ruiz, 2023; Wang et al., 2019). Therefore, transitioning to a circular economy is critical to reducing the carbon footprint of previously mentioned construction materials. The circular economy involves strategies such as designing buildings for material reuse, optimizing material consumption, and extending the life of buildings and materials through proper maintenance. For example, prefabrication of modular concrete components for reuse can significantly lower emissions, while substituting traditional materials with bio-based and earth-based alternatives can provide sustainable options for decarbonizing the sector (United Nations Environment Programme, 2023). To address these challenges, researchers have been working on developing sustainable building materials incorporating circular economy practices. These materials aim to reduce the environmental impact of construction by using renewable resources, minimizing energy consumption during production, and promoting recycling and reuse (United Nations Environment Programme, 2023). Beyond construction, industrial sectors also contribute to environmental degradation through their by-products, often leading to pollution and economic costs associated with waste disposal (Karunasena& Rathnayake, 2013). Integrating waste management practices and adopting recycling technologies can help mitigate these impacts, while government regulations and incentives encourage industries to adopt more sustainable practices (Ramesh et al., 2014). Incorporating these three concepts, sustainable building materials, circular economy practices, and the efficient use of industrial byproducts, it is possible to develop eco-friendly construction materials. This approach not only reduces industrial waste disposal burdens but also minimizes the environmental degradation caused by conventional building materials.

Geopolymerized Mud Concrete masonry unit is one such alternative for cement-based walling materials, which was developed by Udawattha and Halwatura (2018) by utilizing coal fly ash. It integrates two innovative sustainable building material concepts; Mud Concrete Technology and Geopolymer Concrete Technology. Mud Concrete is a soil-based material composed of soil, cement, and water, whereas Geopolymer Concrete replaces cement with alkali-activated aluminosilicate-rich industrial by-products. Various industrial and agricultural waste materials, such as fly ash, silica fume, wood ash, rice husk ash, industrial slags, and municipal solid waste, can serve as geopolymer precursors due to their high aluminum (Al_2O_3) and silicon (SiO_2) content (Amran et al., 2020;

Sbahieh et al., 2023). Alkaline activation typically involves chemical solutions such as Potassium Hydroxide (KOH), Sodium Hydroxide (NaOH), Potassium Silicate (K_2SiO_3), Sodium Silicate (Na_2SiO_3), or combinations of these compounds. However, industrial by-products with high alkalinity can serve as alternative activators (Ali & Sachan, 2022). These activators facilitate the dissolution of Si and Al atoms, enabling their recombination into a stable geo-polymeric network. The choice of activator significantly influences the microstructure, mechanical properties, durability, setting time, and strength of geopolymer concrete (Sbahieh et al., 2023). Other than replacing cement, these materials also mitigate waste disposal challenges and reduce the carbon footprint of the construction industry.

This research investigates the potential of incorporating textile industry by-products to develop sustainable building materials while aligning with circular economy principles. Specifically, wood ash is utilized as an aluminosilicate precursor, and textile wastewater serves as an alkaline activator to produce novel Geopolymerized Mud Concrete mix. The study aims to optimize the moisture content, wood ash content, and textile wastewater concentration to achieve high compressive strength. By embracing these sustainable solutions, the construction sector can significantly lower its environmental footprint and contribute to a more resilient and sustainable built environment.

1.1 RESEARCH SIGNIFICANCE

Currently, Portland-type concrete poses a significant environmental challenge due to its high greenhouse gas emissions. To address this issue, the development of eco-friendly construction materials with enhanced durability and resistance has been proposed. One such innovation is Geopolymerized Mud Concrete, which integrates Geopolymer Concrete technology with Mud Concrete technology and has already shown promise in the development of masonry units.

According to the literature, approximately 780 million tons of fly ash are generated globally each year, yet only about 17–20% of it is utilized. For instance, India alone produces around 220 million tons of fly ash annually, of which only 35–50% is used in construction applications. The remainder is often discarded as waste, occupying vast areas of valuable land (Patankar et al., 2015). In parallel, the textile industry is experiencing rapid growth due to increasing global population and demand. This has led to a substantial rise in industrial waste. The textile sector commonly uses wood as a source of biomass energy, which produces large quantities of wood ash as a by-product. According to recent findings, 4,600 million tons of wood biomass are produced globally each year, with 60% used for energy generation. However, a significant amount of wood ash is still disposed of in landfills, posing environmental and health risks such as airborne dispersion and groundwater contamination due to the presence of heavy metals (Teker Ercan et al., 2023). Moreover, textile manufacturing processes generate large volumes of wastewater containing hazardous chemicals such as NaOH in washing and dyeing (Mohana & Bharathi, 2024). Improper disposal of such by-products can exacerbate environmental degradation and intensify the growing problem of industrial waste management.

This study aims to address these challenges by utilizing wood ash as an aluminosilicate source and textile wastewater as an alkali activator to produce Geopolymerized Mud Concrete. Given the rising environmental concerns surrounding industrial waste disposal,

this approach presents an opportunity to incorporate industrial by-products into concrete mixes, contributing to more sustainable construction practices

2. MATERIALS AND METHODS

Figure 1 illustrates the systematic approach followed to develop the novel Geopolymerized Mud Concrete mix.

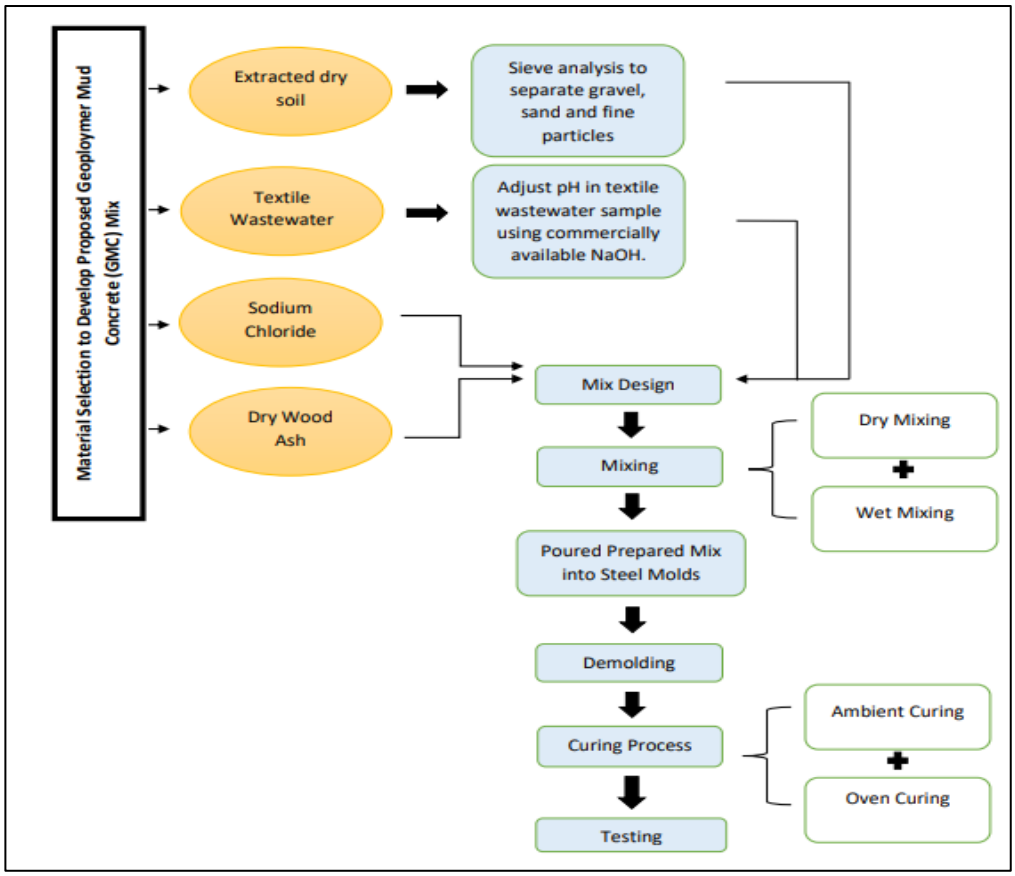


Figure 1: Experimental setup

2.1 MATERIAL SELECTION AND PREPARATION

The materials used to produce novel geopolymer mud concrete mix include mainly soil, wood ash, textile wastewater, and NaCl. The soil for this experiment was taken from the University of Moratuwa premises, a homogeneous layer at a 600 mm depth below the existing ground level and removed the organic matter. The soil was then sun-dried, or oven-dried to remove moisture. After that, dried soil was subjected to sieve analysis to meet standardized requirements for each fine (sieve sized below 0.425 mm), sand (sieved sized 0.425 mm – 4.75 mm), and gravel (sieved sized 4.75 mm – 20 mm) particles to make the proposed concrete mix. Dry sieve analysis and grading curves were prepared according to the BS 1377-2:1990 standard. Figure 2 shows a visual representation of the particle size distribution of soil, showing the percentage of particles that pass through each set of sieve sizes. For the analysis, the weight retained on each sieve was recorded. Then cumulative percentages were calculated. Finally, these values were plotted on a graph of a particle size (X axis- log scale) against cumulative percentage passing (Y axis- linear scale), creating a gradation curve. Here, sand and gravel particles were typically more stable and better suited for use in proposed Geopolymerized Mud Concrete. Fine

particles may have higher compressibility and lower strength. The sample "A" was selected for the study from among the soil samples on the following graph (Figure 02).

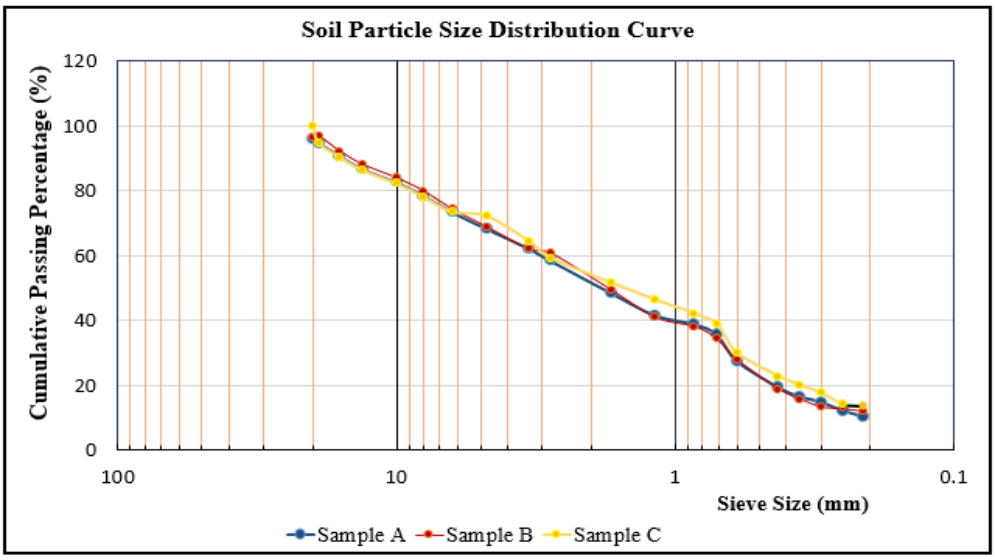


Figure 1: Particle size distribution of soil

Wood ash contains a high amount of silica and alumina compounds, which makes this suitable as an aluminosilicate source material for the proposed mix. Due to its high pH and potential to act as a catalyst in the geopolymerization reaction, textile wastewater was chosen as an alternative alkaline activator for this study. Both wood ash and textile wastewater were obtained from the textile manufacturing industry in Sri Lanka. The pH of the textile wastewater sample was measured using a pH meter. However, due to variations in the factory's production process during the experimental period, the pH of the wastewater fluctuated slightly, ranging between 9 and 10. Therefore, the pH of the textile wastewater was adjusted to the desired value by adding commercially available NaOH. The pH value in the received textile wastewater samples was measured every day before casting the cube.

Additionally, NaCl was used to increase the ionic strength of the alkali solution. This ionic environment may help to dissolve silica (SiO_2) and alumina (Al_2O_3) from wood ash. Also, it helps to speed up the setting time of geopolymer concrete, enhancing the durability of the resulting matrix and potentially improving its compressive strength.

2.2 CHARACTERIZATION OF MATERIALS

2.2.1 Characterization of Wood Ash

Scanning Electron Microscopy with Energy-Dispersive Spectroscopy (SEM-EDX) analysis was performed to characterize the morphology and elemental composition of the wood ash sample. This analysis helps to understand the microstructural and chemical properties essential for its application as a precursor in geo-polymer concrete. SEM micrographs of wood ash showed diverse particle sizes with shapes (Figure 3). Wood ash particles also showed higher porosity. These particle shapes can influence to the mechanical properties of geo-polymer concrete and may also reduce the workability of the concrete mix. Larger particles could indicate unburned carbon, which could impact the geo-polymer concrete workability, reactivity, and strength development. Smaller

particles, especially those with a large surface area, are important for enhancing reactivity in geopolymerization, because they provide more chances for chemical reactions.

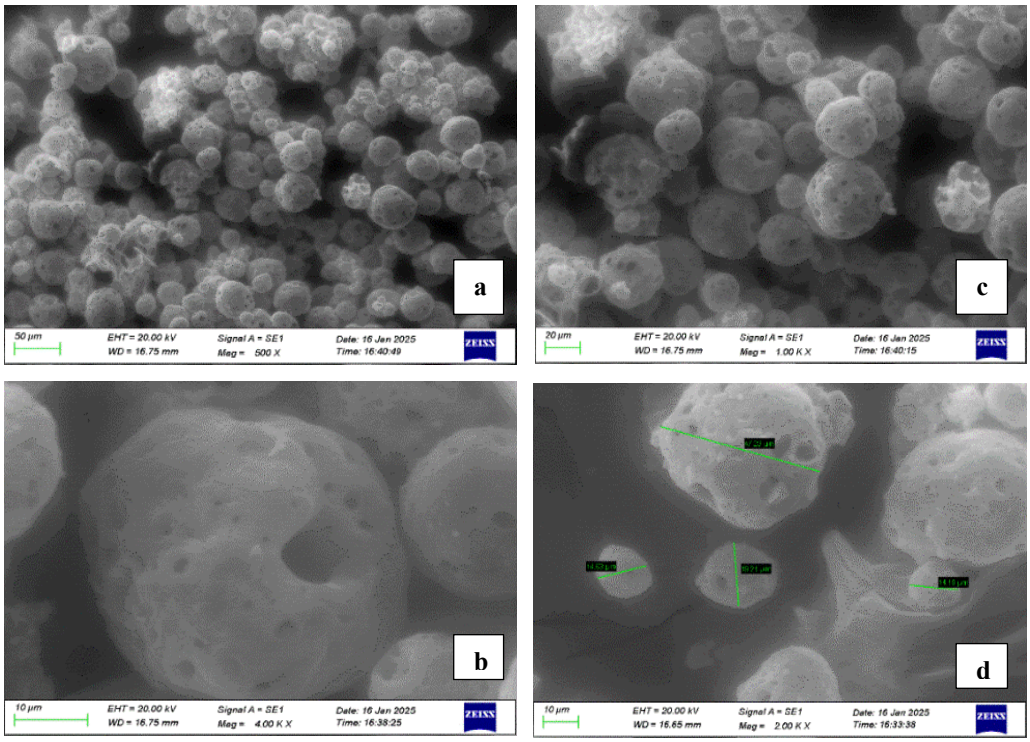


Figure 2: Surface morphology of wood ash (a)- 50 µm size, 500× magnification, (b)- 20 µm size, 1.00 K × magnification, (c) 10 µm size, 4.00 K × magnification, (d)- 10 µm size, 2.00 K× magnification

According to SEM/EDX analysis (Figure 4), the present wood ash sample has contained higher weight of carbon (42.74 wt%) content when compared to other elements, indicating a significant amount of unburned organic matter. It may reduce the compressive strength of geopolymer concrete and inconsistent strength development. Furthermore, in this sample show low silicon (0.35 wt%) by weight and aluminium (0.56 wt%) by weight content.

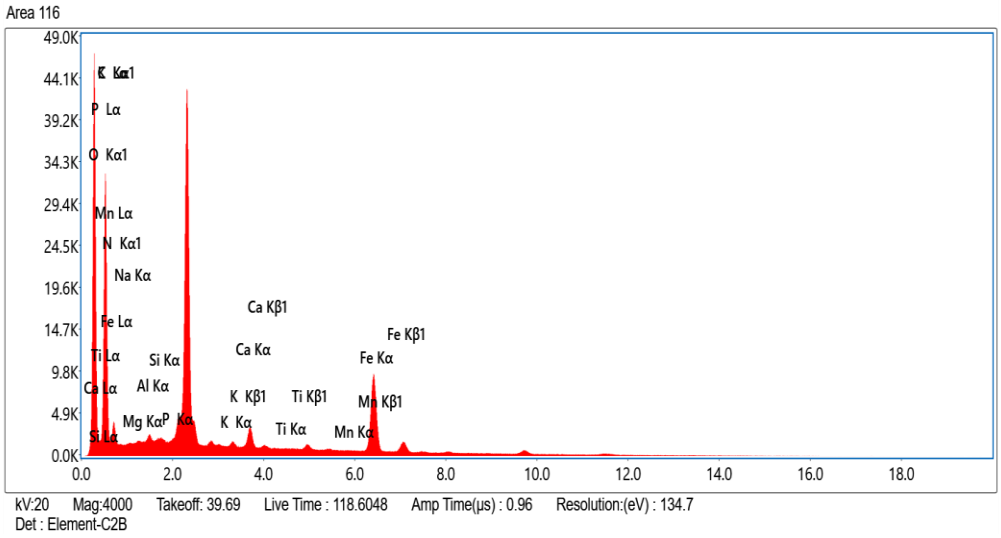


Figure 3: Elemental composition spectrum of wood ash

2.2.2 Functional Groups of Textile Wastewater

Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted to identify the functional groups present in the textile wastewater sample and assess its suitability as an alkaline activator for geo-polymerization. Key functional groups that affect its chemical reactivity and alkalinity, such as hydroxyl (-OH), carbonyl (C=O), sulfate ($-SO_4^{2-}$), and silicate (Si-O) groups, were detected by the FTIR spectrum (Figure 5). A large quantity of free hydroxyl (-OH) groups is shown by a significant absorption peak in the 3800–3900 cm^{-1} region, indicating that textile wastewater has strong alkaline characteristics. These hydroxyl groups play a crucial role in geopolymerization by promoting the dissolution of aluminosilicate precursors, which is essential for the formation of geopolymer bonds. Furthermore, a peak at about 1630 cm^{-1} that is associated with C=O stretching suggests the existence of carbonyl compounds, which could be the result of chemicals used in textile manufacturing. The presence of sulfate ($-SO_4^{2-}$) groups in the 1100–1200 cm^{-1} range suggests possible interactions with aluminosilicate materials during the activation process.

The functional groups present in the textile wastewater sample confirm its suitability as an alternative alkaline activator for geopolymer mud concrete. Its high hydroxyl (-OH) content enhances the breakdown of silica (SiO_2) and alumina (Al_2O_3), facilitating the geopolymerization reaction.

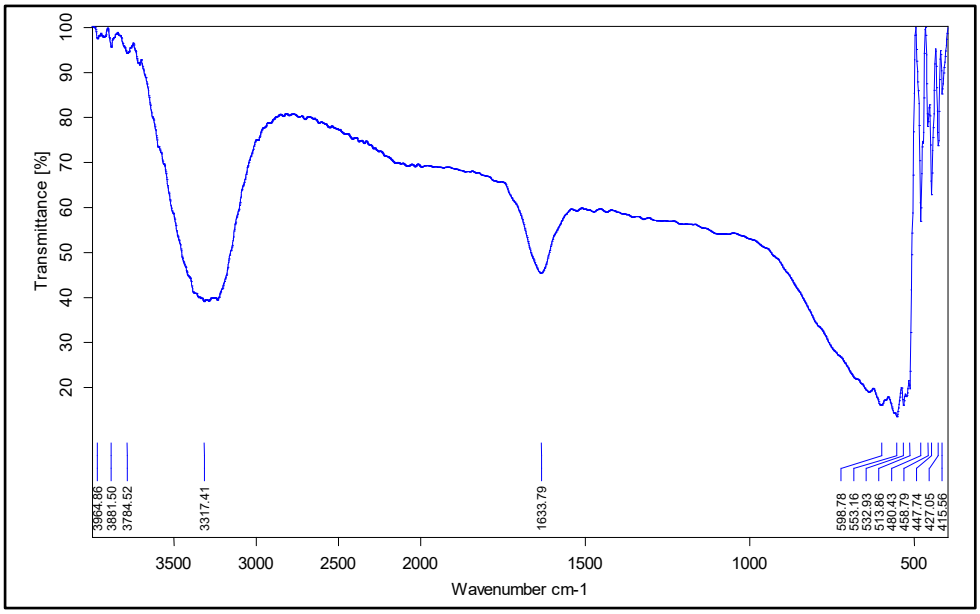


Figure 5: FTIR spectrum for textile wastewater

2.3 MIX DESIGN

There are currently no proper standard guidelines or norms for developing a geopolymer concrete mix. Because geopolymer concrete is still developing with multiple alternative materials. However, we can gain some idea from the literature by referring about previous studies conducted by multiple researchers. In the absence of standardized guidelines, researchers have developed and tested various mix proportions through multiple studies. For example, as shown in Table 1, the literature suggests an optimum mix proportion for coal fly ash-based geo-polymerized mud concrete that has demonstrated success in maintaining strength, workability, and durability.

Table 1: Mix design of coal fly ash-based geopolymerized mud concrete
Source: (Udawattha & Halwatura, 2018)

Material	Optimum Percentage
Coal Fly ash	20%
NaOH	5%
NaCl (Common salt)	2%
Soil	
Fine	5%
Sand	50%
Gravel	45%
Water	20% (from dry mix)

The soil and NaCl content of the mix were kept constant when casting cubes throughout this study. The soil proportion was set at 5 % fine, 45 % sand, and 50 % gravel from the total soil percentage. 2 % NaCl (Common Salt) was used for each set of cubes to increase the ionic strength of the mixture. Also, curing temperature & curing time were maintained at 100˚C and 24 hrs., respectively.

In this study, the moisture content was optimized first. As the first step, a workable concrete mix was developed for various wood ash contents (10 %, 20 %, 30 %, 40 %). For each wood ash content, five different concrete mixes were prepared by varying the moisture content. Then slump diameter vs. moisture content and compressive strength vs. moisture content graphs were obtained. Based on these two graphs, optimum wood ash content and optimum moisture content were determined. In the second step, textile wastewater concentration was optimized. For that textile wastewater samples with four different pH values (pH 10, pH 11, pH 12, pH 13) were prepared while keeping the previously optimized constituents at a constant.

2.4 MIXING PROCEDURE

A small-scale material mixture was used to mix materials in the laboratory. Initially, dried materials were mixed thoroughly for 10 minutes to ensure even particle distribution and avoid material segregation. After that in the wet mixing, the prepared alkaline solution was gradually added into the mixture. This gradual addition ensures that the mix does not become too fluid, which could affect workability. The total mixing duration was 20 minutes, while mixing, the mix was checked from time to time for consistency and homogeneity.

2.5 CASTING TEST SPECIMENS, CURING, AND TESTING FOR COMPRESSIVE STRENGTH

Three test specimens for each concrete mix were prepared according to the BS EN 12390-2:2019 standard by using 100mm×100mm×100mm steel moulds. Then two heat-curing techniques were followed for the prepared test specimens. In the ambient curing process, prepared specimens were kept at room temperature inside the laboratory, while in the oven curing, prepared specimens were kept inside the oven for 24 hours under 100^0C. Finally, the compressive strength test was conducted at 7, 14, and 28 days in accordance with the BS EN 12390-3:2002 standard.

3. RESULTS AND DISCUSSION

3.1 WORKABILITY

For this study, a flow table test for fresh concrete was conducted according to the BS EN 12350-5:2009 standard. First, specimens were cast to determine the optimum moisture content of the workable mix by using a slump diameter for five different moisture contents in four different fly ash percentages. As literature includes, due to sticky characteristics of the alkaline activator solution, the workability of geopolymer concrete is lower than the conventional concrete.

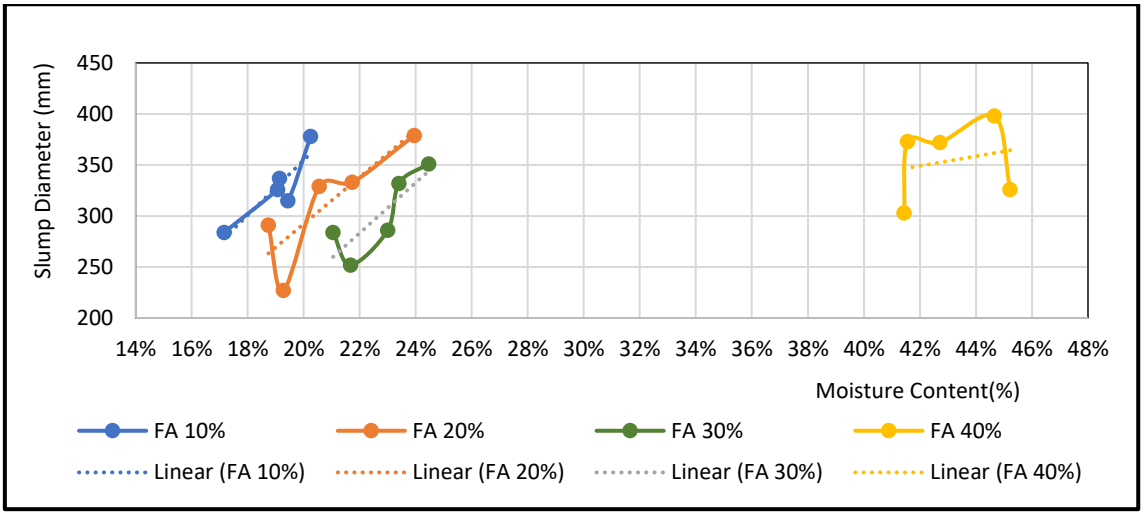


Figure 6: Slump diameter vs moisture content graph

As shown in Figure 6, the slump diameter was measured to evaluate the workability of the mix. Fly ash 20% showed higher and optimum workability. The researchers have stated, that the reduction in workability of concrete containing wood ash particles, irregular shape, and higher specific surface area.

3.2 DETERMINE OPTIMUM MOISTURE CONTENT AND OPTIMUM WOOD ASH CONTENT

Four different wood ash contents (10%, 20%, 30%, 40%) were subjected to study with 05 different moisture contents. Moisture content was varied while keeping the curing temperature at 100 ^{0}C for 24 hr and pH 13 in wastewater concentration at the same value (Figure 7, Figure 8, and Figure 9).

According to test results, 20 % of wood ash content by dry weight showed the highest compressive strength. A comparable result was obtained by literatures showed that higher wood ash contents may hinder workability, because of increased particle interactions. Excessively high percentages can result in poor bonding within the matrix (Ma et al., 2022). It was observed that the moisture content of around 20 % - 22 % provided optimal results to cast the proposed concrete cube.

When compared to 7 days, 14 days, and 28 days' dry compressive strength for the 40% wood ash, the maximum load wasn't shown in the test machine (Since max load ≤ 1kN).

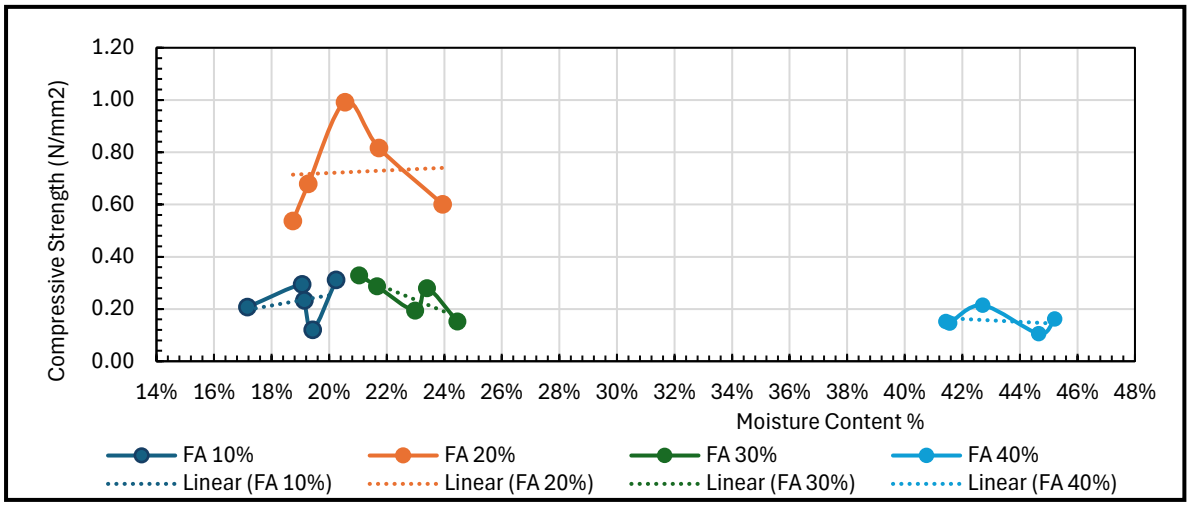


Figure 7: The effect of moisture content on dry compressive strength of various wood ash percentages after 07 days

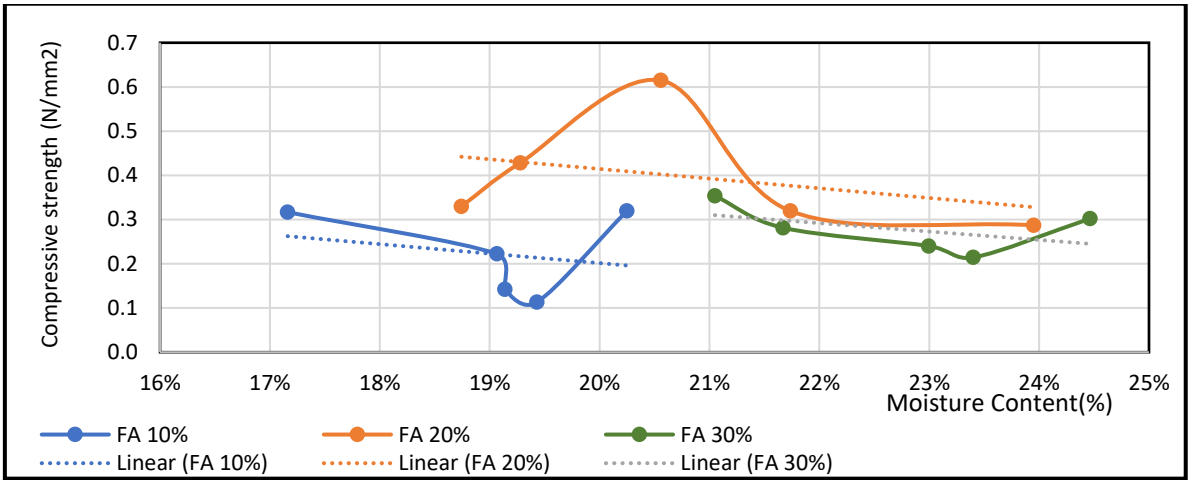


Figure 8: The effect of moisture content on dry compressive strength of various wood ash percentages after 14 days

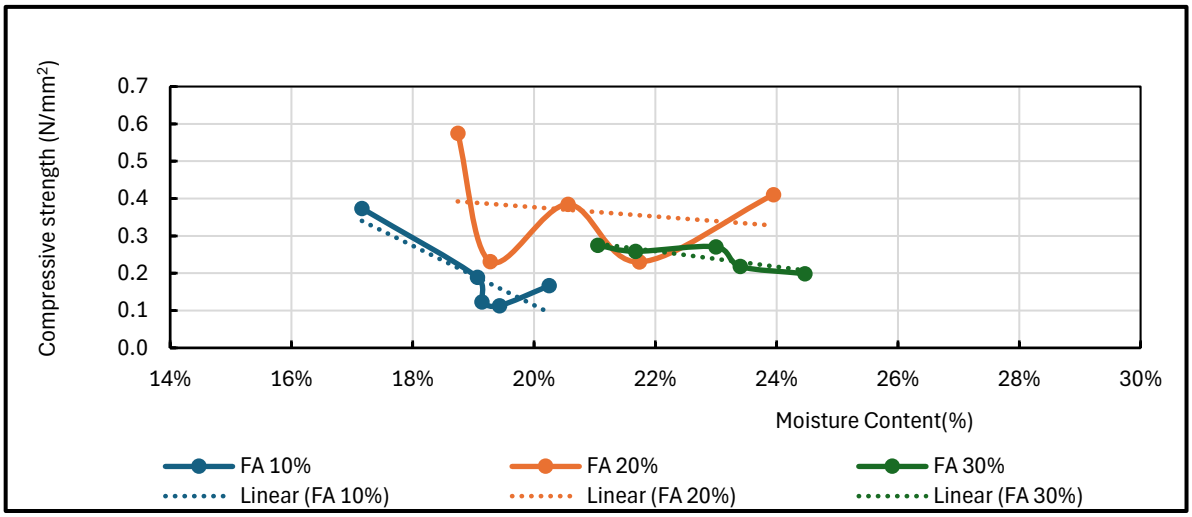


Figure 9: The effect of moisture content on dry compressive strength of various wood ash percentages after 28 days

3.3 DETERMINE THE OPTIMUM TEXTILE WASTEWATER CONCENTRATION

The concentration of the activator affects the strength properties of concrete and setting time (Tennakoon et al., 2017). Four different pH values (pH 10, pH 11, pH 12, pH 13) were used to optimize the textile wastewater concentration (Figure 10). Cubes were cast while keeping optimum moisture content at 20% - 22%, optimum wood ash content at 20 %, and curing temperature at 100˚C for 24 hrs. According to the results shown in Figure 10, pH 12 shows the highest dry compressive strength, and after this value strength decreased.

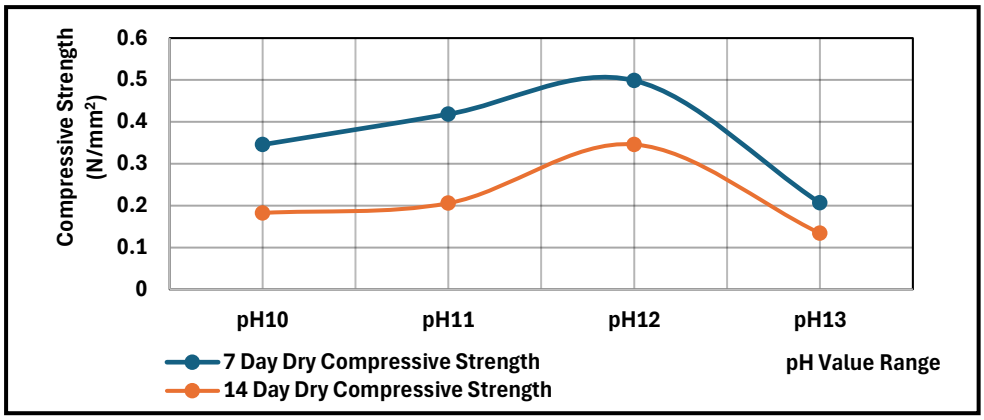


Figure 10: Dry compressive strength variation with different pH value

The obtain results, show that textile wastewater and wood ash can be effectively used to produce Geopolymerized Mud Concrete for sustainable construction. Based on this study, the optimum mix-20% wood ash, 20-22% moisture and pH 12 wastewater achieved higher compressive strength. FTIR analysis confirmed the suitability of textile wastewater as an alkaline activator. The SEM/EDX results showed that the wood ash sample consisted of a higher amount of unburned carbon content and various sizes of particles with higher porosity. Those are may also affect inconsistent strength development and increase water requirements

4. CONCLUSION

This study was conducted to develop existing Geopolymerized Mud Concrete as an eco-friendly alternative to cement-based concrete by using textile industry by-products. Results highlighted the wood ash content, textile wastewater concentration, and moisture content significantly influence the compressive strength of the developed material. The optimal mix- 20% wood ash, textile wastewater at pH 12 (replacing commercial NaOH) and 20% - 22% moisture (with a slump diameter 329mm) achieved a 7-day dry compressive strength of 0.9917 N/mm^2, which satisfied the minimum strength requirements for non-load bearing wall. This experimental result showed inconsistent strength development due to higher porosity and high carbon content of wood ash, which also minimized the mix from achieving wet compressive strength. These finding reflect the need for improve materials consistency to use industrial by-product to sustainable construction. Hence this research study supports the global transition towards low carbon waste-based building materials to prevent global emissions and waste minimization. Future research should be focused on optimizing materials properties and finding alternative methods to strength development of geopolymer mud concrete as a sustainable by product.

5. ACKNOWLEDGEMENTS

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